FINITE ELEMENT ANALYSIS AND TWO DIMENSIONAL NESTING OF SHEET METAL PARTS USED IN RAILWAY COACHES

A MAJOR PROJECT THESIS SUBMITTED

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
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IN
PRODUCTION & INDUSTRIAL ENGINEEERING

SUBMITTED
BY
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UNDER THE VALUABLE GUIDANCE
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<u>CERTIFICATE</u>

This is to certify that the major project work thesis entitled "FINITE ELEMENT ANALYSIS AND TWO DIMENSIONAL NESTING OF SHEET METAL PARTS USED IN RAILWAY COACHES" being submitted by SUKHVINDER SINGH, in partial fulfillment for the award of the degree of Master of Engineering (M.E.) in Production & Industrial Engineering of DELHI UNIVERSITY, is a record of bonafide research work carried out by him.

He has worked under my guidance and supervision and has fulfilled the requirements for the submission of the major project thesis. Further, it is also certified that this work has not been submitted for any degree or diploma in any college to the best of my knowledge and belief.

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SUKHVINDER SINGH

CHAPTER I

<u>INTRODUCTION</u>

In today's competitive environment it has become essential to reduce the cost. The most effective way to reduce cost is by reducing the raw material consumption. However the reduction in the raw material consumption should be carried out after proper planning and analysis so that there is no problem during the manufacturing stage. This becomes even more important in the industries in which raw materials form a large proportion of the cost of the finished product. The most common are the garment, ship-building and railway coach manufacturing industries.

It has been decided in this project work to carry out work on analyzing and validating the designed model of the parts under consideration for various stresses developed due to the different loading conditions. After analysis of the 3-D models of the parts then material consumption minimization has been done to reduce the amount of raw material sheets used for cutting the parts out of rectangular stocks. The parts under consideration are the C-type Carline, D-type Carline and the Bearing support.

As it has been decided in this project work to carryout the stress analysis of carline and bearing support and the material consumption minimization. There are many approaches for carrying out the stress analysis of the carline and bearing support. Experimental stress analysis by using strain gauges would have been a good approach. However, complicated shape of the carline would need very large number of strain gauges. Also the direction of the principal stresses being not known, one will have to use rosette analysis to make the work complete. S.G. analysis will require highly sophisticated equipment.

Because of the complicated shape of the carline, stress analysis by photo-elasticity method will also be difficult. Stress analysis by finite element method is obviously the best choice. Hence finite element technique has been selected for the analysis purpose.

With the availability of the commercial FE analysis software coupled to the solid modeler, it has been observed that finite element method is more convenient method for the component having complicated shape like carline.

Now as far as the material consumption minimization work is concerned, a vast number of different industries are regularly faced with the problem of cutting two-dimensional objects from a stock-sheet as the first stage of their manufacturing process. The problem of forming a cutting plan by laying out the pieces onto the stock-sheet has traditionally been solved manually by an expert. Human intelligence is well able to tackle such problems and many studies comparing layouts obtained using automatic processes with those produced by an in-house expert show the computer generated solutions to be inferior in terms of trim-loss. However there is still considerable interest in generating automatic computerized solutions. In some industries the expertise required to beat the best packages often takes several years to acquire and in others the time required to produce a manual solution may be many times that of the automatic process.

I have been working on the two-dimensional nesting method, which (in short) is the method of packing arbitrary two-dimensional shapes within the boundaries of some container. The objective can vary e.g. minimizing the size of a rectangular container or maximizing the number of shapes in the container, but the core problem which is

addressed is to pack the shapes tightly without any overlap. An example of a tight packing is shown in Figure 1.1.
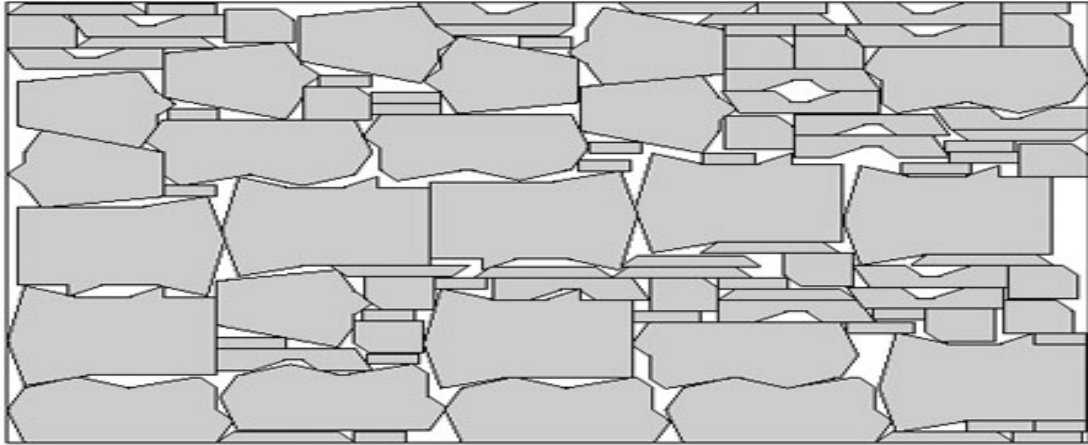
Figure 1.1: A tight packing using 86.5 % of the available area.

A substantial amount of literature has been written about this problem, where most of it has been written within the past decade. A survey of the existing literature is given in Chapter 2.

1.1 <u>Introduction to problem:-</u>

The carline parts are a very important component of the railway coach roof. As such the design of the carline becomes very important in order to minimize the weight and hence the cost. So it is desired to carryout the stress analysis of carline.

As stated above it has been decided to carryout the stress analysis of the carline and bearing support manufactured by rail coach factory, Kapurthala, using finite element technique.

The Figure 1.2 shows the two types of carline and bearing support for the analysis.

C-type carline   D-type carline
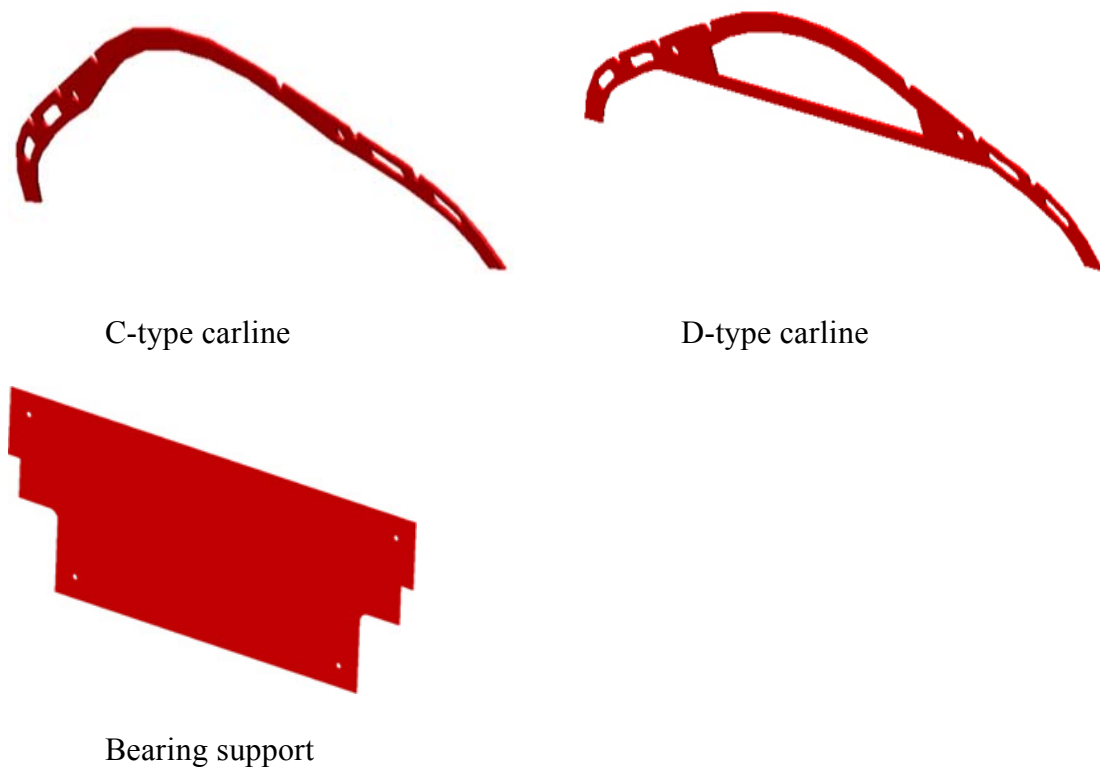
Bearing support

Figure 1.2:   Models of two types of carline and bearing support

The carline is manufactured by cutting the part out of the rectangular sheet of Corten steel material of 3500 x 1250 x 3 mm dimensions. The carline is welded on to the roof and the side walls of the coach. The loading on the C-type carline is mainly due to the electrical wiring passing through its slots and holes. In case of D-type carline, additional load of the AC ducting is applied on it. The bearing support is used in the door of the coach and it is used to cover the internal structure of the door. Hence the stress analysis has been carried out considering these loads only. As there are thirty four C-type carlines in a single coach, the load of the total electrical wiring is divided

equally between them. Also the load due to the AC ducting is equally divided between the eight D-type carlines.

Based on the results of the Finite Element Analysis, it has been concluded that the material and the thickness of the carline parts is sufficient according the loading conditions.

After the FE analysis, material consumption minimization has been done using two-dimensional nesting. The term nesting has been used to describe a wide variety of two-dimensional cutting and packing problems. They all involve a non-overlapping placement of a set of irregular two- dimensional shapes within some region of two-dimensional space, but the objective can vary.

Most problems can be categorized as follows (also see the illustration in Figure 1.3):

- *Decision problem.* Decide whether a set of shapes fit within a given region.

- *Knapsack problem.* Given a set of shapes and a region, find a placement of a subset of shapes that maximizes the utilization (area covered) of the region.

- *Bin packing problem.* Given a set of shapes and a set of regions, minimize the number of regions needed to place all shapes.

- *Strip packing problem.* Given a set of shapes and a width W, minimize the length of a rectangular region with width W such that all shapes are contained in the region.

As noted the region used for strip packing is rectangular and a typical example would be a cloth-strip in the textile industry. All other regions can have any shape. It could be animal hides in the leather industry, rectangular plates in the metal industry or tree boards in the furniture industry.
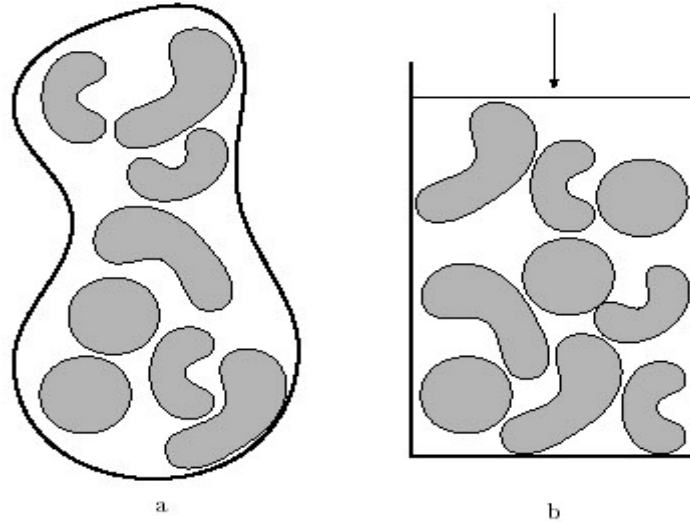
Figure 1.3: a) Most variants of the nesting problem is the problem of packing shapes within some region(s) without overlap (decision, knapsack and bin packing). b) The strip packing variant asks for a minimization of the length of a rectangular region.

In industrial settings a multitude of additional constraints are very often necessary, e.g. the shapes or regions can have different quality zones or even holes (animal hides). Historically, the clothing industry has had special attention. But even though this industry introduces a multitude of possible extra constraints to the problem, these constraints are often not included in the published solution methods. An exception is *Lengauer et al. [1]* who describe and handle a long range of the possible additional constraints posed in the leather and the textile industry. But most of the existing literature does not handle any additional constraints.

As indicated above the nesting problem occurs in a number of industries and it seems to have gotten just as many names. In the clothing industry it is usually called marker making, while the metal industry prefers to call it blank nesting or simply nesting. There is no consensus in the existing literature either. Some call the shapes irregular, others call them non-convex. In a theoretical context the problem is most often called the two-dimensional irregular cutting stock problem.

CHAPTER II

LITERATURE REVIEW

Applied mathematician Richard von Mises came up with the von Mises Criterion in 1913. Also known as the maximum distortion energy criterion, octahedral shear stress theory, or Maxwell-Huber-Hencky-von Mises theory, it is often used to estimate the yield of ductile materials.

Von Mises stress, σ_v, is used to estimate yield criteria for ductile materials. It is calculated by combining stresses in two or three dimensions, with the result compared to the tensile strength of the material loaded in one dimension. Von Mises stress is also useful for calculating the fatigue strength.

Stress is in general a six-dimensional tensor quantity (a symmetric 3×3 tensor). Von Mises stress reduces this to a single number (a scalar) for the purposes of calculating yield criteria.

Von Mises stress in three dimensions is

$$\sigma_v = \sqrt{\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}{2}}$$

where

$$\sigma_1, \sigma_2, \sigma_3$$

are the principal stresses. In the case of plane stress, σ_3 is zero.

