STRESS-FLOW ANALYSIS OF BIO MECHANICAL BI-LEAFLET HEART VALVE

A THESIS

Presented to the Department of Mechanical and Aerospace Engineering

California State University, Long Beach

In Partial Fulfillment

of the requirements for the Degree

Master of Science in Mechanical Engineering

K.Amarendranath Reddy

B.E., Manipal University, Manipal, India.

January 2008

ProQuest Information and Learning Company
300 North Zeeb Road
P.O. Box 1346
Ann Arbor, MI 48106-1346

WE, THE UNDERSIGNED MEMBERS OF THE COMMITTEE,

HAVE APPROVED THIS THESIS

STRESS-FLOW ANALYSIS OF BIO MECHAICAL BI-LEAFLET HEART VALVE

By

K.Amarendranath Reddy

COMMITTEE MEMBERS

Ortwin Ohtmer

Ortwin Ohtmer, Ph.D. (Chair) Department of Mechanical and Aerospace Engineering

C Barclay Gilpin

C. Barclay Gilpin, Ph.D. Department of Mechanical and Aerospace Engineering

H. H

Hamid Hefazi, Ph.D. Department of Mechanical and Aerospace Engineering

ACCEPTED AND APPROVED ON BEHALF OF THE UNIVERSITY

H. H

Hamid Hefazi, Ph.D.
Chair, Department of Mechanical and Aerospace Engineering.

California State University, Long Beach

January 2008

ACKNOWLEDGEMENT

I would like to express deepest appreciation for Dr. C. Barclay Gilpin for being my supervisor and my encouragement throughout my thesis work. Without his guidance and persistent help in the field of Bio-Mechanical Engineering, Computer Aided Design and Computational Fluid Analysis, it would not have been possible for my thesis accomplishment. Also, I would like to thank my committee members, Dr. Hamid Hefazi and Dr. Ortwin Ohtmer for being patient and available when required. I am also indepted to my family for their moral support in all the best possible ways they could which had led to successful completion of my Master of Science in Mechanical Engineering.

TABLE OF CONTENTS

Page

CHAPTER

CHAPTER Page

LIST OF TABLES

TABLE Page

LIST OF FIGURES

FIGURE Page

FIGURE Page

ABSTRACT

STRESS-FLOW ANALYSIS OF BIO MECHANICAL BI-LEAFLET HEART VALVE

K.Amarendranath Reddy

January 2008

The aim of this thesis research is to investigate the stress-displacement distribution of bio-mechanical bi-leaflet heart valve. This stress-displacement analysis was carried out for closed and open positions of the leaflets, where in the leaflets were bounded under symmetric boundary and contact stress conditions performing under a constant pressure acting on them. The number of surfaces associating with contact pairs is more during opening of leaflet rather than closing of leaflet. Finally, the resulting stress-displacement results are studied through a FEM simulation for both the conditions of the leaflet. Later, a preparatory attempt was made to study the flow analysis of the stent of the leaflets. For this, the surfaces forming the boundary of the flow filed are selected and blood vessels were integrated to the selected surfaces. During the flow set up, concerns mainly related to negative volumes and orientation of grid cells were encountered and which were resolved through specific command available through the flow analysis software been used. The flow analysis results indicates flow stagnation especially at the grooves, were the leaflets are hinged, as expected.

CHAPTER 1

INTRODUCTION

Heart valve diseases have a telling impact on human life worldwide. Heart valve disease occurs when one or more of the four heart valves can no longer perform their function adequately in terms of circulation, maintaining a competent unidirectional flow of blood through the heart. Two principal types of valve disease can develop which prevent the valves from opening or closing properly. The first type is the valvar stenosis, which is characterized by a marked narrowing of the valve opening. The second type is called valvar insufficiency which occurs when the valve does not form a tight seal upon closure, resulting in regurgitation of blood. Both disease types burden the heart with an increased work rate to maintain stroke volume, leading to heart muscle dysfunction and eventually heart failure. Although the treatment of choice for many years has been surgical valve repair, complete valve replacement has become eminent in the most advanced of cases [1].

Exploration into heart valve replacement began in the 1950s, with the first successful human valve implantation being performed in 1952. The passing decades have seen the development of more than eighty designs of prosthetic heart valves, which remain the most common treatment for advanced heart valve disease.

Unfortunately, despite many years of research these devices were less than ideal and were accompanied by many complications [2]. Prosthetic heart valves may be either mechanical, consisting entirely of synthetic components, or may be fashioned from biological tissue (bioprosthetic). Fifty-five percent of implanted valves worldwide are mechanical, with the remaining forty-five are bioprosthetic while both types prolong life as well as enhancing its quality, they are associated with a number of major complications that limit their success too. But most researchers could not prevent the intrusion of foreign particles that result in patient's mortality. Hence, patients undergoing biomechanical transplant undergo long term anticoagulation therapy, which is not the same in case of bioprosthetic valves [1].

Among, Mechanical Heart Valve (MHV), the Bileaflet MHV is popular due to its superior Hemodynamics. Advances in engineering and biomaterials have enabled the design of efficient mechanical heart valves. The major advantage of mechanical heart valves is their durability and longevity (life span more than twenty-five years) making them more suitable than bioprosthetic valves. Since their introduction in 1977, the hemodynamics of mechanical heart valves have been studied extensively. Even new technologies were developed for better design, materials, manufacturing and post design verification of mechanical valves. For analysis procedures and due to symmetry, only one-fourth of stent and leaflet are modeled and static contact stress between the stent and the leaflet were studied for different modes of loading and pressure [3].

All this type of research was carried out in order to produce hemodynamically and structurally superior heart valves. The recent trend in newer bileaflet valve design seems to be concentrated on the hinge mechanism with an anticipation of improvement in reduction in the thrombus problem, and leaflet design to improve overall valve performance [4].

In addition to static analysis of mechanical valves, an attempt was made to understand the blood flow thorough the valve design. This would help in optimizing the overall performance of the valve and reduce the potential for blood clotting at the valve. This was possible through a computational fluid dynamics simulation tool that results in a 3-dimensional fluid flow in passages of complicated valve geometry. If Computational Fluid Dynamics is used with good engineering judgment, it could very well help in reducing the cost and risks associated with the development of new heart valve design [5].

Aim

The purpose of this thesis is to study the stress analysis of bio-mechanical curved bileaflet heart valve for two positions of valve. Also, experiment is done to investigate the fluid flow through this curved bileaflet mechanical valve. The fluid flow is analyzed through the open blood vessels of the heart valve.

CHAPTER 2

MODELING PROCEDURE

The mechanical heart valve is an association of leaflet housing (also referred as stent), and two leaflets. This chapter deals with the formulation of geometric model and regulation incorporated in Finite Element model using IDEAS and root reasons for doing the same.

Geometric Model of the Heart Valve

The stent and leaflet geometry is provided and the next step is to configure them into an assembly model in order to have FEA analysis of the valve. Before the FEA analysis can be performed, boundary conditions to be applied have to be considered and care is taken while assembling the model so that the stent and the leaflet don not overlap with each other when the leaflet is hinged at the tip edge of the stent.

Boundary Conditions

Heart valve model being rotationally symmetric, the problem of analysis is made simpler by applying boundary conditions to one-fourth of the total model. Hence, the boundary conditions applied are known as symmetry boundary conditions.

To correctly model the problem, one must apply the boundary conditions in order to account for the shunned part of the model. In short, the boundary condition set must force the displacements on the plane of symmetry of the shunned model in order to have the same displacements, which would occur in the whole model, otherwise.

Boundary Conditions Set for Stent during Closed Condition

The Table 1 details about the restraints acting on the stent. The stent is constrained such that its translation is free along X and Z axes, when Y being constant. The stent rotation is kept free along Y axes, when X and Z axes are constant. In this present model the X, Y and Z axes are acting in the cylindrical co-ordinate system (CS-5).

TABLE 1. Restraints on the Stent

Axes	Translation	Rotation
X	Free	Constant
Y	Constant	Free
Z	Free	Constant

Boundary Conditions Set for Leaflet during Closed Condition

As can be noticed from Table 2 that the symmetric conditions being applied on the leaflet is such that its translation is constant along X axes, when Y and Z axes are kept free. The leaflet rotation is free along all the three axes X, Y and Z. Even in the case too the restraints are acting in the cylindrical coordinate system (CS-5).

TABLE 2. Restraints on the Leaflet

Axes	Translation	Rotation
X	Constant	Free
Y	Free	Free
Z	Free	Free

The boundary conditions above remain similar on stent and leaflet during open condition. Apart from these restraints, a constraint (degree of freedom) is applied at the front tip of the leaflet in order to prevent the back clash due to impact of two leaflets during closing, and the same constraint is not considered for open condition as this constraint obstructs its opening.

TABLE 3. Constrain at the Front Tip of the Leaflet

Axes	Translation	Rotation
X	Free	Constant
Y	Constant	Free
Z	Constant	Free

Error! Reference source not found. Contact Stress

The boundary condition set also includes contact set, which is a type of boundary condition set. A contact is defined between two surfaces or between two element faces in the model and which deform slightly under imposed loads. So, once contact has been established between the desired surfaces, it is easy to get the contact stress subject to load or pressure conditions. This will result in taking into account the effect of contact stress in the analysis of the model. Table 4 shows the pairs of contact set, which have been established.