Finite element analysis results are typically presented as Von Mises stress.
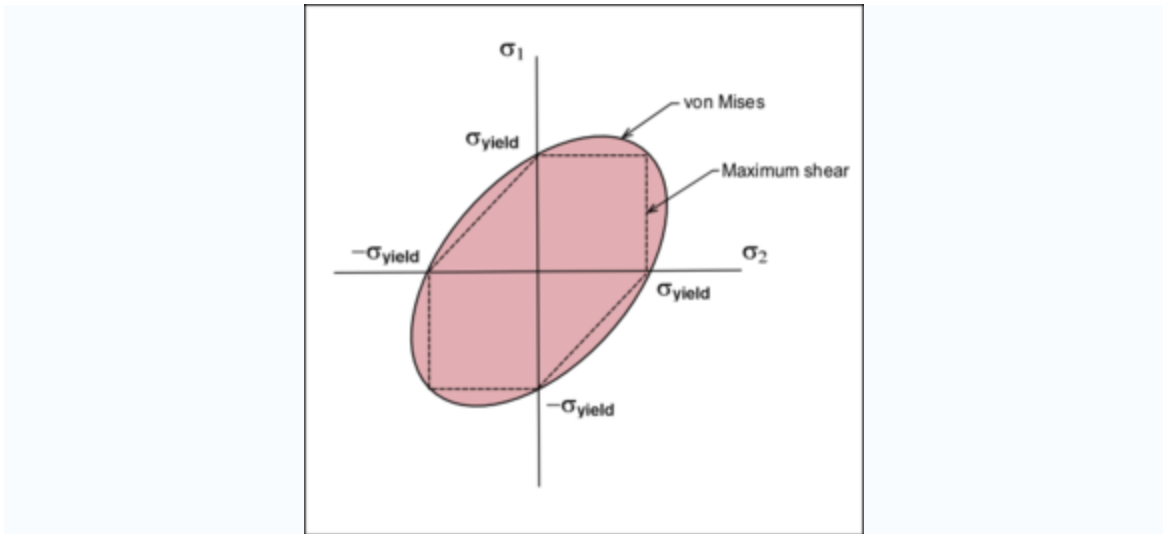
Figure 2.1: Von Mises ellipse

The Von Mises criterion states that failure occurs when the energy of distortion reaches the same energy for yield/failure in uniaxial tension. Mathematically, this is expressed as,

$$\frac{1}{2}\left[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2\right] \leq \sigma_y^2$$

In the cases of plane stress, $\sigma3 = 0$. The Von Mises criterion reduces to,

$$\sigma_1^2 - \sigma_1\sigma_2 + \sigma_2^2 \leq \sigma_y^2$$

Also shown in the Figure 2.1, is the maximum shear stress (Tresca) criterion (dashed line). This theory is more conservative than the Von Mises criterion since it lies inside the Von Mises ellipse.

In addition to bounding the principal stresses to prevent ductile failure, the Von Mises criterion also gives a reasonable estimation of fatigue failure, especially in cases of repeated tensile and tensile-shear loading. Therefore, for the analysis of carline, I have calculated Von Mises stresses.

Since the 1950s the nesting problem has received considerable attention because of the extensive use of computers, which have provided fast and economical computation, number crunching power, and the development of optimization techniques. A method of solving a version of the two-dimensional cutting-stock problem was given by *Adamowicz and Albano [4]*. In their version of the problem one was given a number of rectangular sheets and an order for a specified number of each of certain types of rectangular shapes. They observed that when an experienced person approached the problem of laying out rectangles on a rectangular sheet, he usually tried to lay the rectangles out in groups. In order to simplify the problem and speed up the solution he often attempts to lay out sets of shapes having at least one common dimension, so as to form large rectangular strips and blocks. Moreover he would backtrack: he would remove some part of the current layout and reposition the shapes. Although such an approach seldom provided an optimum solution, the solutions were usually extremely good.

The approach is centered on an iterative procedure that first decided whether to fill a sheet or a rectangular subpart of it. Then it generated candidate groupings of rectangles called strips and select a subset of them to layout on the sheet part currently under examination. If that general layout was not acceptable, a different subdivision of the sheet was decided. Otherwise the algorithm determines a new subset to fill and the procedure was repeated as long as there were pieces to allocate. When the algorithm terminates, it did not in general yield the true minimum waste solution. However the complete process was quite efficient in terms of computer time.

Extending their work further **Adamowicz and Albano [5]** published another paper on nesting two-dimensional shapes in rectangular modules describing an algorithm for

clustering irregular pieces in rectangular modules. Each piece was marked by a processing option. The set of options available to the user permits him to determine the types of clustering produced and to control the amount of processing time required per shape type. The principal task of the algorithm was to accept an order for a specified number of various types of shapes (which may include irregular as well as rectangular shapes) and to produce a list of rectangular modules. These modules will, in general, be obtained from:

1. Rectangular shapes

2. Rectangular enclosures for irregular shapes

3. Rectangular enclosures for pairs of irregular shapes

4. Rectangular enclosures for various clustering are of irregular and rectangular shapes.

The algorithm assumed that each shape is either a rectangle or a polygon. A rectangle is described by giving its length and width. The reference point of a rectangle is originally assumed to be its lower left-hand corner. A polygon is described by providing a list of the points (vertices) of the polygon given in a counter-clockwise (CCW) direction. The co-ordinates of each point of the polygon are given relative to the polygon reference point, which may or may not lie on the point on the original polygon. Using these representational schemes one could completely describe the placing of a shape (rectangle or polygon) by specifying the position of the reference point and the orientation (CCW) of the shape about the reference point.

An alternative method for completely describing the placing of a shape, often useful at various stages of the processing of polygons, involves translating and rotating each point of the polygon. Suppose that one wish to rotate a given polygon by θ degrees

CCW about the reference point (x_0, y_0) and then translate it by $(\Delta x, \Delta y)$. Then for each point (x_i, y_i) one can compute the corresponding point (x'_i, y'_i) of the repositioned polygon as follows:

$x'i = x_i \cos \theta - y_i \sin \theta + \Delta x$

$y'i = x_i \sin \theta - y_i \cos \theta + \Delta y$

The position of the reference point remains the same.

A paper by *Sanders and Bronsoiler [6]* can also be classified as a heuristic search approach. They appeared to be the first authors who developed method for objective testing of irregular parts nesting algorithms. With a fractional factorial design and a specially designed random generator for irregular parts, they tested sensitivity of their algorithm to several variables, such as part sizes, part shapes and number of parts in the BOM. Their algorithm accepts a variety of irregular shapes and when adding another part to the existing nest, the algorithm tries the various possible orientations of the part (by rotating the part) in various possible locations along the upper and right sides of the existing nest. The price they paid for the flexibility is a requirement of considerable computing time. For a BOM with five types of parts, the time required per sheet was around 3 minutes on a small desktop microcomputer. For situations where BOM is relatively large, or where inventory or sheet sequence selection problems are under study, a faster heuristic method is required.

Qu and Sanders [7] developed an algorithm that considered the entire bill-of-materials at one time and laid out several sheets at the same time. They also introduced an automatic algorithm for nesting of irregular-shaped parts, whose geometries are approximated by a composite of non-overlapping rectangles. They performed a test using a randomly generated bill-of-materials and showed that the algorithm is efficient,

in terms of computation time and material usage. The time required for nesting each sheet was linearly related to number of unique parts and the number of parts laid on that sheet. The maximum length of time for laying one sheet was about 25 seconds. But, the major limitations of their algorithm are the approximation of blank geometry by non-overlapping rectangles and the assumption that good layout patterns will not be non-orthogonal.

Another approach researched over the past decade is the No Fit Polygon NFP approach. In nesting problems the combinatorial problem coexists with a geometric problem, since solutions must be "geometrically" feasible: pieces may not overlap and must completely fit inside the plate. The concept of nofit polygon was used by *Albano [8]*.

The nofit polygon of piece B relative to piece A (NFP_{AB}) is the locus of points traced by the reference point of B, when it slides along the contour of A. The relative orientations of A and B are maintained during this orbital movement. Piece B (the orbital piece) must never intersect piece A (the stationary piece) and they must be always in contact (see Figure 2.2).
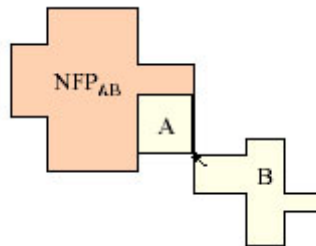
Figure 2.2:   The no fit polygon of piece B relative to piece A.

From this definition it immediately follows that:

- If the reference point of piece B is placed in the *interior* of NFP$_{AB}$ then B *intersects* A.

- If the reference point of piece B is placed on the *boundary* of NFP$_{AB}$ then B *touches* A.

- If the reference point of piece B is placed in the *exterior* of NFP$_{AB}$ then B *does not intersects or touch* A.

To achieve a feasible (non-overlapping) and tight layout, each piece should have its reference point in the boundary of at least one nofit polygon relative to another piece and in the exterior of the nofit polygons relative to all the other pieces. The combinatorial problem arises when choosing a placement point for each piece, among its set of feasible placement points, knowing that the choice made will restrict the feasible set of placement points of all the other pieces.

Another approach researched by *Jeffrey W. Herrmann and David R. Delalio [9]* is based on Dynamic Nesting. The manufacturer uses a manufacturing planning and control system that maintains a master production schedule. The planning system uses material requirements planning (MRP) to explode the end-item requirements into work orders for components and subassemblies. Also, the planning system has detailed routings (process plans) that specify the resources required for each product. Thus, production planners can identify, for next week and each week after that, the orders that will require the punch presses in the sheet metal area. (In this setting there are no filler parts available for consuming remaining open areas.)

Because the product mix changes greatly each week, the sheet metal area will use dynamic nesting to nest the orders. Dynamic nesting periodically considers the specific orders to be punched in the next period and creates customized nests for those

orders. That is, before each week, the production planners will identify and nest the orders that will be released into the shop that week. Orders that require the same NC punch press, the same material type, and the same sheet thickness can form a nest. Then, the production planners will use existing software that arranges the required parts on the minimum number of unsheared sheets, leaving room for the clamping area and leaving room between the parts. This software also creates the required NC program by combining the NC programs for each different part. After the orders are released, the operator loads this NC program onto the punch press and starts punching the nest, loading unsheared sheets and removing punched sheets as required. Punched sheets are sent to a deburring operation, where an employee removes the individual parts from the sheet, removes any burrs from the part, and sorts the parts into the individual work orders for additional processing. For a simple example, consider Figure 2.3
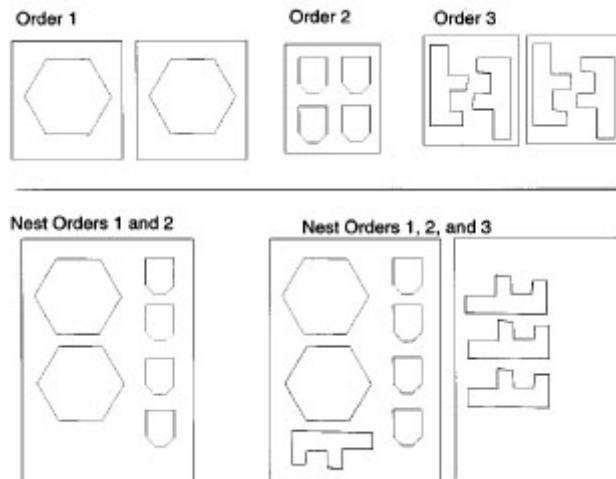
Figure 2.3: Three orders and two possible nests.

Order 1 requires two parts, one on each sheared sheet. Order 2 requires four parts, all on one sheared sheet. Order 3 requires four parts, two on each sheared sheet. All three orders require the same material type and thickness. Thus, they can form a nest. Nesting all three orders creates the nest in the bottom right of the figure. The nest

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requires two unsheared sheets. If the nest includes only Orders 1 and 2, then the nest requires only one unsheared sheet, as shown in the bottom left of the figure. Order 3 is processed separately.

CHAPTER III

<u>FE ANALYSIS OF CARLINE</u>

3.1 <u>Overview of FEM</u>:-

The finite element method is a numerical technique, well suited to digital computers, which can be applied to solve problems in solid mechanics, fluid mechanics, heat transfer and vibrations. The procedures to solve problems in each of these fields are similar; however this discussion will address the application of finite element methods to solid mechanics problems. In all finite element models the domain (the solid in solid mechanics problems) is divided into a finite number of elements. These elements are connected at points called nodes. In solids models, displacements in each element are directly related to the nodal displacements. The nodal displacements are then related to the strains and the stresses in the elements. The finite element method tries to choose the nodal displacements so that the stresses are in equilibrium (approximately) with the applied loads. The nodal displacements must also be consistent with any constraints on the motion of the structure.

The finite element method converts the conditions of equilibrium into a set of linear algebraic equations for the nodal displacements. Once the equations are solved, one can find the actual strains and stresses in all the elements. By breaking the structure into a larger number of smaller elements, the stresses become closer to achieving equilibrium with the applied loads. Therefore an important concept in the use of finite element methods is that, in general, a finite element model approaches the true solution to the problem only as the element density is increased.