The contact set pairs listed in Table 4 remain same for both closed and open positions of the leaflets. But, there are two extra contact set pairs for the open positions. These two contact pairs are necessary as they account for necessary contact stress on the model for proper opening of valve. A full view of contact elements acting on the model is shown in Figure 10. Table 4 is created while looking at the model along the Y axis direction

Table 3 below shows the constraint acting at the front tip of the leaflet. This front tip is also constrained in cylindrical co-ordinate system (CS-5), where in the translation is free along X axes and constant along Y and Z axes respectively. Similarly, rotation is kept constant in X-axes, when Y and Z axes are free. Figures 1 and 2 shows the constraint on the leaflet and all the symmetry boundary constraints acting on the stent and leaflet, respectively.

TABLE 4. Contact Set Pairs

Pairs	Hitting Region	Target Region	Reference Figures
1	Front surface of the leaflet	Inside front surface groove edge of the stent	Figure 3

2	Back surface of the leaflet 4	Inside back surface groove edge of the stent	Figure 4
3	Outer surface of the leaflet	Inside surface of the stent	Figure 5
4	Stent groove	Corresponding cylindrical surface of the leaflet	Figure 6
5	Flat surface of the Stent	Corresponding cylindrical surface of the leaflet	Figure 7

TABLE 5. Contact Set Pairs (Extra Pairs in Open Condition)

Pairs	Hitting Region	Target Region	Reference Figures
6	Front surface of the leaflet	Vertical face of the stent grove above the leaflet	Figure 8
7	Back surface of the leaflet.	Vertical face of the stent groove below the leaflet	Figure 9

The contact set pairs listed in Table 4 remain same for both closed and open positions of the leaflets. But, there are two extra contact set pairs for the open positions, as seen in Table 5. These two contact pairs are necessary as they account for necessary contact stress on the model for proper opening of valve. A full view of contact elements acting on the model is shown in Figure 10.

Model Solution and Post-Processing

Model Solution is the penultimate step before the FEA Post-processing. Here a solution is set up which will imbibe all the details inculcated in the boundary condition set, so that the solution can be run. Once the solution is ready, it is stored in the model file, and used in the post-processing task to display the analysis results.

In the post-processing task, FE results of a finite element model consisting of heart valve assembly which is derived from the parts referring to the integral instances of the assembly can be seen.

CHAPTER 3

RESULTS AND DISCUSSIONS

This chapter discusses consummate results gathered during the development of Finite Element model. These developments give us the information on stress distribution on the stent and leaflet and dynamic contact stress due to impact between the leaflet and the walls of the stent and displacement for corresponding load conditions.

For Closed Position

Initially, In spite of applying the symmetric boundary conditions and applying contact sets at the appropriate surfaces between the stent and leaflets, difficulties did encounter in getting right stress results. Enquiry into this yielded the following reasons:

1. The gap between the stent and the leaflet was towards the higher side, when the leaflet is attached at the tip edge of the stent, because of which we were not able to set up contact pair between the desired surfaces.
2. There used to be backlash of the leaflets due to impact between them during their closing.

The above problems were solved by reassembling the stent and the leaflet and care was taken that the gaps between the two be minimal all along from the tip to the bottom. By doing so desired contact stress is established and later the second problem was solved by putting the constraint at the tip of the leaflet.

Once, the boundary condition is set up for closed position, contact stress is observed between inside surface of the stent (above the leaflet) and corresponding surface of the leaflet, and the maximum contact stress noticed was 665 psi as shown in Figure 11. Similarly, stress acting on the model is noticed at the front tip of the leaflet, because of a special constraint acting at that point, which was put in order to prevent backlash (as explained in modeling procedure) and maximum stress is developed at the one of the extreme end of the stent and also at the bottom tip of the leaflet, which is in accordance with symmetry boundary conditions. In this case, maximum stress observed is 12,300 psi Figure 12. Finally, the displacement of the leaflet which is under a standard test pressure of 3.82 psi is minimal. The reason being is as the leaflet is in its closed position, the back pressure acting on the leaflet induces the stress, described above, and hence forth the leaflet has no more room for movement Figure 13.

For Open Condition

For this case symmetric boundary conditions were applied. Similar kind of care was taken like closed condition but with a change in direction of pressure being applied. The constraint at the front tip of the leaflet had to be taken off as it cramps the free movements of the leaflets while they open.

Once the conditions are set for open position, contact stress is confirmed between the vertical face of the housing groove and corresponding surface of the leaflet. The maximum contact stress obtained at above mentioned region is 1130 psi, Figure 14. Similarly, the maximum stress is attained at the front bottom tip surface of the leaflet is 74800 psi, and it is believed that this stress distribution is due to restraints applied as part of symmetry boundary conditions Figure 15. Lastly, the maximum displacement of the leaflet during open position obtained is 0.00995 inches, when it is subjected to a standard test pressure of 3.82 psi Figure 16.

Verification with References

Based on the experimental results obtained for bileaflet valves in this case and other different types of valves identified like carbomedics (CM) and Jyros (JR) in reference of Akutsu [2] have small differences in hinge location and leaflet configuration. Which results in noticeable change in the static contact stress acting on the above valves and ultimately affect the change in the flow phase of the valve. In addition to this reference from Yuan [4] talks about bileaflet mechanical heart vlave, where in the valve leaflets are in the fully closed position and static contact stress is observed between the leaflet and the housing. And during the full closure of the leaflets, a noticeable rebound is noticed between the leaflets, similar to present model. The maximum dynamic von-misses stress noticed near the hinge of the leaflet is 3.9 E3 psi. While, the maximum von-misses stress in the same vicinity of the present model is 3.06 E3 psi.

The present model results and reference of Akutsu [2] make it evident that leaflet is to be designed with minimum impact stress acting on the leaflet contact areas on collision with the inner walls of the bileaflet mechanical valves.

CHAPTER 4

FLUID-FLOW ANALYSIS

A fluid-flow analysis is carried out in order to address the significant three dimensional features of fluid stent interaction, aimed at understanding hemodynamics and possible blood clotting. Hence, for this kind of approach Computational-Fluid Analysis (CFA) software known as STAR-CD is employed. This software is basically divided into Pro-Surf, Pro-Am and Pro-Star.

As told above, the starting point of the CFA is Pro-Surf; were in a CAD model file, exhibiting the required geometrical surfaces in IGES format is imported into it. Once this is done, Pro-Surf conducts an automatic or manual repair of the exported CAD data, in order to ensure the constancy and quality of the surface mesh to be generated. After the CAD model is repaired for desired fidelity, the surface mesh is generated. At the end of the Pro-Surf operation, a Pro-Surf restart file and a database file are created containing all the surface grid operation data. In Pro-Am, the database file created in Pro-Surf is utilized further to generate a high quality computational fluid dynamics grid. This volumetric grid generation process is divided into Geometry import and surface preparation, subsurface generation, volumetric meshing and cell layer extrusion, which are accessible through a GUI (Graphic User Interphase) panel within the Pro-Am environment.

Finally, the Pro-Star module helps in administrating the boundary conditions in terms of geometry of the flow domain, fluid properties, running the solution parameters and post processing the results.

Surface Preparation in Ideas

The required geometric model consisting of stent surfaces is prepared in Ideas. As explained earlier, only one-fourth of stent geometry is available, but for purposes of fluid analysis, the available geometry is reflected to obtain the stent geometry in its entirety. Once the entire stent surface is available, free edges from this new surface are projected onto a reference plan created at either sides of the stent at a distance of 1 inch away from the stent. Then, these curves are used to generate lofted surfaces at either side of the stent, which will act as blood vessels for the stent Figure 17.

Later an iges file of this whole section is created, which is then imported into Pro-Surf of Star CD.

Surface Mesh Preparation

An iges file containing the stent surfaces is imported into Pro-Surf. Then this CAD model is made to go through a CAD repair tool in order to check for any kind of free edges, which will define the outer boundaries of the surfaces. If there are any then, this repair tool fixes those edges. Later, a grid is generated on the stent surface and this grid generation is divided into coarse grid of size 0.45 inches. On the blood vessels, a fine grid of size 0.09 inches is developed on the stent grooves in order to have a good definition of the grid, because of the complexity of groove geometry Figure 18. Also, a minimum length scale due to curvature is maintained at 0.0552038 inches. The reasons for this minimum length scale are discussed in the paragraphs describing volumetric meshing.

Once the gird generation is completed a restart file is saved for future purposes in the Pro-Surf in case any changes are required for surface triangulation and a database file is also saved for use by Pro-Am.

Volumetric Mesh Preparation

Pro-Amm provides a convenient way of generating meshes for complex geometries through a Graphic User Interface (GUI), which guides through a process oriented environment. Pro-Am follows a systematic methodology for generating a high-quality finite volumetric grid, which is divided into four main groups.

Geometry Import and Surface Preparation.

The gometry is imported through a database file created in Pro-Surf. The imported geometry consists of no end caps, so the Pro-Am identifies them as holes. Before proceeding with Surface Preparation, a surface check is recommended in order to check the integrity of the surface. This is generally done for defects that are inherent in the data transfer Figure 19.

Once the check is preformed, any unclosed surfaces, sharp angles, shell orientation, multiple edges are taken care of, by closing the holes, which is only possible if the cell size specified during the surface triangulation in Pro-Surf is greater than 0.05 inches. Also, the edge feature angle is maintained at twenty degrees as a lesser value might not result in filling up the holes and also might affect the edge definition of the model geometry and which ultimately helps in identifying the inlet and outlet during the boundary condition setup. Finally, shell orientation and multiple angles are taken care of, by using the option of orient cells in surface check (Figures 20 and 21).

Subsurface Generation

A subsurface is generated in order to create extruded cell layers at a later stage of Pro-Am meshing process. During the subsurface generation, Pro-Am shrinks the original surface mesh, along the surface by a distance and in this case, a subsurface thickness of 0.01 inches is used. Any shell surface types that do not require extrusion layers are identified as no subsurface cell types, for example, the inlet and outlet for the flow Figure 22.

Volumetric Mesh Preparation

Once the subsurface is generated, it is then used to generate Pro-Am volumetric mesh. This can be carried out using trimmed, tetrahedral or hybrid cell types; in this case, volumetric mesh is carried out with trimmed cell type. The volumetric mesh of Pro-Am proceeds by building a structured grid, adjusting the grid vertices that are close to the subsurface. In addition to this, the cells which straddle the subsurface are cut by Pro-Am to follow the subsurface and discarding the cells which fall completely outside the subsurface Figure 23.

Generate Template

Generate template step determines the quality of mesh, which verifies that the template of the mesh generated is suitable for further use with the trimmed cells or if it requires changes to improve the cell transition during meshing.

Extrusion Layer and Generation

In Pro-Am assembly, the generation of extrusion layer is the last stage. During this step, the surface for extrusion is created between the surface and the respective concerned surface. During this step, the surface wall thickness is mentioned, which is the same as the thickness of the layer near the wall, in order to maintain the uniformity near the wall layers. Also, it is necessary to mention the type of cells that do not require the subsurface, namely the cells defining the holes. Later, the fluid cells are assembled with the cells generated during this step.

Flow Analysis

It is the Pro-star module of Star CD which deals in creating boundary conditions, checking the model setup, establishing fluid property definitions and finally setting up the analysis preparation. The Pro-star is controlled using a graphics user interpahse (GUI) of Star CD and also through a command driven output window. Before flow analysis can start, boundaries are located by defining the regions of wall, inlet fluid, and outlet fluid, which are regarded as holes during the process of volumetric meshing. During this setting, an inlet velocity of -0.22 meters per second is chosen on the basis of calculation shown below; the negative sign is due to the co-ordinate system of the model.

Volume flow rate is defined as, $Q = V \times A$

Where V is the velocity at the inlet and A is circular area which is equal to $\frac{\pi}{4}d^2$

So, on calculation, the velocity at the inlet is

$$V = \frac{Q}{A} \approx \frac{8.33\times10^{-5}}{\frac{\pi}{4}\times\left(21.91278\times10^{-3}\right)^2} = 0.220970 \text{ m/sec}$$

TABLE 6. Flow Data

Diameter of Housing in inches	0.8100
Diameter of Housing in millimeter	21.91278
Volume flow rate of blood in one min	5 liters
Volume flow rate in min, Q_m	$5\times10^{-3}\, m^3/\text{min}$
Volume flow rate in sec, Q_s	$8.33\times10^{-5}\, m^3/\text{sec}$
Density of fluid (Water)	$993.45\ kg/m^3$

Model Setup

During model setup, care is taken to check for illegal cells, illegal boundaries, coupling between cells, negative volumes, aspect-ratio and cracks on the surface. So, when this check was performed, problems related to negative volumes, aspect ratio, and cell coupling were discovered, because of which it was not possible to start the final analysis preparation.

The above problems were solved individually. To begin with negative volumes and left handed defined cells were fixed first. This problem was taken care of through a command prompt window, using a command called CFIX, which solves the problem of redefining the cells by reordering their respective constituent vertices. But before doing this, all the negative volume cells and left handed cells were placed in a new cell set called CSET. And after all the cells were placed in this CSET, the command prompt CFIX was applied on this CSET.

It is also necessary to have an improved mesh definition, and in order to have that it is required to take care of the aspect ratio, which generally has to be close to unity or a little more; the angle of intersection between the cell faces too should be minimum. Generally, the above two issues are not very serious in terms of running the flow analysis but it is always better to take care the deformed cells if any, because it would certainly delay the numerical convergence and will also result in numerical instability.

Again, all the vertices which need to taken care of are put in a new set called vertex set, VSET. For this case a command called MORTHO is used through the command prompt window. This results in improving the internal angle or wrap angle. Also, a command called VSMOOTH is used, which indeed moves the vertices so that distances between these vertices are uniform as possible. Sometimes the number of cells which need improvisation in their shape are very few. So in those cases, there are commands which works on a "cell after cell" basis. These commands are known as VADJANGLE and UNSKEW, which work on the same principles as the commands

MORTHO and VSMOOTH, with the difference that values are specified by the user in their case.

Cell coupling is another serious issue which needs attention. In this case, the master cells are not in proper association with the slave cells. In the other words when the master and slave cell cannot generate a perfect couple between them. Which happens, when normal cell coupling algorithm is not able to build a proper couple generation between the cells because of improper mesh definition involving changes in cell size and cell faces. For this, a command called CPFACE is used through command prompt window. This results in defining a proper single couple, with respect to the monster cell and its corresponding slave cells. This command also enumerates the face numbers of the cells as also of those that need to be coupled.

If there are any cells which are not properly coupled, then all the cells are accumulated into a new set, called cell set, CSET. Then a command called CPGENERATE is used through the command prompt window. This results in couple generation between the cells stored in the CSET. Also, using a command called CMODIFY, it is easy to modify the couple definition by either changing the master or slave cell numbers involved in the couple or modifying the specific cell faces that are to be coupled or even swapping the master and slave cell definition.

Results and Discussion

Figure 24 shows velocity section profile. It can be seen that stagnation of flow is observed where the blood vessels meet the housing (0.1635 m/sec). Due to reduction in size of cross section, an increase in velocity is observed in the main stream. Once, the flow moves out of the housing into the blood vessel, a large area of stagnation is observed which is the result of an increase in the cross section (0.7846 m/sec). Also, reduction in main stream velocity is observed (0.2286 m/sec). The values shown in the bracket can be seen in the legend along with the velocity section profile.

Figure 25 shows pressure section profile. At the point of entry to the housing, reduction in cross section is noticed; hence the amount of fluid that can pass through the housing reduces. This results in accumulation of fluid volume around this region, which in turn causes back pressure to the incoming flow from the blood vessel causing the recirculation of the fluid (34.77 m/sec). Due to this the pressure profile shows an increase in pressure at the point where the blood vessel and housing meet. The value shown in the bracket can be seen in the legend along with the pressure profile. Figures 26 and 27 are in keeping with the above findings.

Verification with References

The computational results of a CFD model discussed by Kelly [5] show unsteady flow through the leaflet where in symmetry boundary condition are applied to the model. A forward flow of a homogeneous Newtonian fluid with a density of 1050 kg/m^3 is subjected through the leaflets during their open position. A large recirculation zone along the downstream of the pivot is observed. A similar phenomenon is observed in the present model case too when a flow of density 993.46 kg/m^3 is subjected (Figures 26 and 27). Research by Yoganathan [3] and Kelly [5] model analyzes and identifies small scale flow features in the hinge region of the valve, where clotting behavior and flow separation around the adjacent sides of the valve is observed like the in present model.

Further, the present study and Kelly's research [5] aims to study working aspect of the heart valves which is made of critical complex features and understanding the flow aspect through these valves. CFD quickly investigate the effects of design changes on blood flow, reducing the risk of unexpected effects which would otherwise become apparent at a later stage. This kind of a design development process would further help researchers in integrating CFD, along with other computational tools like finite-element analysis leading to development of a simpler engineering heart valve model at a reduced time cost and risk.

CHAPTER 5

CONCLUSION

The whole purpose of finite element analysis is to understand the approach of Degree of Freedom, which is being implemented. This approach helped in learning and analyzing the displacement and maximum amount of principal stress acting on the model.

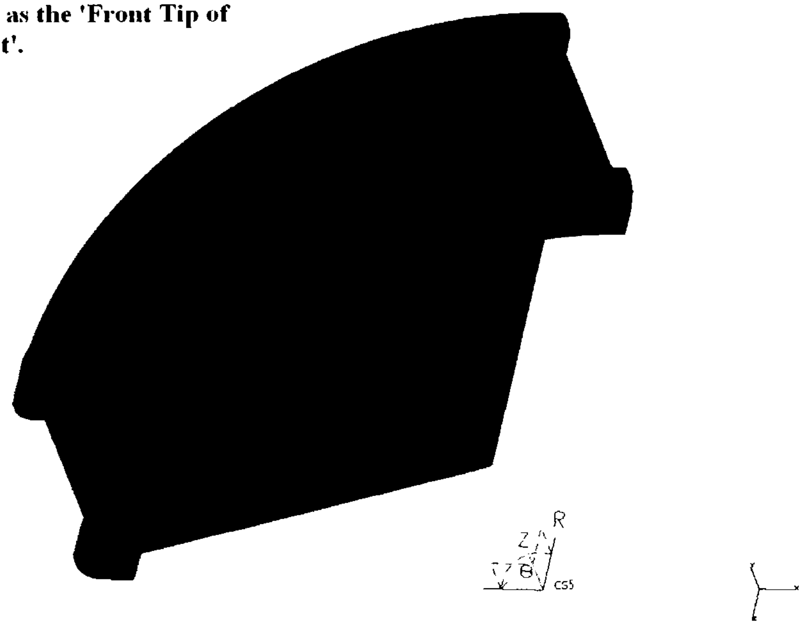
It is these stresses and displacement which gives the correct indication of refined movements of leaflets during the closed and open position of bi-leaflet heart valve. But before accepted stress and displacement results were attained, care was taken with regards to the restraints being applied on the model, followed by contact stress between the leaflet and housing stent. Of course, the contact stress between the leaflet and stent housing is a little different for closed and open positions, as the positions infers. Also, there is difference in pressure being applied during both cases. This research was carried over to computational fluid analysis. But the geometric model had to undergo some changes. Blood vessels, for example, were created before it was brought into Star-Cd, the flow analysis software, through an IGES file from Ideas. The aim of this flow study is to understand the transformation of geometric model from Ideas to Star-Cd, while keeping the geometric surface parameters intact with the provision of controlling the mesh check, grid generation parameters which are available through

Star-Cd flow analysis software. Also, optimizing the number of elements defining the fluid model (this is derived from geometric model) is of essence because it is easier and very lucid to understand the fluid flow when the number of surfaces which are going to come into direct contact with the flow during the flow analysis are few. In other words, lesser surfaces result fewer complications coming up during the flow because there might be problem of flow stagnation with more number of cross section surfaces. This thesis did result in getting acquaintance with flow analysis software in setting up the boundary parameters, flow parameters and analyzing the flow set-up.