3.2 Basic steps in FEM :-

Stress analysis using finite element method has become highly popular, economical and versatile method. Many design engineers are familiar with finite element method; however the basic steps in FEM for stress analysis are described in short as follows.

1. Discretization of the continuum :-

   The Discretization is simply to sub-divide given body into an equivalent system of finite elements. The finite elements may be triangles, quadrilaterals, tetrahedrons etc. depending upon the type of analysis.

2. Selection of the displacement models :-

   The assumed displacement functions or models represent only approximately the actual distribution of the displacements. A displacement function is commonly assumed in polynomial form.

3. Derivation of the element stiffness matrix :-

   The stiffness matrix consists of the coefficients of the equilibrium equations derived from the material and the geometric properties of the element. The equilibrium relation between the stiffness matrix [k], nodal force vector {Q} and the nodal displacement vector {q} is expressed as below.

   $$[k]^e \{q\}^e = \{Q\}$$

4. Assembly of the algebraic equations for the overall discretized continuum :-

   The process includes the assembly of the overall stiffness matrix for the entire body from the individual element stiffness matrices and the overall force vector from the element nodal force vectors. The overall equilibrium relations between the total stiffness matrix [k], total load vector {R} and the nodal displacement vector {r} will be as below.

[k] {r} = {R}

These sets of equations can be solved by making use of boundary conditions.

5. Solution for unknown displacements :-

The algebraic equations assembled in step 4 are solved for unknown displacements by using matrix algebra techniques.

6. Computation of the element strains and stresses :-

More often, stresses/strains are computed from the nodal displacements calculated in step 5. Usually the stresses are calculated at the center of the element.

In the present work FE analysis of the carline and bearing support has been carried out using ANSYS 9.0 package.

3.3 About ANSYS Multiphysics 9.0 package

ANSYS is a general purpose finite element modeling package for numerically solving a wide variety of mechanical problems. These problems include: static/dynamic structural analysis (both linear and non-linear), heat transfer and fluid problems, as well as acoustic and electro-magnetic problems.

1. ***Preprocessing: defining the problem***; the major steps in preprocessing are given below:
    * Define Key points/lines/areas/volumes

    * Define element type and material/geometric properties

    * Mesh lines/areas/volumes as required

The amount of detail required will depend on the dimensionality of the analysis (i.e. 1D, 2D, axi-symmetric, 3D).

2. ***Solution: assigning loads, constraints and solving***;
    Here we specify the loads (point or pressure), constraints (translational and rotational) and finally solve the resulting set of equations.

3. ***Post processing: further processing and viewing of the results;*** in this stage one may wish to see:

- Lists of nodal displacements

- Element forces and moments

- Deflection plots

- Stress contour diagrams

3.4 <u>Features of ANSYS 9.0</u>

- Analysis of one dimensional , two dimensional and three dimensional finite element models
- Linear and nonlinear analysis
- Static & Dynamic analysis
- Heat Transfer Analysis
- Multi Point Constraints facility
- Elastic, Creep Material Models
- Buckling Analysis
- Big Element Library
- Preprocessing facility
- Post-processing facility

3.5 <u>Analysis:-</u>

Following are the different stages of FE analysis discussed in detail using the ANSYS 9.0 software.

3.5.1 <u>Pre-Processing:-</u>

This stage involves preparation of the geometric model using Pro Engineer (Wild-fire 2.0) solid modeler. The model is discritized selecting the suitable finite element boundary conditions like fixity etc. as well as material properties are also given at this stage.

3.5.1.1. Geometric Modeling:-

Geometric modeling is the process of generating three-dimensional objects of the real world for the purpose of analysis, design, drafting and manufacturing etc. Geometry of the part can be created in several different ways. These include starting from primitives. A key philosophy in geometric modeling is to sketch sections on work plane or on a face of an object and modify the dimensions later. Geometric modeling creates a data base in the computer, which represents the object generated. This object database is used to display the object, to prepare drawings of the object with different views, to prepare data for analysis and design and also to manufacture the object using CNC machines. There are three types of geometric models commonly used to represent physical objects. They are as follows:

- Wire-Frame Modeling

- Surface Modeling

- Solid Modeling

a) Wire-Frame Modeling

Figure 3.1 shows an example of wire frame model. As seen from the figure it consists of finite set of points, lines or polygons in space. Point, line and polygon are basic elements of the wire frame modeling. In wire frame model, the equations of the boundary curves of the object are stored. Wire frame models are used to create models of simple objects.

Figure 3.1: Wire-frame Model

Many CAD systems provide wire frame Modeling where a sequence of commands generate wire frame models of three dimensional objects, first generating points and lines and then applying Modeling transformation like translation, rotation and scaling. In the construction of wire frame model, the edges of the object are shown as lines. For object in which there are curved surfaces, contour lines can be added to indicate contour. The image assumes the appearance of frame construction out of wire – hence the name "Wire-Frame" model.

Wire-frame models are easy to create and use. In many cases they are quite adequate for two-dimensional representation.

Limitations:

- There are limitations to the models, which use the wire-frame approach to form the image, especially in the case of three-dimensional models. All of the lines that define the edges of the model are shown in the image. Consequently, the lines that indicate edges at the rear of the model are also shown. This can cause the image to be somewhat confusing to the viewer.

- With a just wire frame representation, it is impossible to check for three-dimensional interference, since there is no representation for the surface between wires.

- As it does not distinguish between inside and outside of the surface of the object they are inadequate to be used for generating cutting path to drive NC machine to manufacture the objects.

Applications/ Uses:

- Enhancing visualization of 3D objects.

- Automatically generating standard and auxiliary views.

- Generating a wire frame on which to create surfaces.

- Visual interference checking.

- Reducing the need to create prototypes.

- Approximating volume & mass.

- Perspective viewing.

b) Surface modeling

Figure 3.2 shows an example of surface modeling. In surface modeling, surface entities are introduced to the wire frame model. Surface models define part geometry more precisely, as compared to the wire frame model. A surface model stores equations representing each of the surfaces of an object as well as the edge boundaries. Many methods are available to generate the surfaces. Objects with complex shapes are generated by combining planes, ruled surfaces of revolutions, sweep surfaces and fillet surfaces.
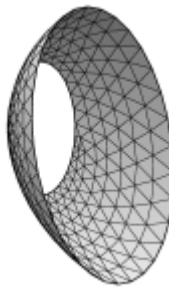

Figure 3.2:   Surface model

An object generated through surface modeling can be displaced on a screen, in such a way that it look like a solid object. Techniques like hidden surface removal and hidden line removal makes to display the objects as a solid object and can be viewed from any point.

Limitations:

- In surface model, it may still be difficult to check for interference, since we might not know for sure which is the inside or the outside of each surface. For the same reason, it will be difficult to compute mass inertial of such an object, especially if the surface model is not completely closed.

- As these models also do not truly represent the solid nature of the object, a still higher level of sophistication is required in geometric modeling, which makes it possible to represent the information on the solid nature of the object, which is necessary to carry out engineering analysis of the object.

Applications:

Surface modeling is applicable for analysis of aircraft and automobile surfaces. A fancy animated 3D graphics generated for television "flying logos" only need surface modeling, since mass properties and other mechanical applications are not a concern.

c) Solid Modeling

The example of solid model is as shown in the Figure 3.3. It contains enough information to fully describe the boundaries, surfaces and topology of the object. If we cut a solid object, the result is another solid object, not an ambiguous collection of partial lines or surfaces. Solid model is represented by volume. With this, interference volumes can easily be computed, and the properties of area, volume and mass can be calculated. The object can be displayed as hidden line removed or as shaded image to show clearly how the parts look like in three dimensions.
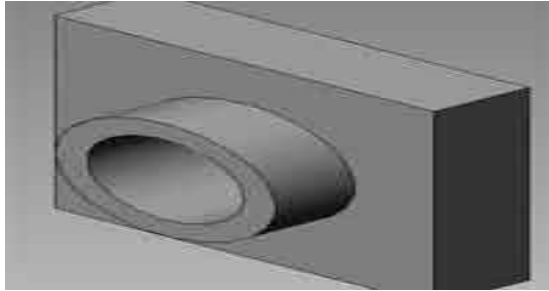
Figure 3.3: Solid model

Since solid modeling is complete representation, it can be used to support any type of design and analysis application that requires geometry information. These applications may include drafting, finite element analysis, packaging studies, kinematics, visual displays and manufacturing.

There are two methods used to construct solid models.

1. Constructive solid geometry (CSG):

This method uses basic shapes like cube, prism, cylinder, sphere etc. as primitives to build the model of complex objects. In this approach primitives are combined to generate complex objects by Boolean operations such as union, intersection, difference etc. The primitives are first positioned in the proper place and the Boolean operations are carried out.

CSG modeling is more useful to generate the shapes whose surfaces are more standard. The CSG method is slower, but has the advantage of greater accuracy and flexibility of making changes to the object.

2. Boundary Representation (BREP):

Boundary representation provides an efficient solution where the model has complex surfaces. In this approach, the perimeter on the boundary of the model is used to represent the solid objects. In this modeling both topology and geometry of solid models are defined and stored in database. The solid is first assumed to be made up of

surfaces, then the surfaces are formed by combining edges and finely the edges are formed by combining vertices. This representation contains all the necessary information regarding geometry of solid. The boundary representation is more suitable for generating different views of the solid model as well as for computing geometric and inertial properties.

Most commercial solid modeling programs are based on either Boundary Representation (BREP) or Constructive Solid Geometry (CSG). BREP modelers store results of operations (i.e. what exists after creation and manipulations), and CSG modelers store a history of the objects and operations required to construct the part. This geometric model is used for FE analysis.

3.5.1.2   Properties of Corten steel

Corten steel is a steel alloy that has a very high tensile strength. It is about twice as strong as sheet metal of comparable thickness. Hardness and tensile strength are important properties, but Corten's main advantage is its resistance to corrosion. Corten will not rust; rather it will oxidize slowly to a dull grey-brown color. Over time it may appear almost purple.

The chief application of Corten is in outdoor sculptures, marine vessel fabrication and as exterior facades for its rustic antique appearance. All the areas where rust and corrosion resistance is of extreme importance. Corten steel is also popularly used in bridge and other large structural applications. In some geography it may be known with the hyphen as "Cor-ten steel". This is the material which is used to make the railway coaches in Rail Coach Factory, Kapurthala.

Mechanical properties of Corten steel

It is essential to know physical and mechanical properties of the material. These are given below.

Table 3.1: Physical and mechanical properties of Corten steel

S.No.	Properties	Values
1.	Density (1000 kg/m³)	7.85
2.	Elastic Modulus (GPa)	190
3.	Poisson's Ratio	0.3
4.	Tensile Strength (MPa)	956
5.	Yield Strength (MPa)	648
6.	Hardness (Brinell 3000 kg)	150

3.5.1.3   Meshing:-

The meshing operation is a two step process. First the parameters defining the size and type of elements and other attributes are defined on the particular edges, surfaces or volumes of the part. The second step is to generate the mesh on this geometry.

Three-dimensional solid element tetrahedron type having a length of .75 mm for all side is selected, considering nature and shape of the carline. Figure 3.4 shows a ten node tetrahedral element having three degree of freedom at each node, i.e. translation in the nodal x, y & z directions. The element has large deflection and large strain capabilities. This element is used, since the use of this tetrahedron results in realistic geometry.
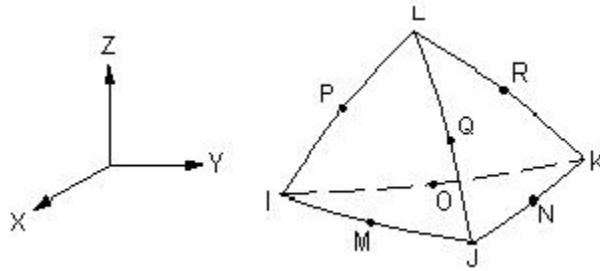
Figure 3.4: 10 Node Tetrahedral Element