Lastly, the linear finite element model explained above shows the simulation of closing and open position of the bi-leaflet heart valve. While the flow analysis model gives the simulation of of fluid flow through the blood vessels of this bi-leaflet heart valve. In short attempt has been made to analyze the fluid structure interaction and the different kind of forces and pressure involved in closing and opening the leaflets, which in this is fluid which is flowing through the vessel and the cylindrical cross section of the bi-leaflet valve.

APPENDIX

FIGURES



The encircled region is what is refered to as the 'Front Tip of the Leaflet'.

Figure 1. Degree of freedom at the tip of the leaflet.

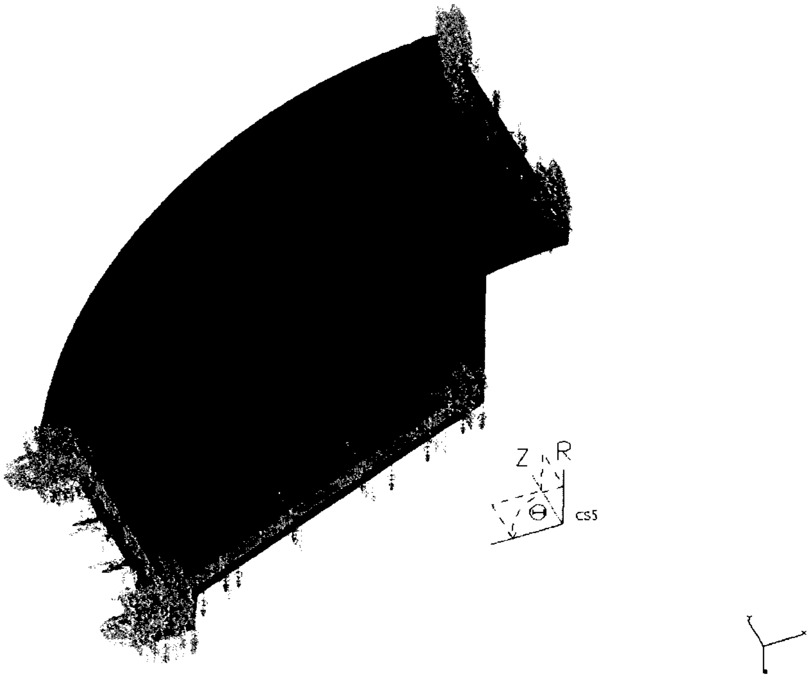


Figure 2. Full view of restraints applied on the stent and leaflet.

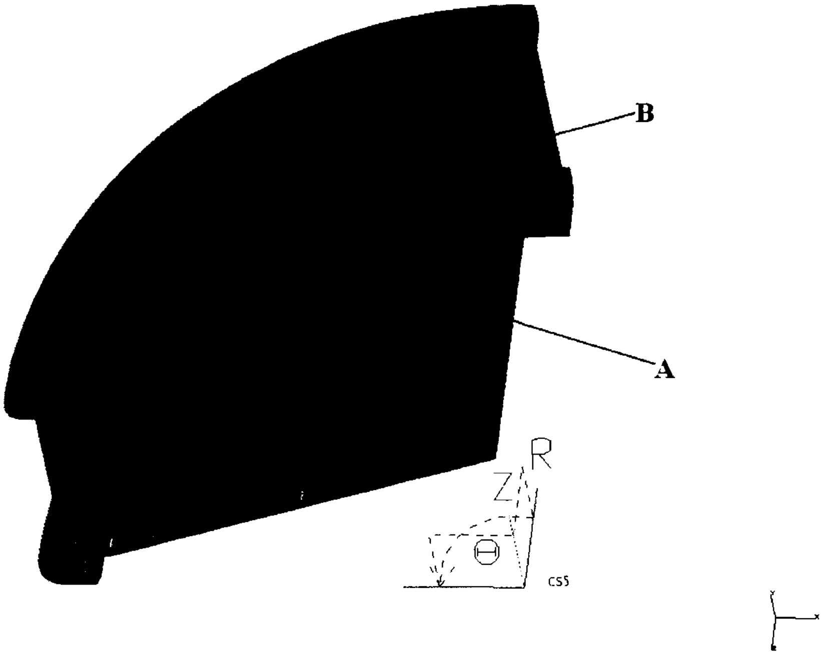


Figure 3. Front surface of the leaflet (A) with the inside surface of the stent (B).

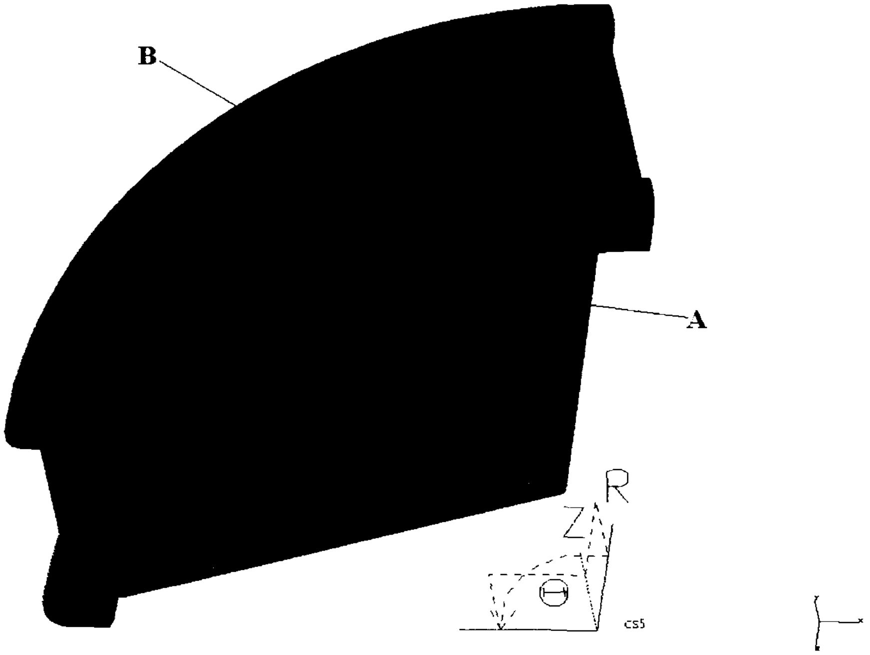


Figure 4. Back surface of the leaflet (A) with the inside back surface groove of the stent (B).

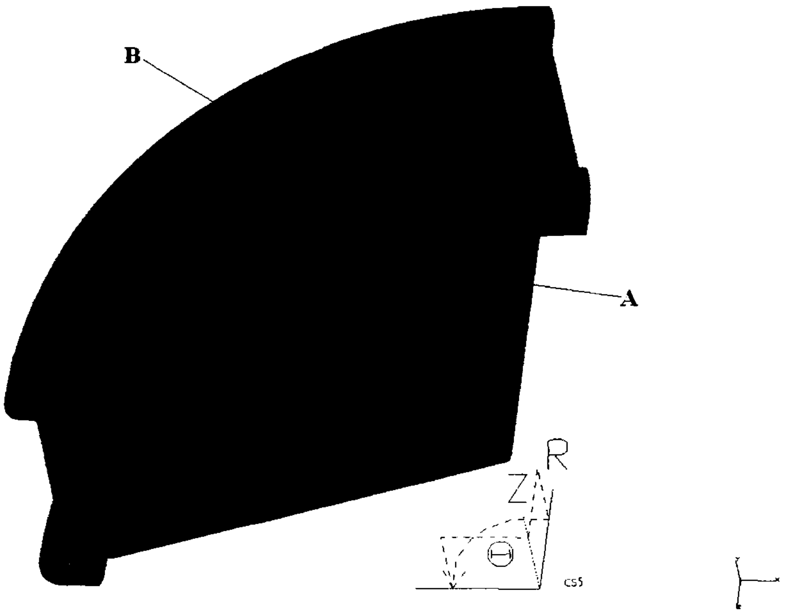


Figure 5. Outer surface of the leaflet (A) with inside surface of stent (B).

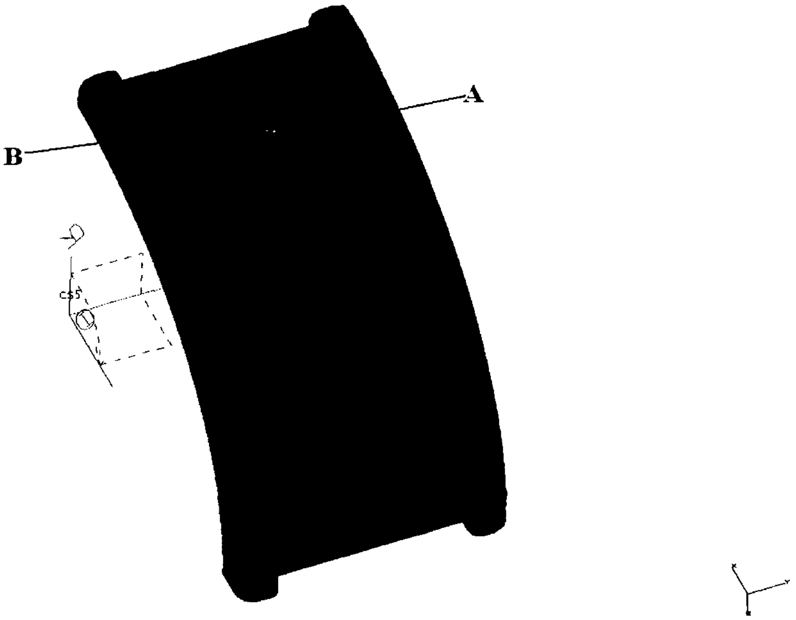


Figure 6. Stent groove (A) with corresponding surface of the leaflet (B).

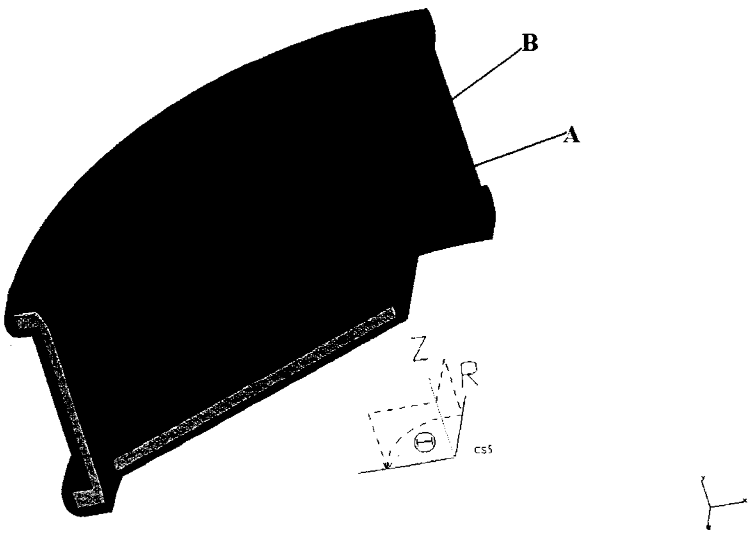


Figure 7. Flat surface of stent (A) with corresponding flat surface of leaflet (B).

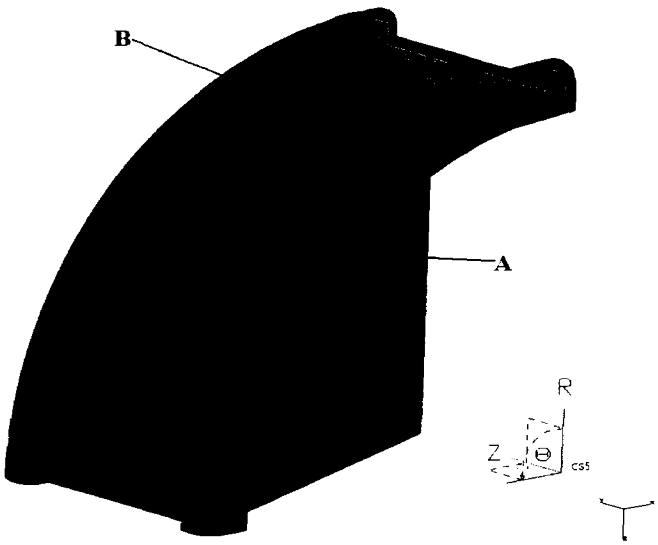


Figure 8. Front face of the leaflet (A) with vertical face of the stent (B) groove above the leaflet.

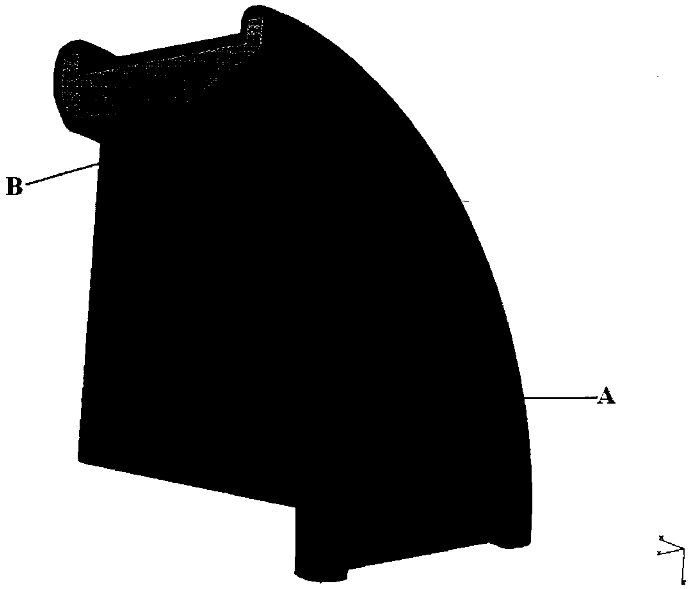


Figure 9. Back surface of the leaflet (A) with vertical surface of the stent (B) below the leaflet.

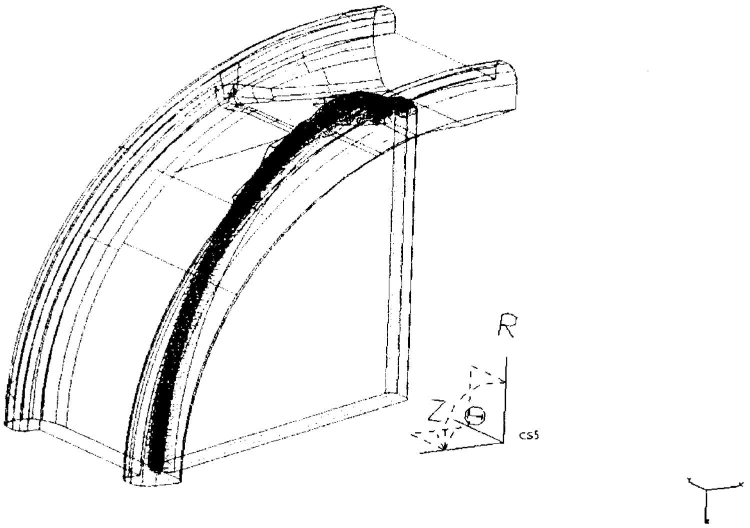
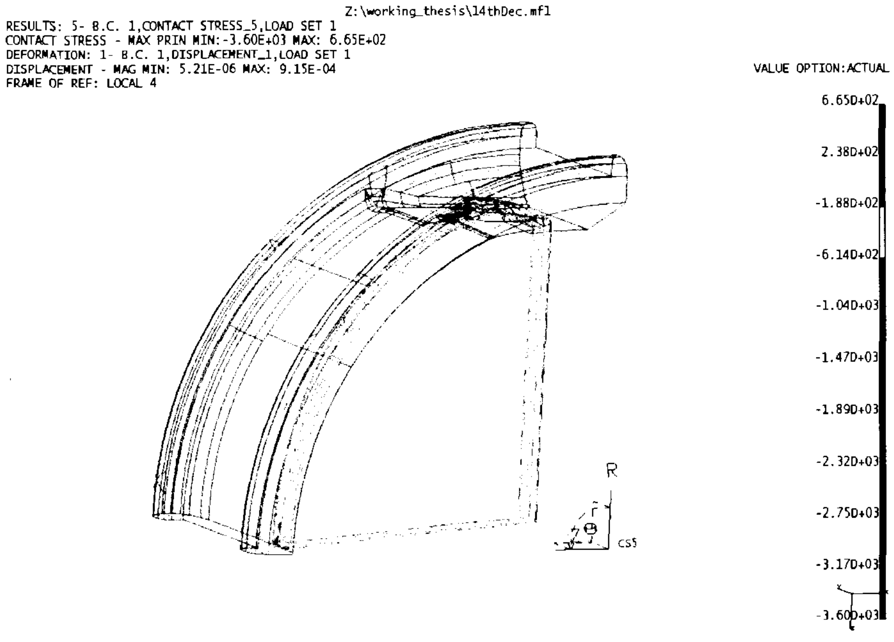
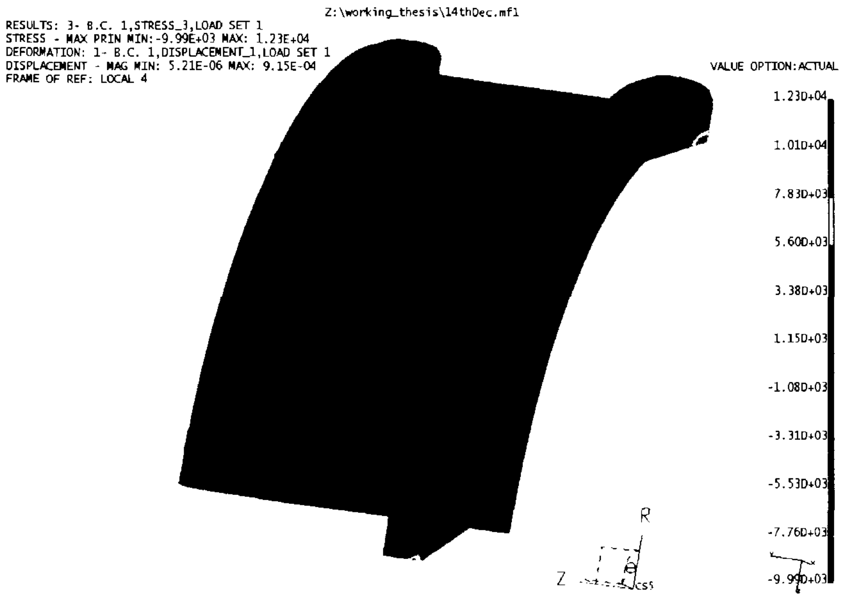