The complete part is meshed by automatic free meshing option in meshing task of the ANSYS software. Figure 3.5 shows the meshing of the carlines.
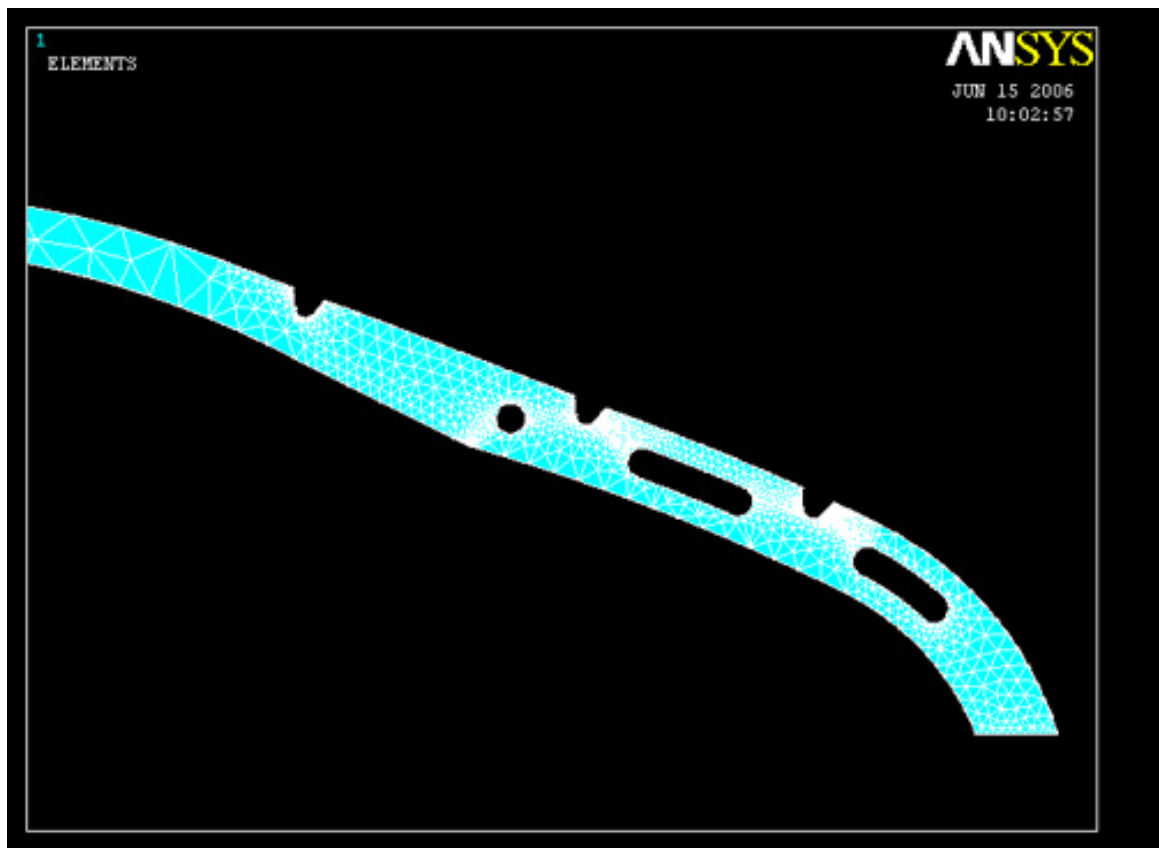
Figure 3.5a: Meshing of C-type Carline
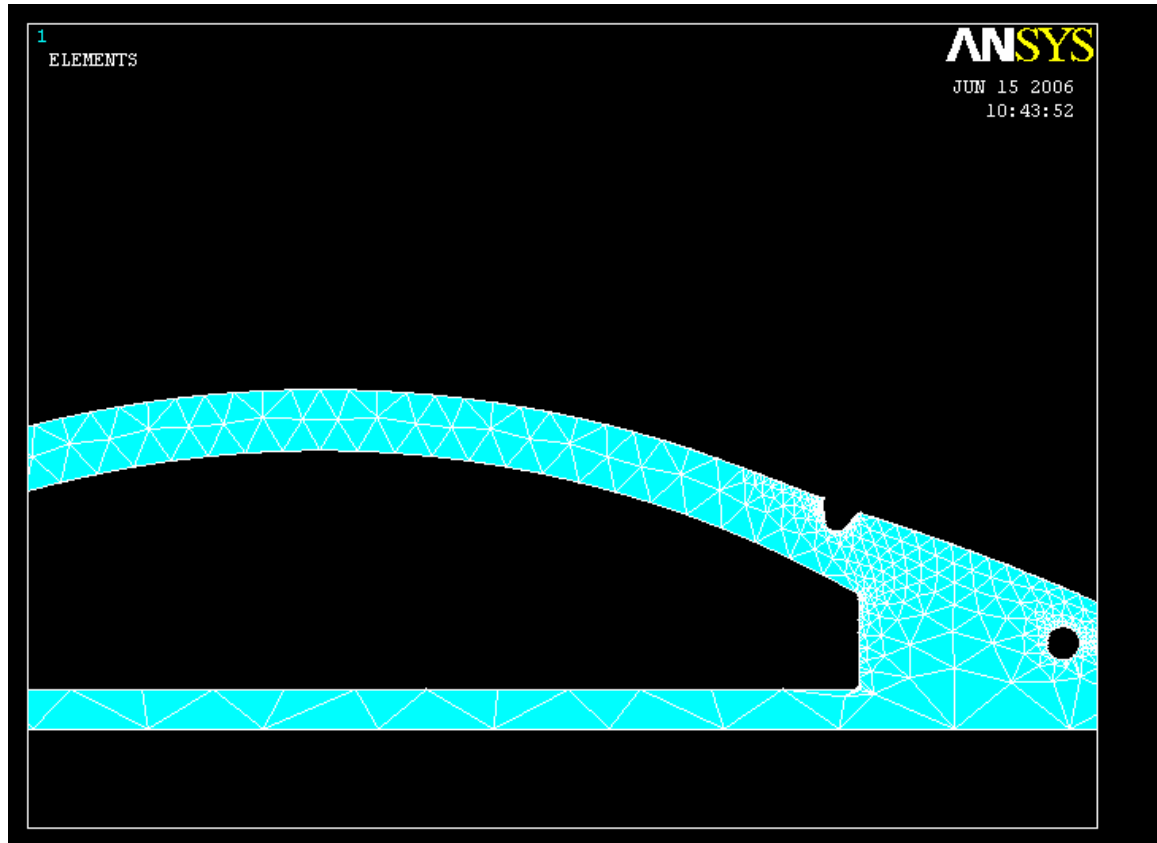
Figure 3.5b: Meshing of D-type Carline

Several checks are applied while giving the model for meshing. These are as follows.

- Element free edge check will plot the free edges of element not connected to another element.

- Check for duplicate nodes.

- Check for duplicate or missing elements.

- Check for distorted or warped element (Value given >04)

- Check for warping out of plane, interior angles, mid side node placements and coincident elements.

In first iteration the following data is obtained –

Table 3.2:   Details of Meshing

S.No.	Name of Part	Total number of tetrahedron	Total number of nodes
1.	C-type Carline	19756	41096
2.	D-type Carline	20010	41889

3.5.1.4 Displacement Condition:-

The carlines are welded on to the roof at the top surface and at the two bottom end surfaces. So the X, Y, Z translations at those nodes is zero.
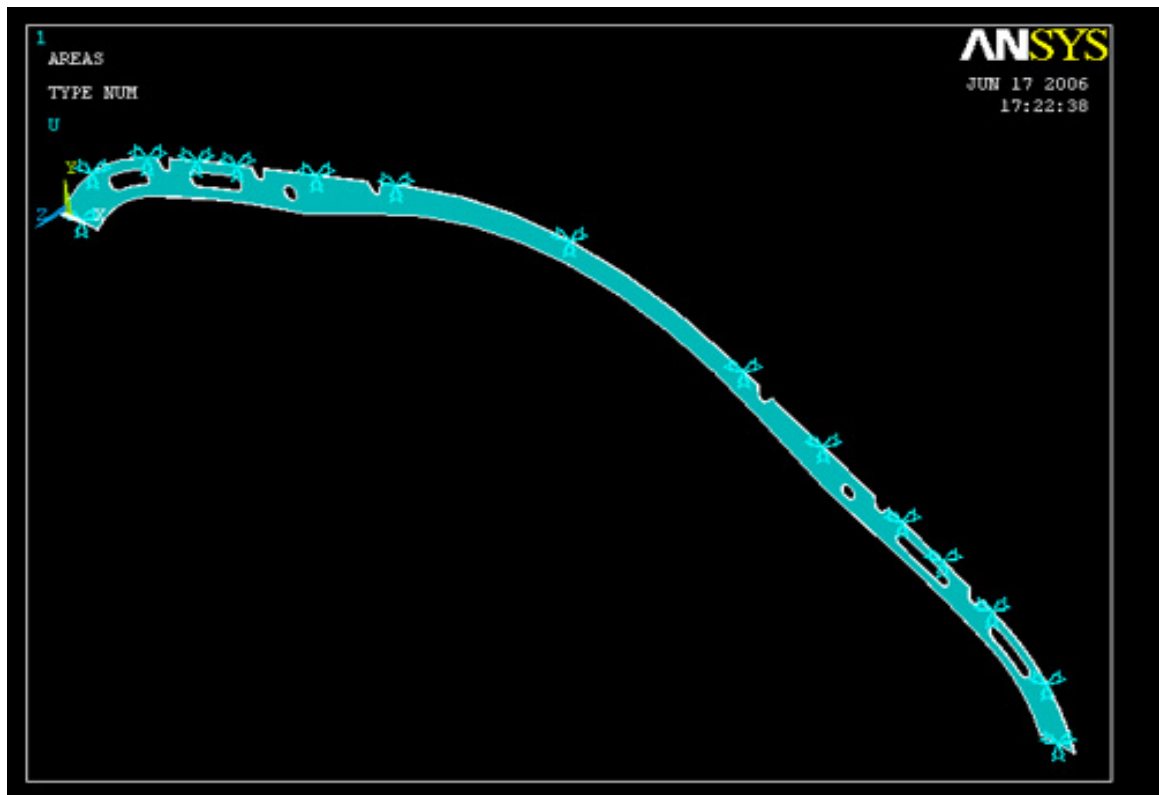
Figure 3.6a: Displacement condition of C-type Carline
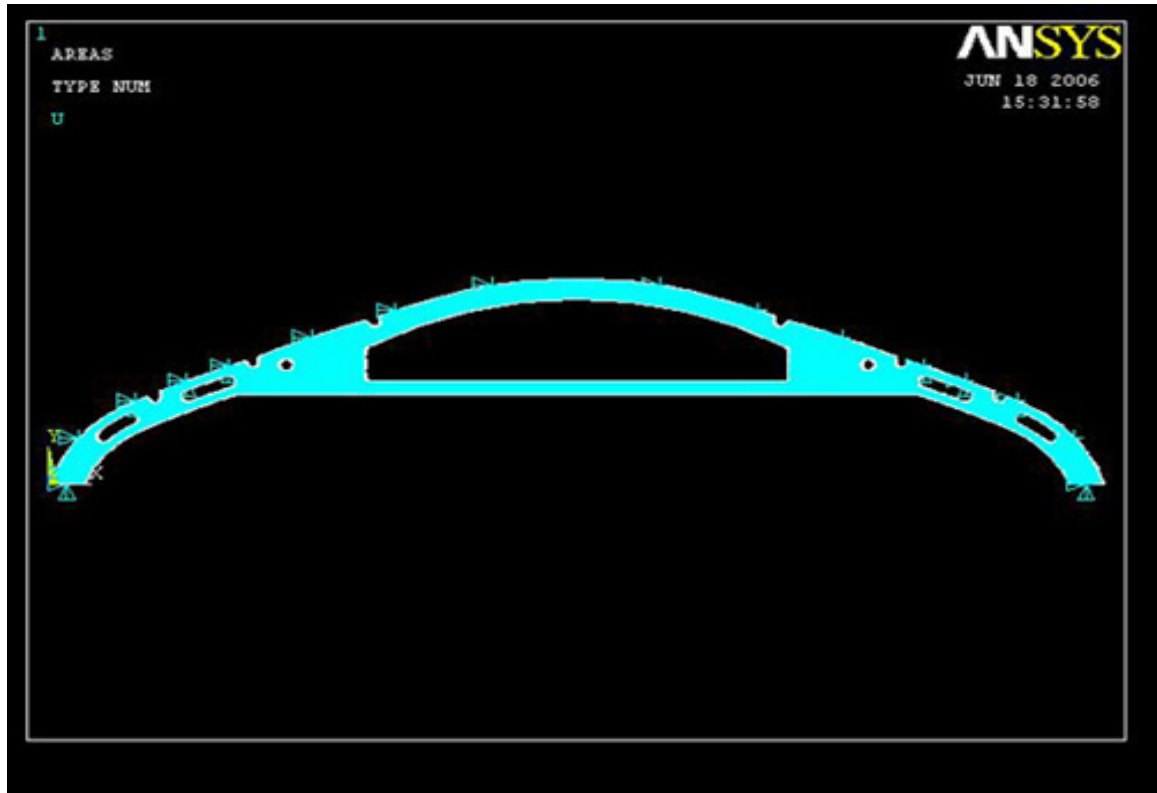
Figure 3.6b: Displacement condition of D-type Carline

3.5.1.5 Force Condition:-

The loads applied on the different parts are as per the loading conditions specified in the design. In the C-type carline the loads are applied as follows.

Table 3.3:   Loading values

Name of Part	Closed Slots in Newton	Open slot in Newton	Circular Hole in Newton	AC duct slot in Newton
C-type Carline	12.2625	7.3575	5.350	NA
D-type Carline	12.2625	7.3575	5.350	24.525

The above loads are applied on the carline. ANSYS has the facility to apply boundary condition to carline itself; software transmits this load to the elements appropriately.

3.5.2 Processing:-

In this phase of the analysis, the computer takes data and solves the simultaneous equations that the finite element method generates. The results of the solution are displacement and stress values at the nodal point. With the finite element model created as described above, static analysis was performed using ANSYS software.

In processing, the Iterative Solver is used. This solver starts with element matrix formulation and assembles full global matrix. The solver then gives solution for each degree of freedom by iterating to convergence.

3.5.3 Post-Processing:-

Post-processing involves reviewing the results of the FE analysis by way of color contours, tables, graphs, charts etc. and comparing these results with failure criteria imposed on the design such as maximum deflection allowed, the static and fatigue stress limit for materials etc.

It is probably most important step in the analysis. ANSYS software is used to display the results.