Figure 10. Contact elements between the leaflet and the stent.



```
Z:\working_thesis\14thDec.mfl
RESULTS: 5- B.C. 1,CONTACT STRESS_5,LOAD SET 1
CONTACT STRESS - MAX PRIN MIN:-3.60E+03 MAX: 6.65E+02
DEFORMATION: 1- B.C. 1,DISPLACEMENT_1,LOAD SET 1
DISPLACEMENT - MAG MIN: 5.21E-06 MAX: 9.15E-04
FRAME OF REF: LOCAL 4
```

Figure 11. Contact stress (red in color) during the closed position.



```
Z:\working_thesis\14thDec.mfl
RESULTS: 3- B.C. 1,STRESS_3,LOAD SET 1
STRESS - MAX PRIN MIN:-9.99E+03 MAX: 1.23E+04
DEFORMATION: 1- B.C. 1,DISPLACEMENT_1,LOAD SET 1
DISPLACEMENT - MAG MIN: 5.21E-06 MAX: 9.15E-04
FRAME OF REF: LOCAL 4
```

Figure 12. Maximum Stress (red in color) acting on the model during closed position.

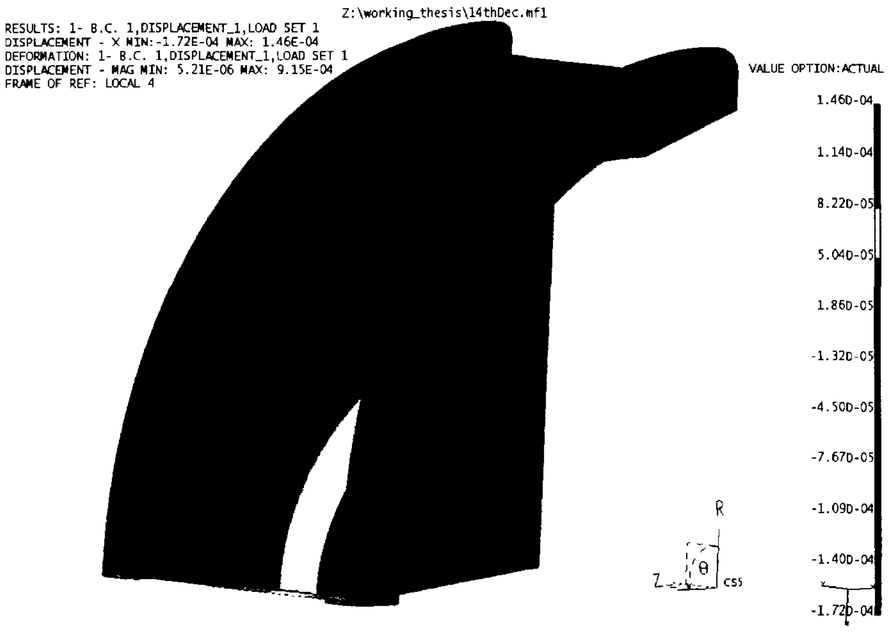


Figure 13. Displacement results during closed position.

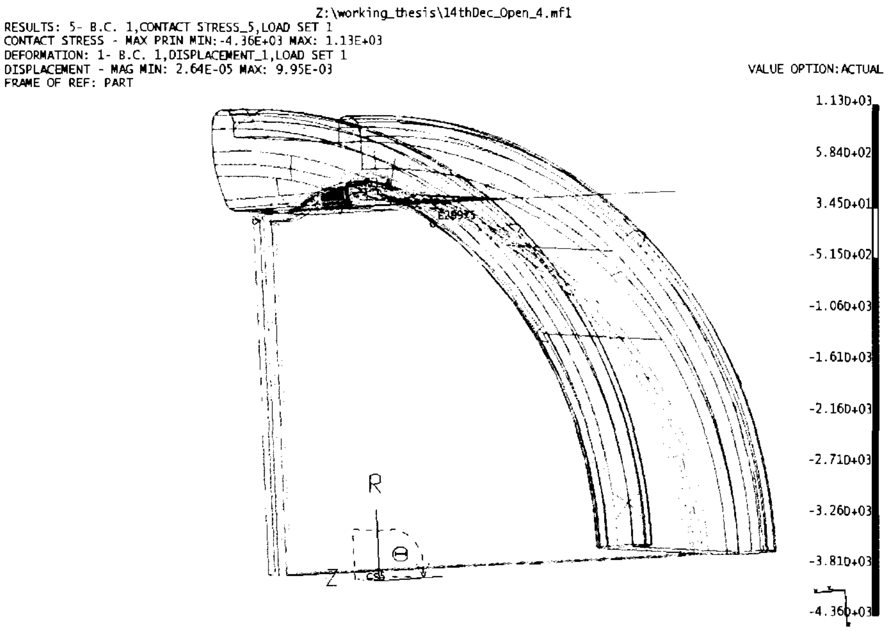


Figure 14. Contact stress (orange in color) during the open position

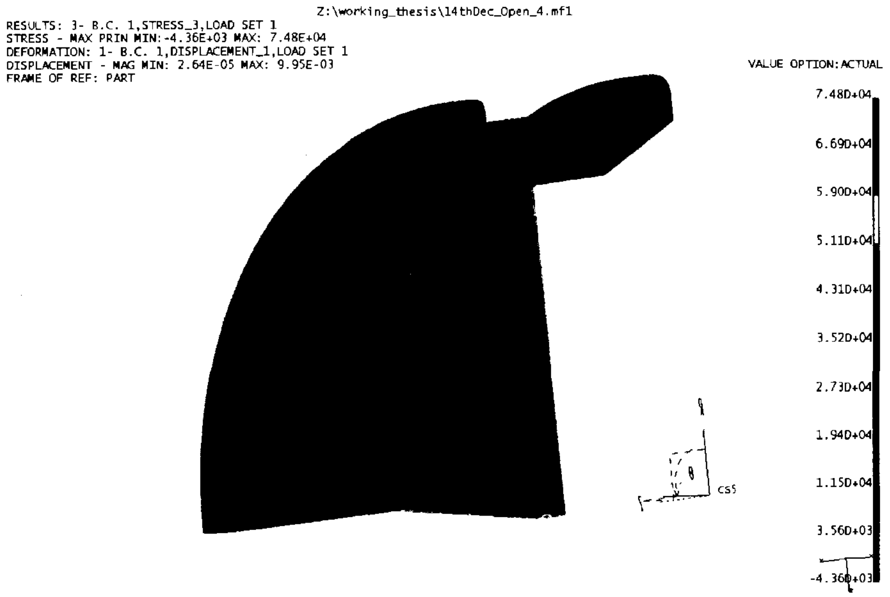


Figure 15. Maximum stress (red and green in color) acting on the model during open position.

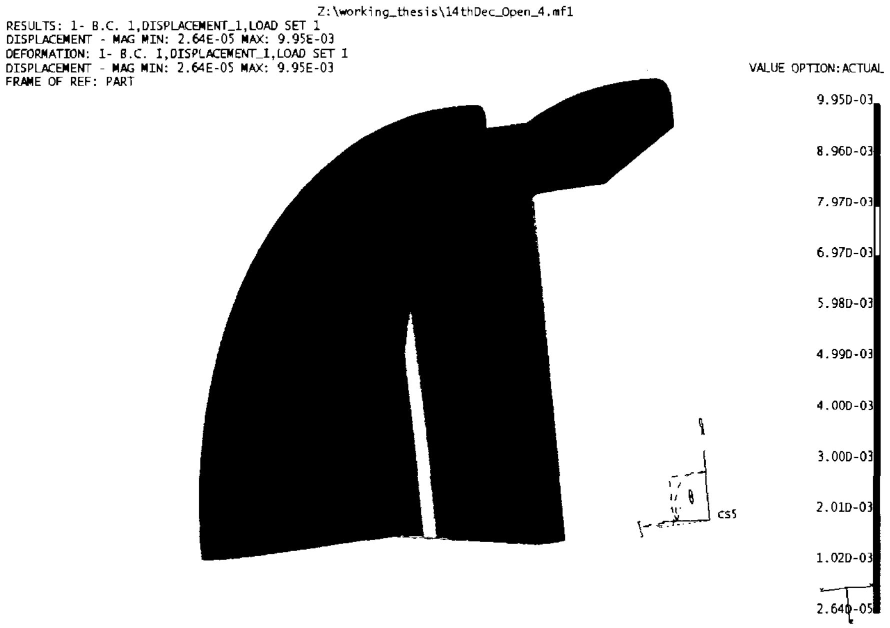


Figure 16. Displacement results during open position.