The results of FE analysis are as follows-

1. Displacement contour occurred after loading is shown in Figure 3.7.
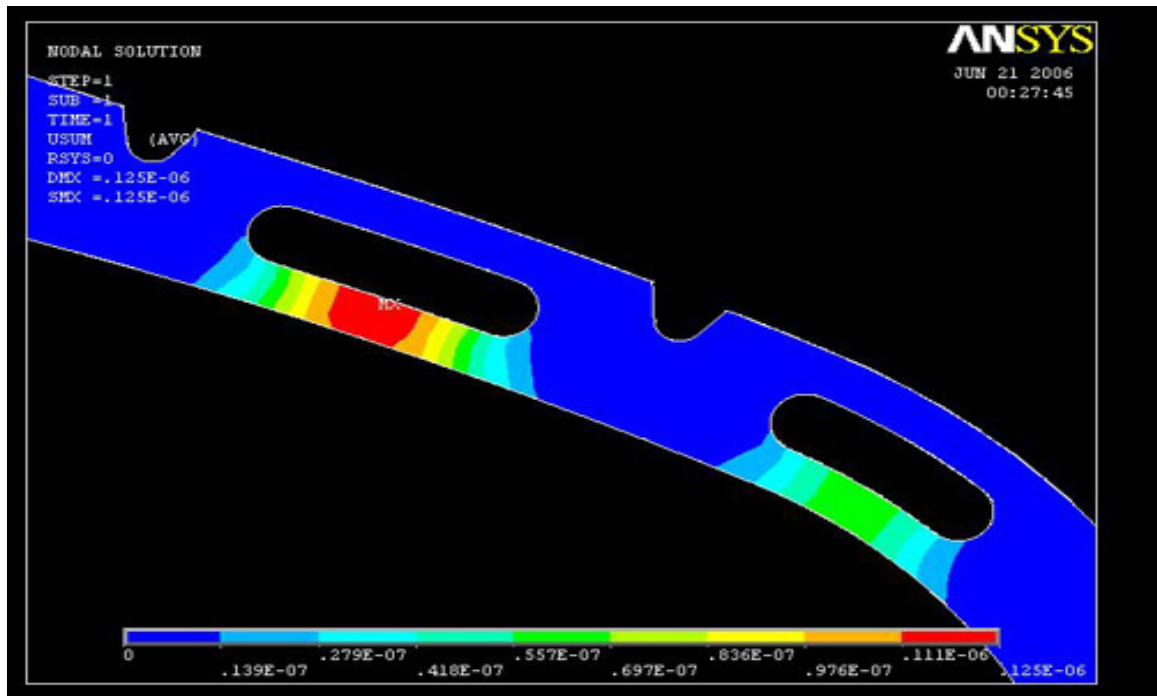
Figure 3.7a: Displacement plot of C-type Carline
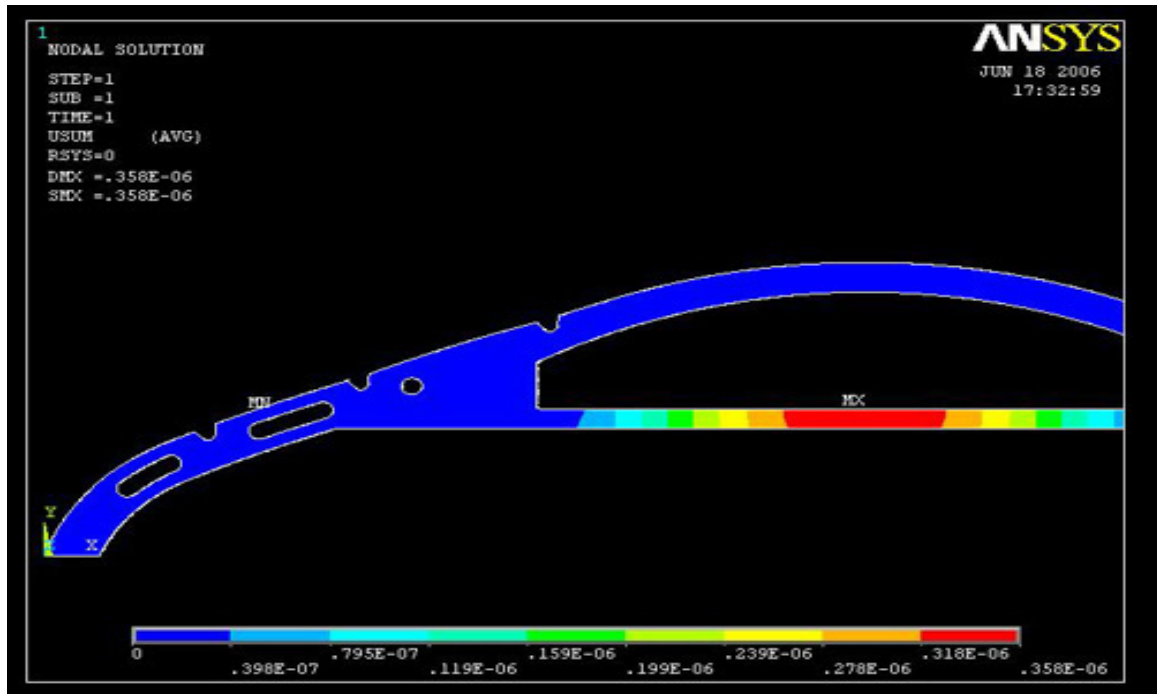
Figure 3.7b: Displacement plot of D-type Carline

It is seen that the maximum deformation in the parts is negligible and are as follows.

Table 3.4: Maximum deformation details

S.No.	Name of part	Maximum Deformation (m)
1.	C-type Carline	0.125E-06
2.	D-type Carline	0.358E-06

2. Stress contour plots are shown in figures 3.8. The magenta and yellow colors show maximum and minimum stresses in the parts.
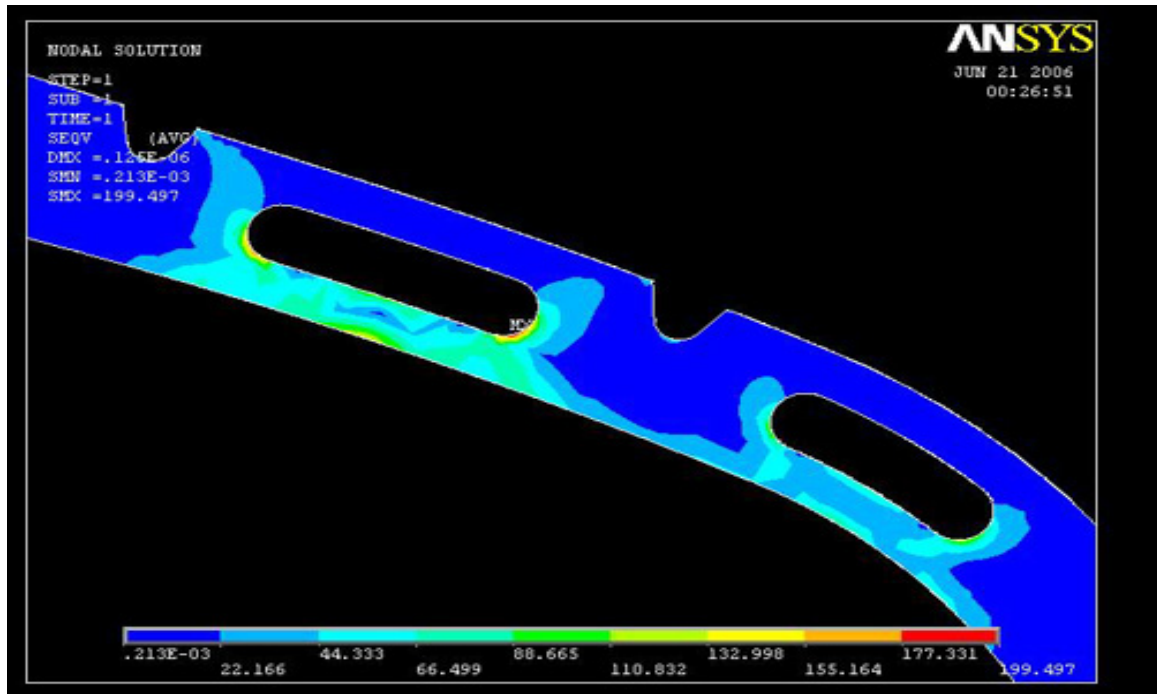
Figure 3.8a: Von mises stress in C-type Carline
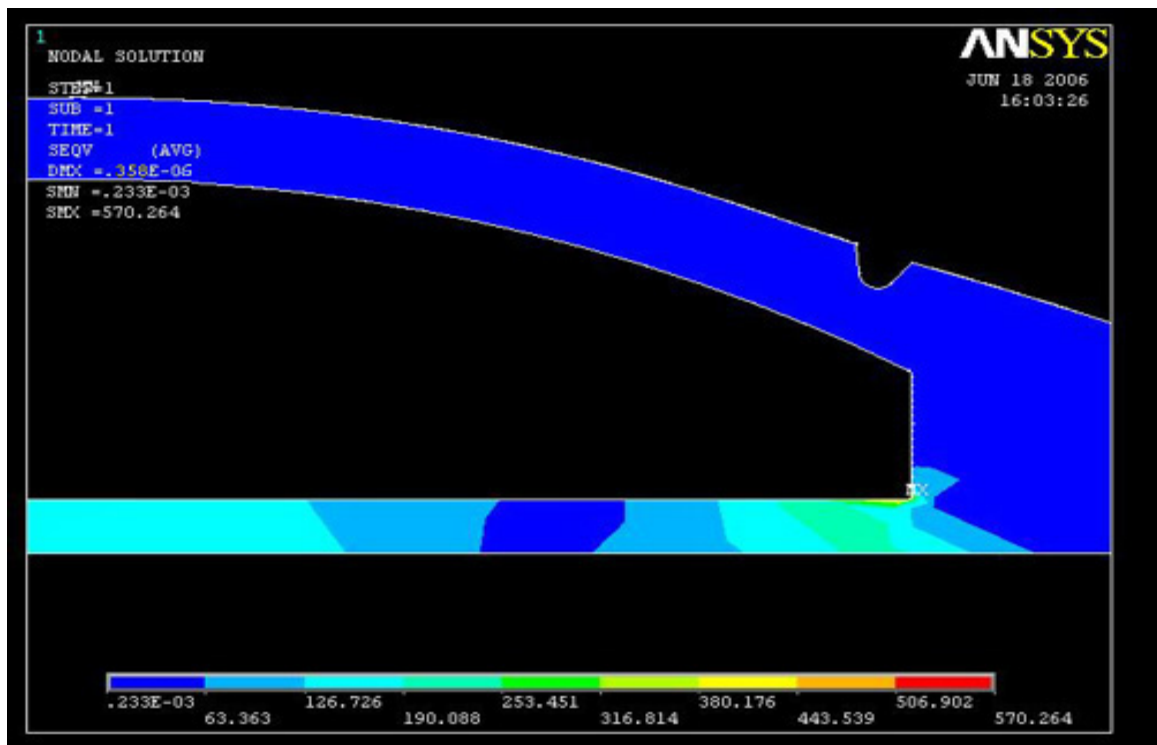
Figure 3.8b: Von mises stress in D-type Carline

The maximum stresses occur only at few locations and is tabulated below.

Table 3.5:   Maximum stresses details

S.No.	Name of part	Maximum Stress (in Mpa)
1.	C-type Carline	199.497
2.	D-type Carline	570.264

3.6 Conclusion:-

The following conclusion may be drawn from the finite element analysis carried out during study of the parts.

1. Maximum deformation in C-type carline is 0.125E-06, for D-type carline is 0.358E-06 which is quite negligible.

2. Maximum Von Mises stress in C-type carline is 199.497 MPa and in D-type carline it is 570.264 MPa. The most of the area of the parts is well below the allowable stress of the material which shows that the thickness is sufficient for the purpose.

CHAPTER IV

MATERIAL CONSUMPTION MINIMIZATION USING MOST 2D

4.1 Introduction:-

MOST 2D is nesting software for generating layouts for profile cutting applications. MOST 2D is primarily used for reducing scrap in sheet metal cutting as well as heavy fabrication. The software can also generate CNC codes for all the popular oxyfuel, plasma, laser and water jet cutting machines.

ITEM, the cad module accompanying this software allows you to generate simple 2-D shape drawings and supports a batch mode converter for reading dxf / dwg / g-code files. Material Engineer is another module that allows you to define cutting properties (like kerf/ speed / leadin length) for various types of raw materials. For customized applications, the software may support additional modules / functions.

4.2 Nesting method used by Most 2D:-

Nesting has great cost-saving potential since a nest requires only one setup and fewer standard sheets. However, finding the optimal nest (which minimizes the set-up and material costs) is not a simple problem. The production planners need a tool to help identify good nests. However, they must make this nesting decision before they can generate the actual nest layout (and the associated NC program). To overcome this obstacle, the layout problem was simplified by considering only the area that each part requires and the total usable area of a sheet. A part's required area, which may have a complex profile, includes the necessary interpart spacing and any internal area that no other part could possibly use.