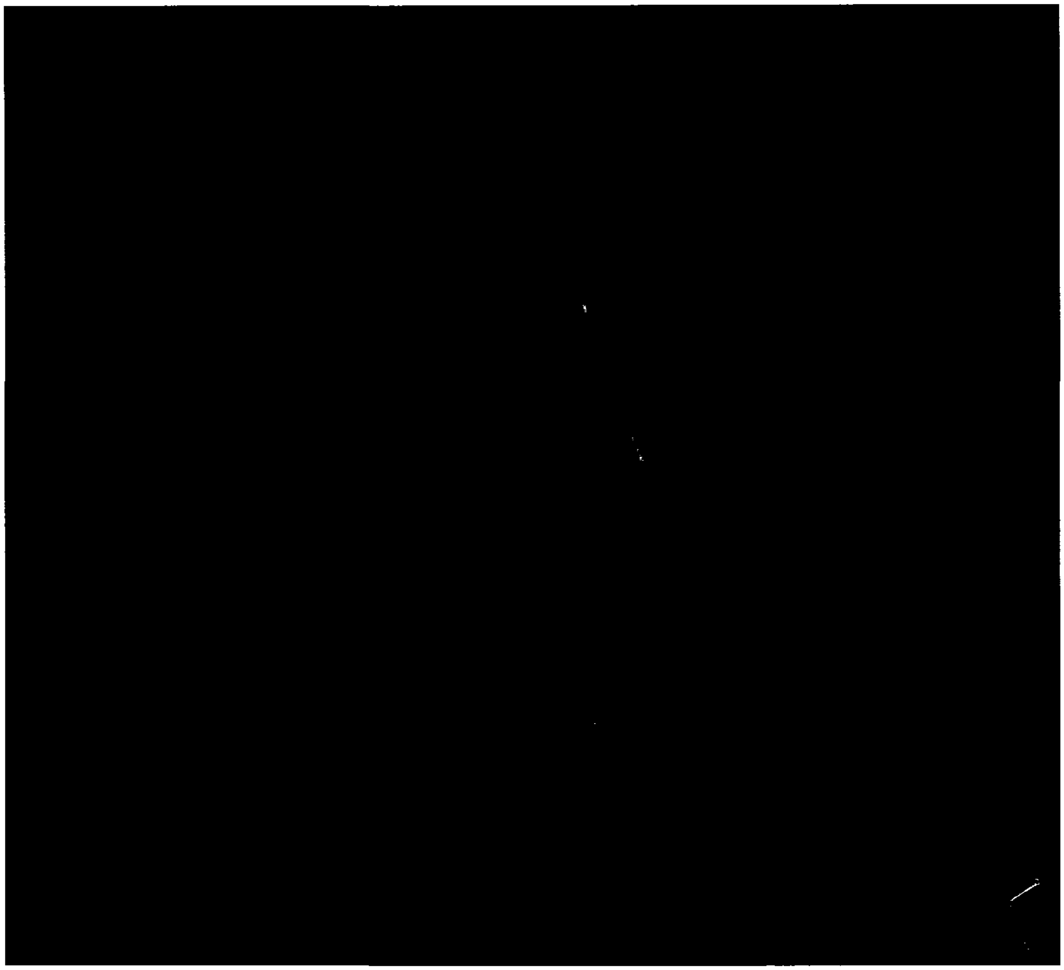


Figure 17. Iges file of stent and blood vessels.

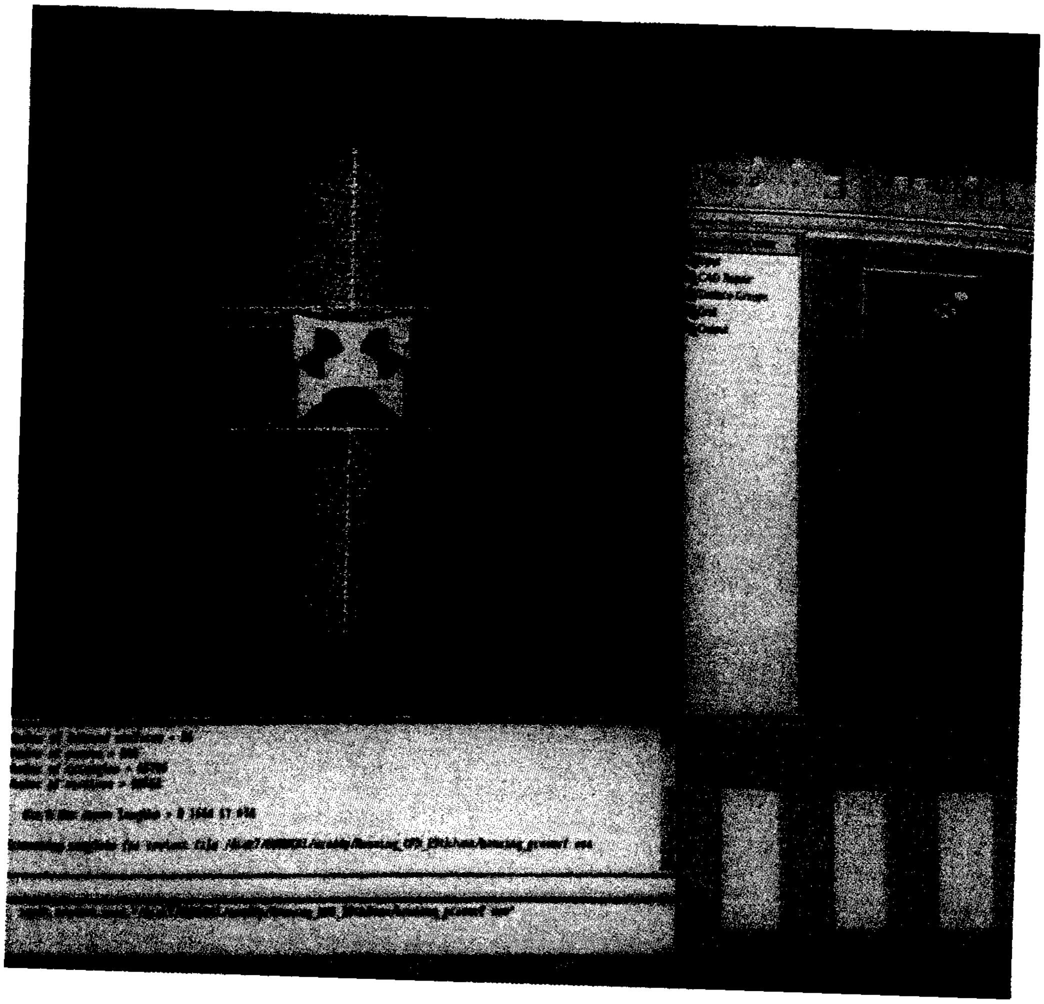
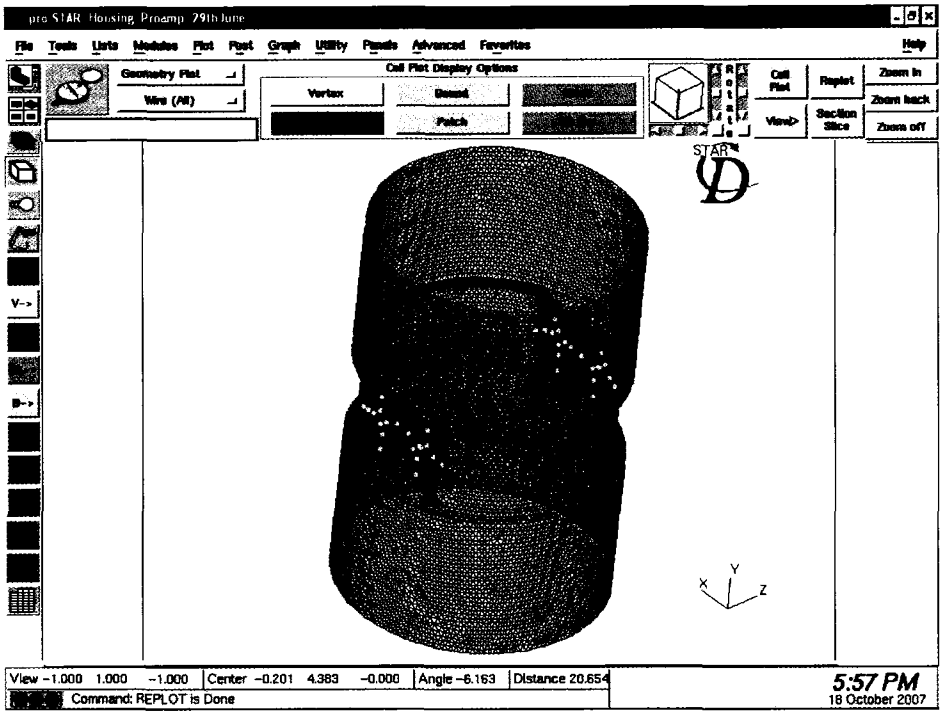


Figure 18. Surface mesh preparation in pro-surf.