It is assumed that parts will fit onto a sheet if the total area is sufficient. If many of the parts were large, then this approximation would be poor, and then it would create the need to consider the part geometry and part layout explicitly in the nesting decision process. However, in practice, the parts were small compared to an unsheared sheet, so the approximation is acceptable. Note that the nesting decision determines which orders (and parts) the nest should include, but it does not create a layout for the parts on the sheets. If the actual part layout for the nest did require more unsheared sheets than the nesting decision predicted, there would be time to modify the nesting decision. Thus, the area approximation for making the nesting decision.

Dynamic nesting reduces set-ups and material requirements. However, finding the most cost-effective nest is a problem. The nesting decision for a group of orders is based on the point that the parts should have same material type and thickness. The objective is to minimize the total cost of setup and material. When beginning to implement dynamic nesting, nesting all orders may seem like a good strategy. Unfortunately, it could lead to poor solutions. It is assumed that parts will fit onto a sheet if the total area is sufficient.

4.3 Steps performed:-

In the Rail Coach factory, Kapurthala, many different types of coaches are made requiring different variety of parts. The nesting procedures combines multiple orders that require the same type of sheet metal so that the CNC machine can complete all of the parts in these orders as one job. The important point in the start is that we have to identify the parts which we want to nest as they should be of the same material and the same thickness. Therefore after thorough observation it was decided to nest C-type, D-

type carline and bearing support as these parts fall under the same group set. Groups set of Corten steel material and thickness 3 mm.

The step by step procedure of using the software efficiently and getting the desired results is given below.

4.3.1 CAD - Make the 2D part drawing:-

1. For creating a new item drawing, start ITEM – CAD.

2. Create the item drawing using commands under the sketch menu in ITEM - CAD and proceed to the next step.

3. Select the command View => Zoom out to see the complete item drawing. (Shift + O)

4. Select the command Tools => Validate to check the item drawing.

5. Select the command File => Save to save the drawing in an MDF file. (Control + S)

4.3.2 <u>Nesting – Make nested layouts:-</u>

1. Specify all the default options / settings, after installing the software. (This is a one time activity.)

2. Define a new input job for nesting.

3. Start MOST 2D.

4. Select the command File => New to start a new job in MOST. (Control + N)

5. Select OK button in the new job dialog box.

6. Define constraints i.e. cutting parameters for the job. (This step is not required if you use material database.)

7. Select the command Job => Constraints. (F-10)

8. Specify tool size (kerf) as well as clearance limit (additional distance between parts, after leaving 2*kerf distance) in the constraints dialog box. Select OK button in the dialog box.

9. Select the command Job => Export => Full Job in order to save the input job in a foundation file. (Control+F)

10. Define the stock list i.e. the inventory of fresh and off cut stocks, which are available for nesting.

11. Select the command Job => Stock list. (F-11)

12. If you want to add a fresh rectangular stock to the stock list, execute the following steps.

13. Select Add Fresh Stock button in the stock list dialog box. Type the stock dimensions and select OK button in the dialog box that appears on the screen. Type stock name (say, "fresh stock 1") and select OK button in the dialog box that appears on the screen.

14. Specify stock properties using the options shown in stock properties dialog box.

   (In particular,
   Specify total number of stocks available using General => Total quantity,
   Stock material using Physical => Material
   and stock thickness using Physical => Thickness options.)

15. Select OK button in the dialog box.

16. Select the command Job => Export => Full Job in order to save the input job in a foundation file. (Control+F)

17. Define the shape list i.e. bill of materials, containing the list of all the parts which have to be nested.

18. Select the command Job => Shape list. (F-12)

19. If you want to add a new shape for nesting, execute the following steps.

20. Select Add Shape button in the shape list dialog box.

21. Select the part drawing file (typically, an MDF file generated using steps 1 to 5 described earlier in CAD steps) from the file selection dialog box and select the OK button. Note, you can also select multiple part drawing files by keeping the Control key pressed, while selecting the part drawing files from the dialog box.

22. Type shape name and select OK button in the new dialog box that appears on the screen.

23. Specify shape properties using the options shown in shape properties dialog box.

    (In particular,
    specify total number of shapes to be cut using General => Total quantity,
    shape material using Physical => Material
    and shape thickness using Physical => Thickness options.)

24. Select OK button in the dialog box.

25. If you want to change the properties of an existing shape, select the shape with the mouse and click on the properties button in the shape list dialog box. If you want to remove an existing shape from the shape list, select the shape with the mouse and click on the Remove button in the shape list dialog box.

26. Select the Close button in the shape list dialog box, after making all the modifications in the shape list.

27. Select the command Job => Export => Full Job in order to save the input job in a foundation file. (Control+F)

28. Nest the job.

29. Select the command Fit => Go to nest the job automatically. (F-5). So after entering all the details step by step in the MOST 2D software as discussed in Chapter 5, we generate the automatic nest. The results are displayed below.

The nested layouts which the software makes are as follows:

Layout 1: Nested 2 parts of D-type Carline and frequency is 4.
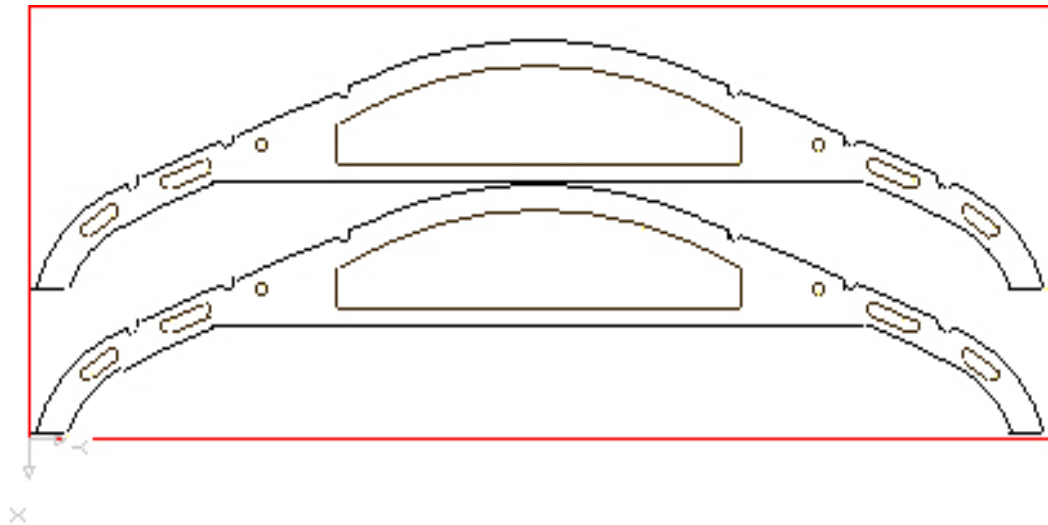
Frequency 4 means that the same nest is made on 4 stocks of Corten steel sheet totaling the number of parts cut to 8 which is the requirement.

Layout 2: Nested 8 parts of Bearing support
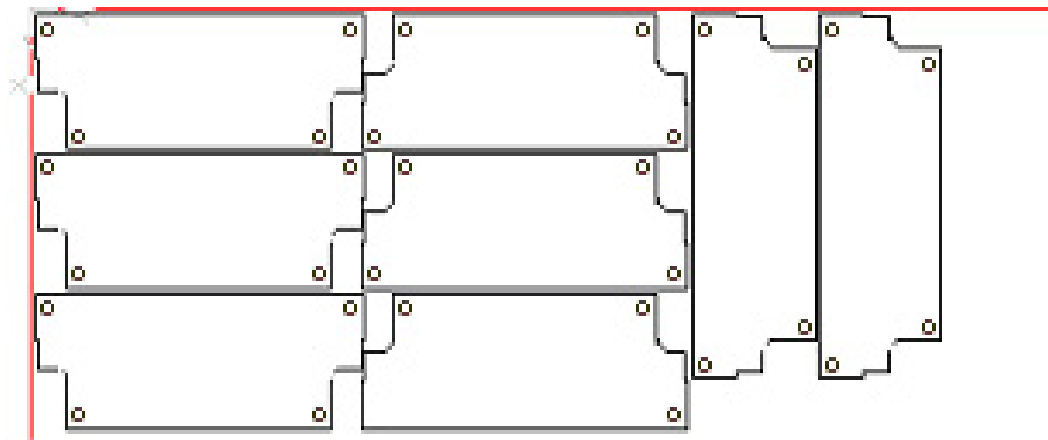
In this layout 8 parts of Bearing support are nested and the frequency is 1.

Layout 3:   Nested 3 parts of C-type Carline and frequency is 11.
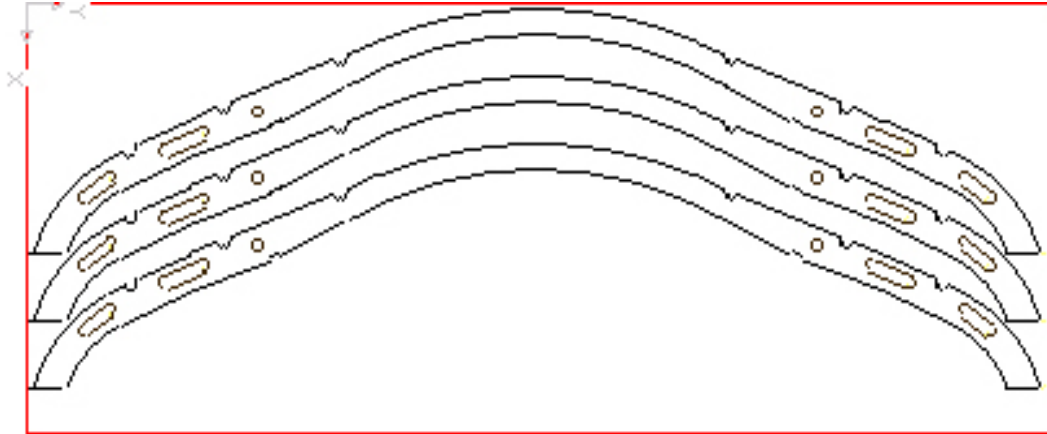
Here we can see that the nest of C-type Carline is of in a group of 3 pieces each on the stock sheet and the frequency is 11 which totals to 33 pieces of C-type Carline.

Layout 4: Nested 1 remaining part of C-type Carline.
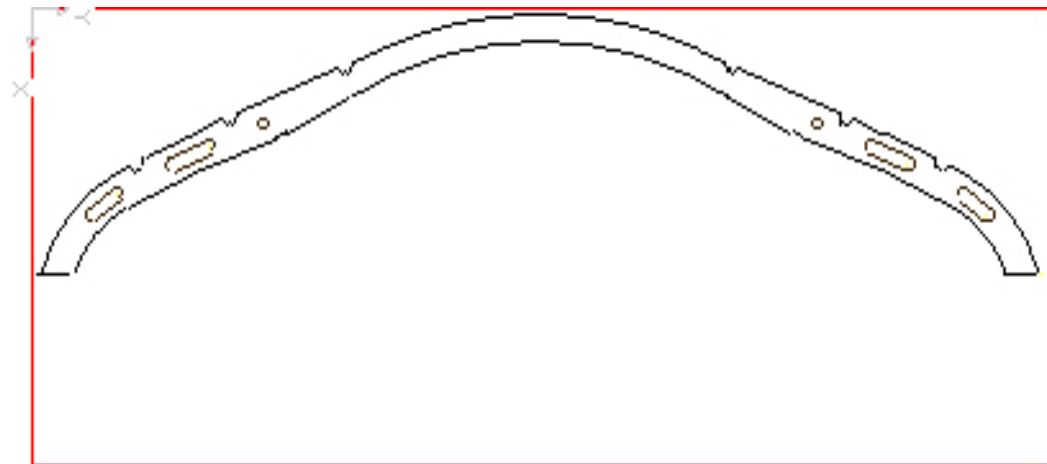
Here we can see that the last remaining part of the C-type Carline is nested on a separate stock.

30. Select the command File => Save to save the nested job in a job file, which is a binary file having the extension JOB. (Control +S) You can open this file for further editing in your next session with MOST, if required.

31. Study each nested layout using commands like zoom-in, zoom-out, pan, etc. under View menu.

32. Modify the layouts manually using commands like move, slide, rotate, mirror, add, remove, etc. under Fit menu.

Now the question was whether the given nest could be further improved to minimize material consumption. So to improve it further, shapes were added and moved in the nest and it was build again.

33. Select the command Fit => Build, if you would like to nest the layout automatically, without removing those shapes which have been already nested on the stock.

Layout 5: Nest of 2 units of C-type Carline, 1 unit of D-type Carline and 2 units of bearing support.
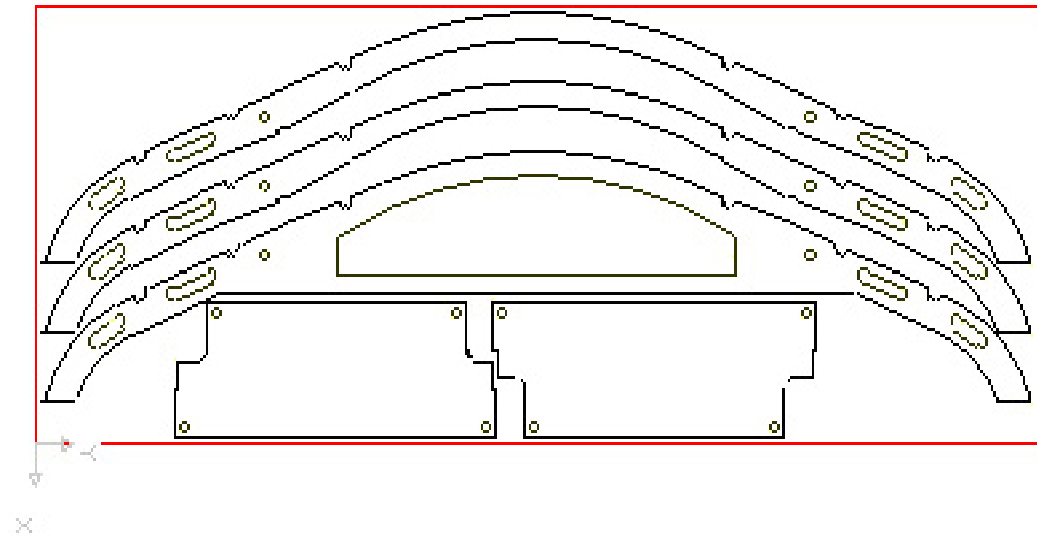
Here we see that the on one stock sheet, we have nested 2 units of C-type Carline, 1 unit of D-type Carline and 2 units of Bearing support. The frequency of this layout is 4. So total, 8 units of C-type Carline, 4 units of D-type Carline and 8 units of bearing support are nested.

Layout 6: Nest of 2 units of C-type Carline and 1 unit of D-type Carline.
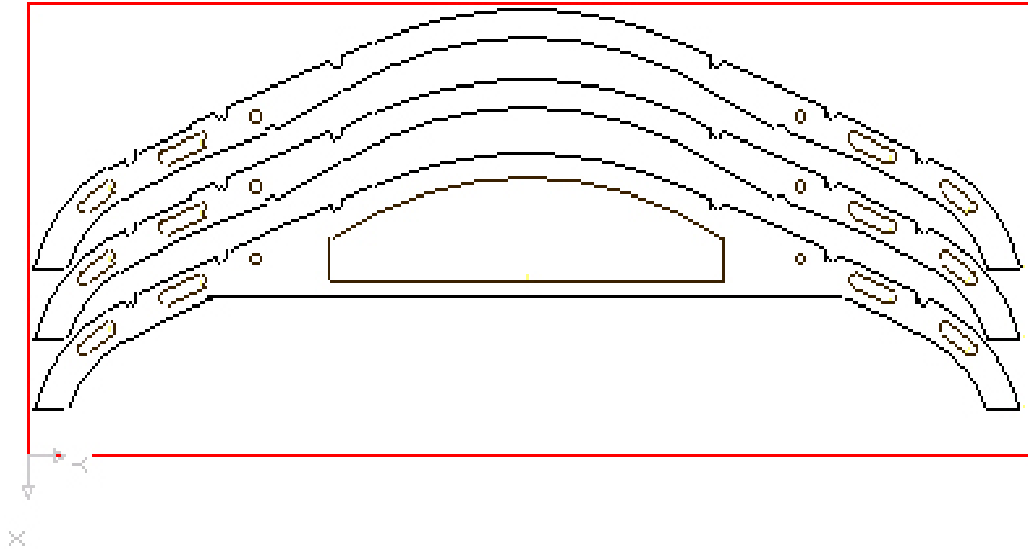
Now the requirement of bearing support is exhausted, so it was removed from the nest. Here in layout 2, we see that there are 2 units of C-type Carline and 1 unit of D-type Carline. The frequency of this layout is 4, which means that total 8 units of C-type Carline and 4 units of D-type Carline will be nested. After this the requirement of the D-type Carline is exhausted as all 8 parts have been nested.

Layout 7:   Nest of 3 units of C-type Carline.
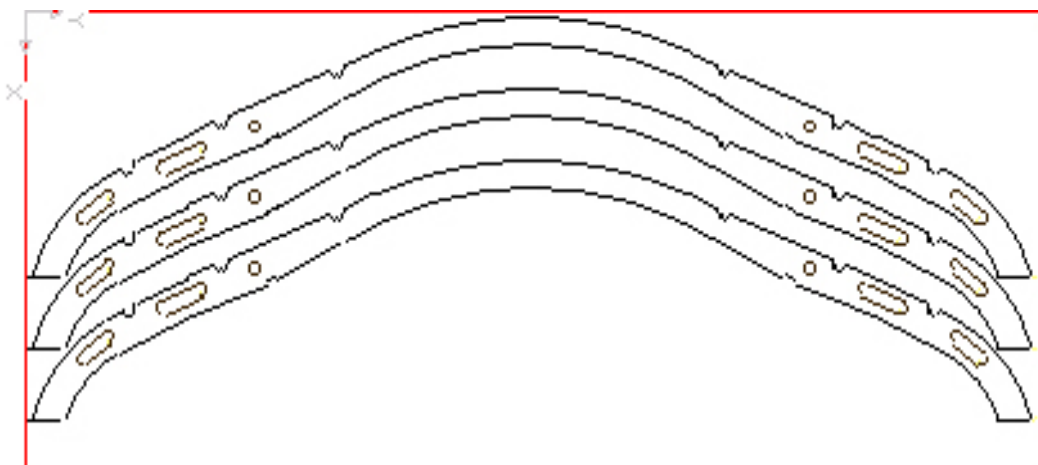
Here we see that 3 units of C-type Carline are nested and the frequency is 6.

So total 18 units of C-type Carline are nested. Including all the 3 layouts 5, 6 & 7, we get the desired nest.

34. Select the command File => Save to save the modified nested job once again in the job file. (Control +S)

CHAPTER V

RESULTS, DISCUSSIONS & CONCLUSIONS

Initially finite element analysis has been carried out to studying, analyzing and validating the designed model of the parts under consideration for various stresses developed due to the different loading conditions. After analysis of the 3-D models of the parts then material consumption minimization has been done to reduce the amount of raw material sheets used for cutting the parts out of rectangular stocks.

5.1   Displacement plots of parts
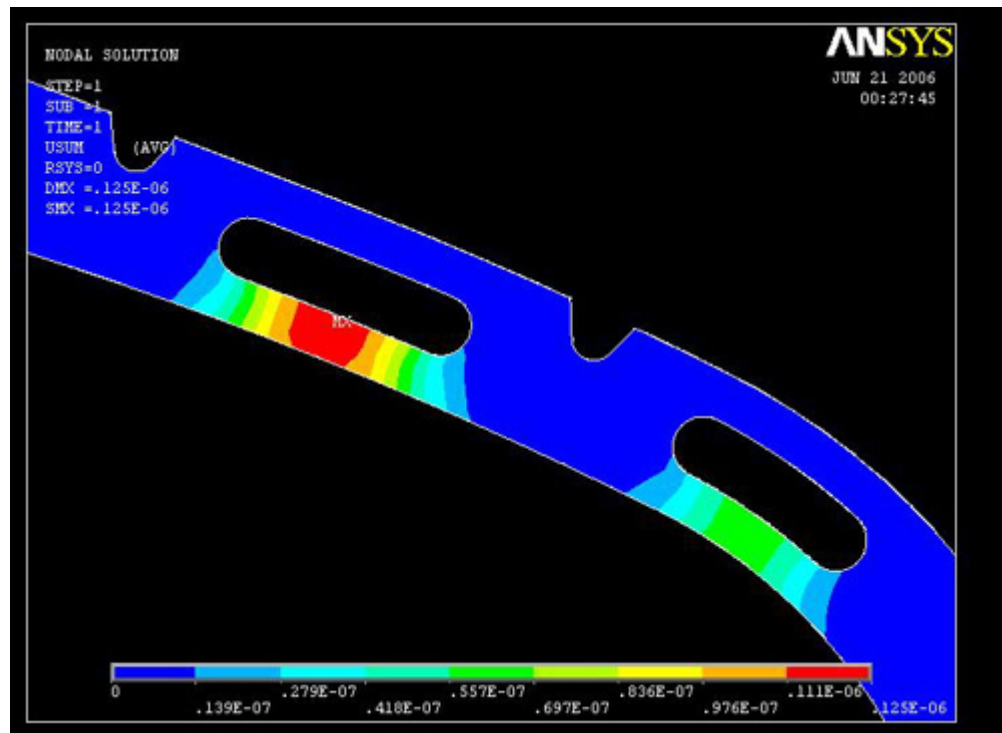
Figure 5.1a: Displacement plot of C-type carline
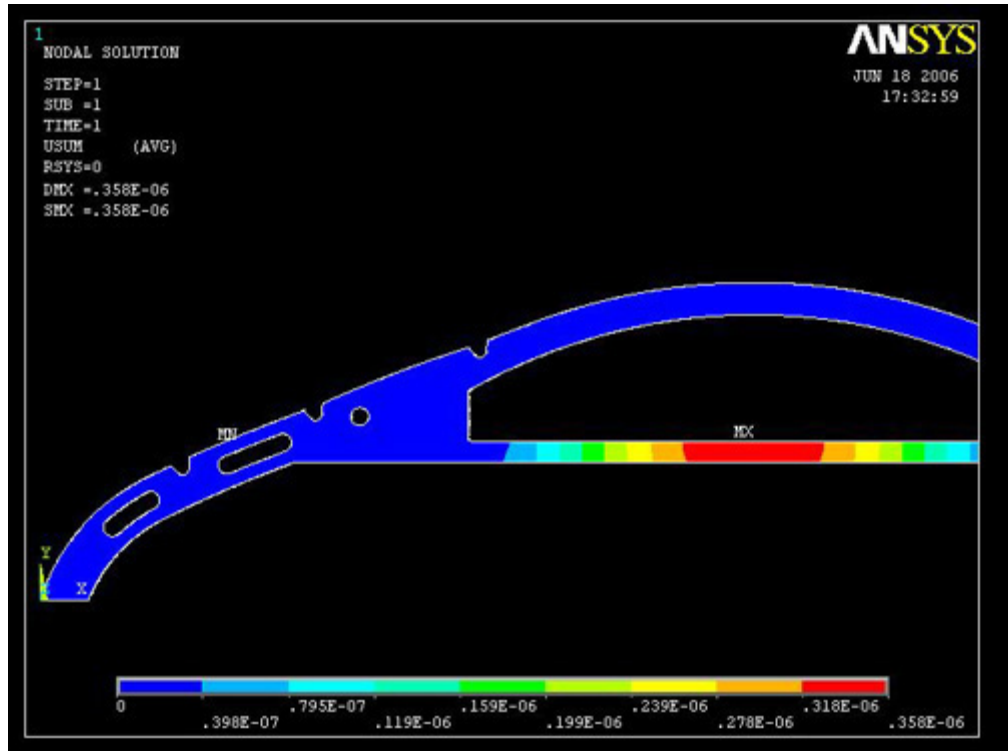
Figure 5.1b: Displacement plot of D-type carline

Table 5.1: Maximum deformation details

S.No.	Name of part	Maximum Deformation (m)
1.	C-type Carline	0.125E-06
2.	D-type Carline	0.358E-06

It is seen that the maximum displacement/deformation in all the parts analyzed as tabulated above is quite negligible.

5.2   Nodal Solution of stresses developed in parts

The nodal solution of the different types of stresses developed in the parts is tabulated below.
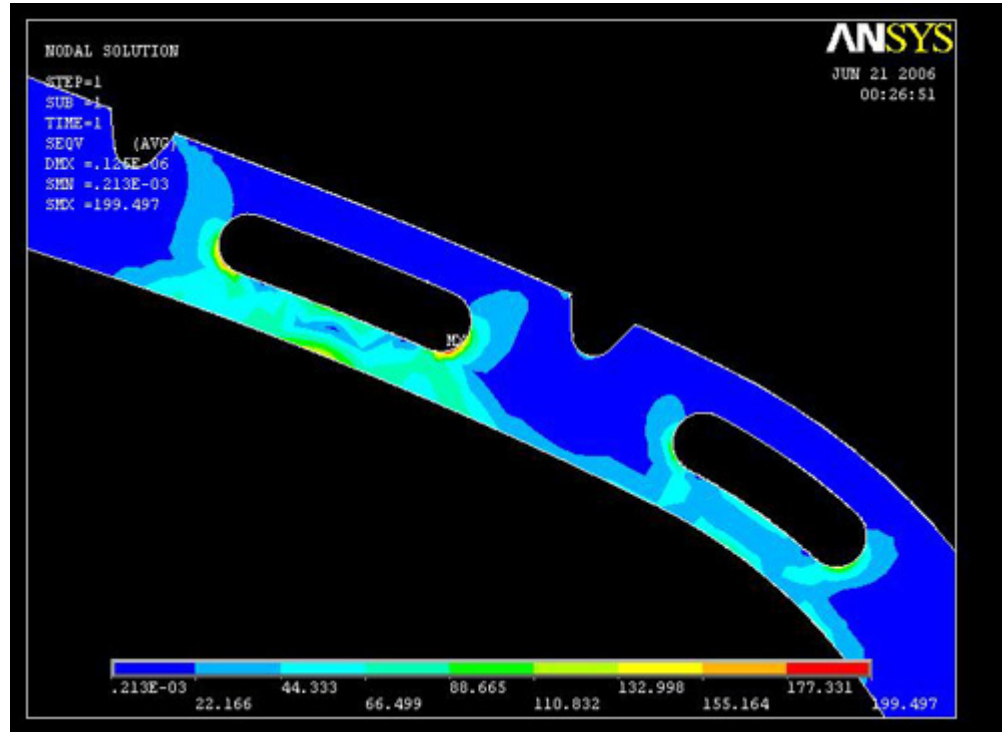
Figure 5.2a: Von mises stresses in C-type carline

Table 5.2a: Minimum von mises stresses in C-type carline (in MPa)

	S1	S2	S3	INT	SEQV
NODE	1736	1509	16276	496	496
VALUE	-4.3697	-14.663	-107.75	0.25560E-03	0.22382E-03

Table 5.2b: Maximum von mises stresses in C-type carline (in MPa)

	S1	S2	S3	INT	SEQV
NODE	27230	13142	13142	16238	16238
VALUE	196.94	40.402	31.424	203.36	199.36
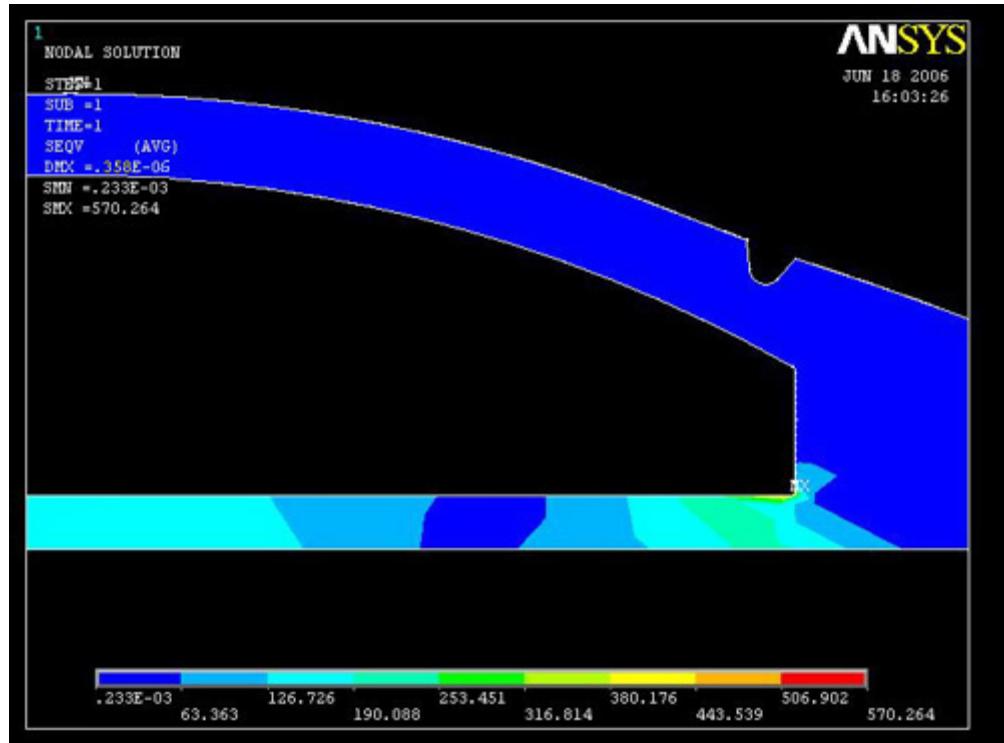
Figure 5.2b: Von mises stresses in D-type carline

Table 5.3a: Minimum von mises stresses in D-type carline (in MPa)

	S1	S2	S3	INT	SEQV
NODE	12060	1112	1110	14061	14061
VALUE	-12.467	-41.839	-306.94	0.28038E-03	0.24572E-03

Table 5.3b: Maximum von mises stresses in D-type carline (in MPa)

	S1	S2	S3	INT	SEQV
NODE	1694	24426	27425	1694	1694
VALUE	562.79	106.26	81.825	581.25	569.87

It is seen that the maximum stress occurs only in a select elements. Rest of the elements in the parts are under very less stress. The maximum von mises stress developed is well below the allowable limits.

Table 5.4:   Properties of Corten

S.No.	Properties	Values
1.	Tensile strength (MPa)	956
2.	Yield strength (MPa)	648

Therefore we can safely say that the design of the parts is satisfactory.

5.3   **Material Consumption minimization results**

Coming to the material consumption minimization part of the project work, the following are the specifications of each part.

Table 5.5: Specifications of each part

Shape Name	Dimensions	Quantity (per coach)	Area (sq m) (per part)	Perimeter (mm) (per part)
AE16361A (C-type carline)	714.33 x 3200.83	34	0.28	9211.74
AE16363A (D-type carline)	714.33 x 3200.83	8	0.40	11940.84
cc10858a (Bearing support)	391 x 1042.00	8	0.37	2844.54

It is observed that the part AE16363A has the largest area of 0.40 sq m followed by cc10858a having area 0.37 sq m and then part AE16361A having area 0.28 sq m.

And as the working of MOST 2D is based on area wise priority used in dynamic nesting, whenever the nesting is done the software tries to fit the largest area part first in the stock and after it has exhausted the part, then it goes for the second largest area part and nests it. And like wise the procedure is followed in descending order of area until all the parts are nested.

The automatically generated nest as discussed in Chapter IV consisting of four nested layouts gives the results as below in Table 5.6

Table 5.6: Details of results of automatic nesting

Layout Number	Stock Area (sq m)	Item Area (sq m)	Scrap Area (sq m)	Consumed Area (sq m)	No. of Stocks Consumed	% Utilization
Layout 1	4.0624	0.8062	3.2563	4.0625	4	19.85
Layout 2	4.0625	2.9706	1.0919	4.0625	1	73.12
Layout 3	4.0625	0.8538	3.2087	4.0625	11	21.02
Layout 4	4.0625	0.2846	3.7779	4.0625	1	7.01

We observe that a total of 17 sheets of the stock raw material are consumed for the cutting the desired nest of pieces when that nest is generated automatically by the MOST 2D software.

Now the question was whether the consumption of the stock sheet could be minimized further. To reduce it, shapes were added and moved in the nest and it was build again which gave the following nested layouts for the same BOM.

Table 5.7: Details of results of built nest

Layout Number	Stock Area (sq m)	Item Area (sq m)	Scrap Area (sq m)	Consumed Area (sq m)	No. of Stocks Consumed	% Utilization
Layout 5	4.0624	1.7150	2.3475	4.0625	4	42.21
Layout 6	4.0625	0.9723	3.0902	4.0625	4	23.93
Layout 7	4.0625	0.8538	3.2087	4.0625	6	21.02

From the Table 5.7 it is clear that the built nest has given us better results as compared to the automatic nest.

Table 5.8: Comparative analysis of Automatic vs. Built Nest

Point under Consideration	Type of nesting scheme	
	Automatic	**Built**
Number of Parts nested	C-type carline 34 D-type carline 08 Bearing support 08	C-type carline 34 D-type carline 08 Bearing support 08
Number of Stocks Consumed	17	14
% Utilization (weighted avg.)	22.9582	27.9057

The below mentioned results have been achieved by using the material consumption minimization method discussed in chapter 4.

1. The consumption of rectangular stock sheets has come down by 3 units for every bill of material. Less number of layouts have to be made.

2. The % utilization of the stock sheet area has gone up by 4.9475 %.

3. It has been estimated that the CNC machine producing these parts has an operational cost of Rs. 1500/- per hour. This cost is inclusive of the wage paid to

the operator to operate the machine. The total setup time for setting up one rectangular stock sheet for cutting is 5 minutes. So considering that we have reduced the consumption of material i.e. the rectangular stock sheets, by three units. That directly means that the net setup time saved is of fifteen minutes which in rupees is of Rs. 375/- for cutting the three parts for one coach. Also saving of 3 stock sheets leads to saving of Rs. 13780/- as one sheets costs around Rs. 4593/-.

The results which have been obtained using the nesting approach described in previous chapters indicate that the built nests keeping in view the results obtained in automatic nests turns out to be an effective tool in designing minimal waste layouts for problems that involve 1) a set of standard rectangular sheets, 2) order to produce a large number of various types of shapes which include irregular as well as rectangular-like shapes, 3) the requirements that no two shapes may overlap and that only the exact types and numbers of shapes ordered are to be produced, and 4) minimize waste.

Although the layouts obtained by automatic nesting did not in general give the best possible % utilization of the stock sheet, still they can turn out to be fairly good in the case when complexity of the nest is very high, i.e. a large number of different shape parts have to nested. When the complexity is very high then manual nesting might be very time consuming process and may generate lots of errors as it is dependent on the skill and experience of the operator.

CHAPTER VI

<u>FUTURE SCOPE</u>

The FE analysis has been carried out for the stresses and deformations. The work can be extended to cover the dynamic analysis giving the natural frequency, mode shapes etc. This is very essential to avoid resonance.

As we saw in the material consumption minimization, that even after applying the dynamic nesting method, we could not get the best results. This opens up a lot of scope for future research. In our approach there was no constraint of grain direction, but this can be very well important in the case of leather, garment industry etc. Also the generalization of the nesting technique has to be there so that it can be applied in different fields.

The second scope of research in the future is in the improvement of the nesting algorithm. It should be able to deeply analyze the given constraints and be able to give desired results with minimum computation time.

Lastly, the priority setting of different shapes was not covered in this project work as it was not required as all the parts were of same priority. But in case if some of the parts have high priority than the other parts then things might work out differently. That would be too complex a decision to be made by a human operator. So I think the nesting algorithms can be researched and improved in this direction as well.

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APPENDIX - I

1. CNC CODE FOR LAYOUT 5

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N1226G99
&

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APPENDIX – II

G & M CODES

G – Functions

Code	Function
G00	positioning (rapid traverse) (M,T)
G01	linear interpolation (feed) (M,T)
G02	circular Interpolation CW (M,T)
G03	circular Interpolation CCW (M,T)
G04	dwell, a programmed time delay (M,T)
G05	unassigned
G06	parabolic interpretation (M,T)
G07	cylindrical diameter values (T)
G08	programmed acceleration (M,T)
G09	exact stop check (M,T)
G10	data setting
G11	data setting mode cancel
G14 - G14.1	used for scaling (M,T)
G15 - G16	polar coordinate programming (M)
G15 - G16.1	cylindrical interpolation - c axis (T)
G17	XY plane selection (M,T)
G18	ZX plane selection (M,T)
G19	YZ plane selection (M,T)
G20	input in inch
G21	input in mm
G24	single-pass rough facing cycle (T)
G28	return to reference point (M,T)
G29	return from reference point (M,T)
G30	return to alternate home position (M,T)
G33	thread cutting, constant lead (T)
G34	thread cutting, increasing lead (T)
G35	thread cutting, decreasing lead (T)
G38	measure dia. and center of hole (M)
G40	cutter compensation cancel (M)
G41	cutter compensation left (M)
G42	cutter compensation right (M)
G43	cutter offset, inside corner (M,T)
G44	cutter offset, outside corner (M,T)
G45	tool offset decrease

G46	tool offset double increase
G47	tool offset double decrease
G48	scaling off
G49	tool length compensation cancel
G50	tool offset increase
G50.1	cancel mirror image (M,T)
G51.1	program mirror image (M,T)
G52	offset axis w/ respect to 0 point (M,T)
G53	motion in machine coordinates (M,T)
G54	work coordinate system 1 select
G55	work coordinate system 2 select
G56	work coordinate system 3 select
G57	work coordinate system 4 select
G58	work coordinate system 5 select
G59	work coordinate system 6 select
G60	single direction positioning
G61	exact stop check mode (M,T)
G62	reduce feed rate on inside corner (M,T)
G64	cutting mode (M,T)
G65	custom parametric macro (M,T)
G67	stops custom macro (M,T)
G68	coordinate system rotation ON (M)
G69	coordinate system rotation OFF (M)
G70	inch programming (M,T)
G71	metric programming (M,T)
G72	circular interpolation CW (M)
G72	finished cut along z-axis (T)
G73	peck drilling cycle (T)
G74	counter tapping cycle (M)
G74	rough facing cycle (T)
G74	cancel circular interpolation (M,T)
G75	circular interpolation (M,T)
G76	fine boring
G80	canned cycle cancel
G81	drilling cycle, no dwell (M,T)
G82	drilling cycle, dwell (M,T)
G83	deep hole, peck drilling cycle (M,T)
G84	right hand tapping cycle (M,T)
G84.1	left hand tapping cycle (M,T)
G85	boring, no dwell, feed out (M,T)
G86	boring, spindle stop, rapid out (M,T)

Code	Function
G87	boring, manual retraction (M,T)
G88	boring, spindle stop, manual ret. (M,T)
G89	boring, dwell and feed out (M,T)
G90	absolute dimension input (M,T)
G91	incremental dimension input (M,T)
G92	set absolute zero point (M,T)
G93	inverse time feed rate (M,T)
G94	per minute feed (M,T)
G95	per revolution feed (M,T)
G96	constant surface speed control (T)
G97	stop constant surface speed control (T)
G98	return to initial point in canned cycle
G99	return to R point in canned cycle

M – Functions

Code	Function
M00	Stop program
M02	End of program
M03	Spindle clock wise rotation
M04	Spindle counter clock wise rotation
M05	Stop spindle rotation
M06	Tool change on spindle
M08	Start coolant
M09	Stop coolant
M19	Stop in spindle position
M20	Axis lubrication manual command
M21	Head lubrication manual command
M22	Vacuum table activation
M23	Vacuum table deactivation
M30	End of program and rewind the program
M48	Reset M49