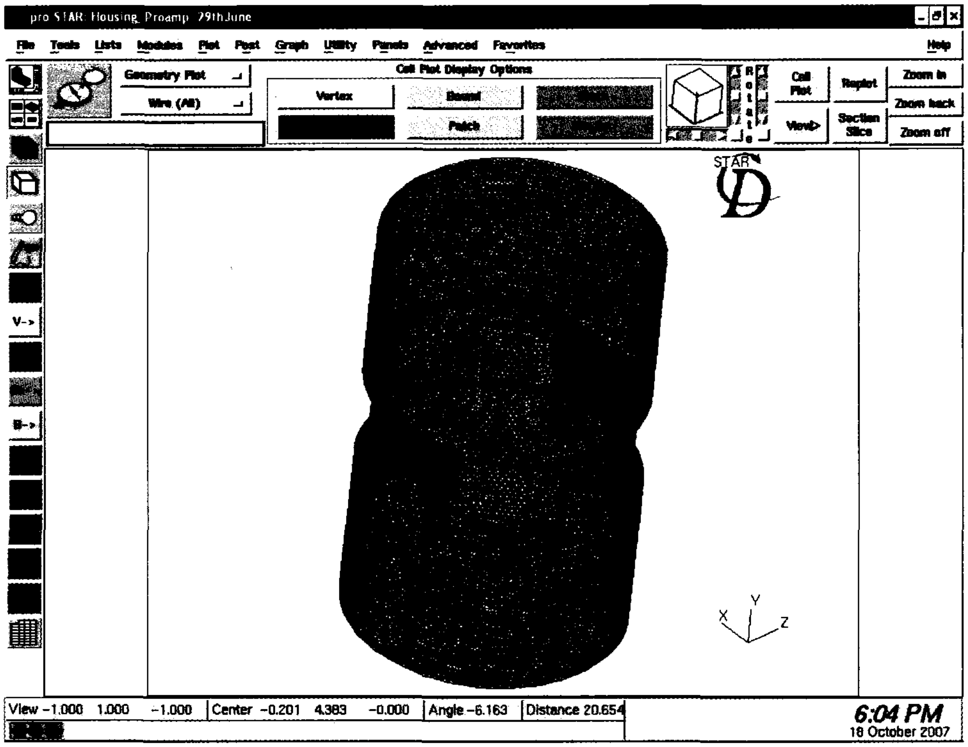


View -1.000 1.000 -1.000 | Center -0.201 4.383 -0.000 | Angle -6.163 | Distance 20.654

Command: REPLOT is Done

5:57 PM
18 October 2007

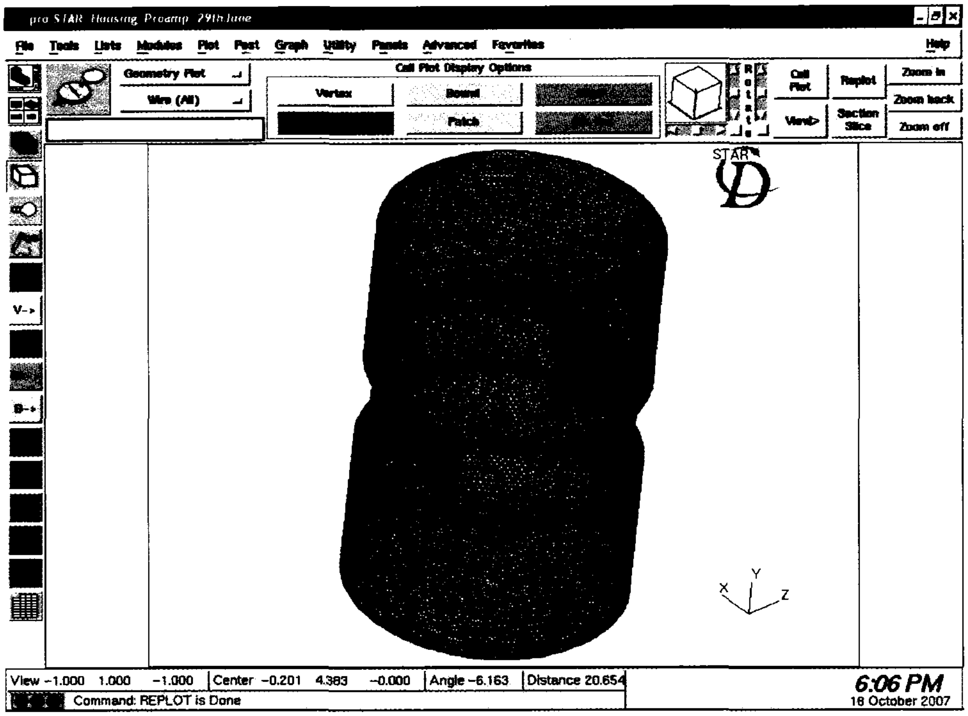
Figure 19. Imported cad data into pro-am from pro-surf.



View -1.000 1.000 -1.000 | Center -0.201 4.383 -0.000 | Angle -6.163 | Distance 20.654

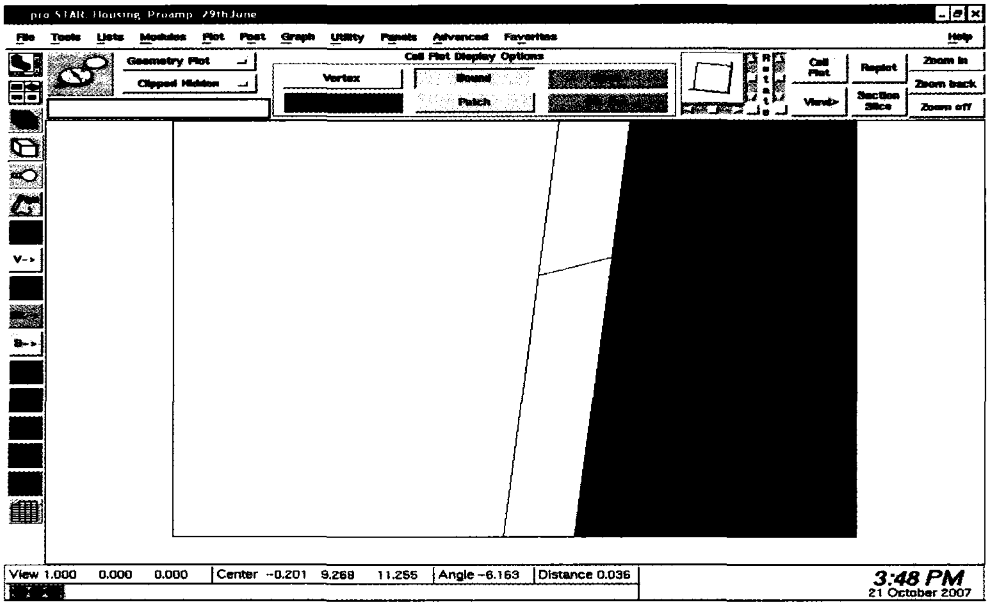
6:04 PM
18 October 2007

Figure 20. Geometrical fixed cad surface.



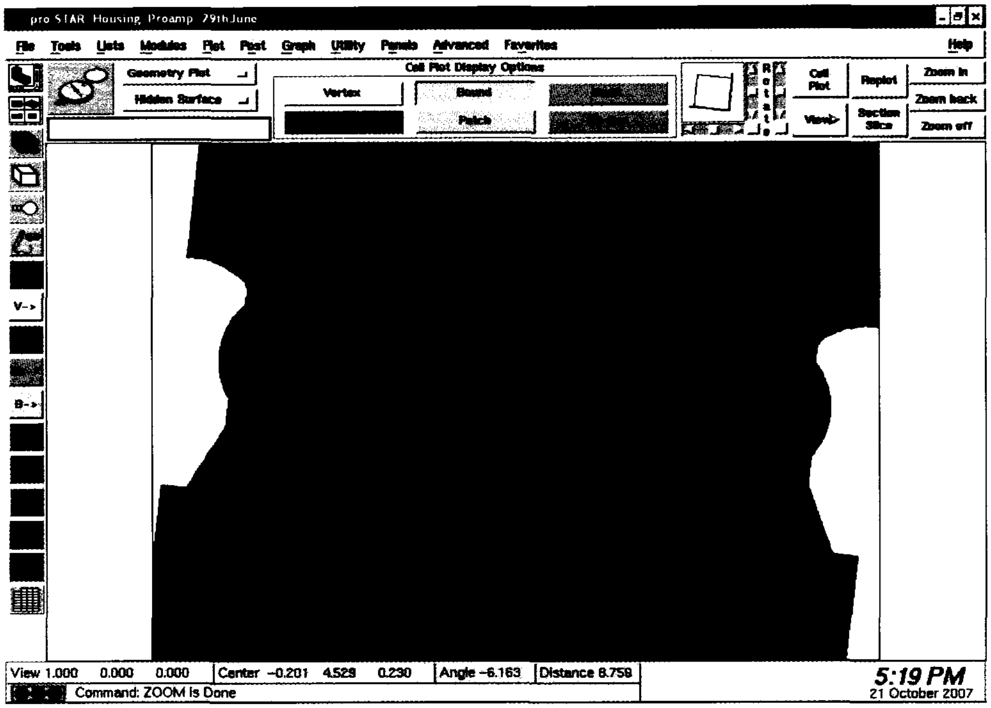
```
View -1.000 1.000 -1.000 |Center -0.201 4.383 -0.000 |Angle -6.163 |Distance 20.654
Command: REPLOT is Done
```

Figure 21. Creation of feature lines and end points.



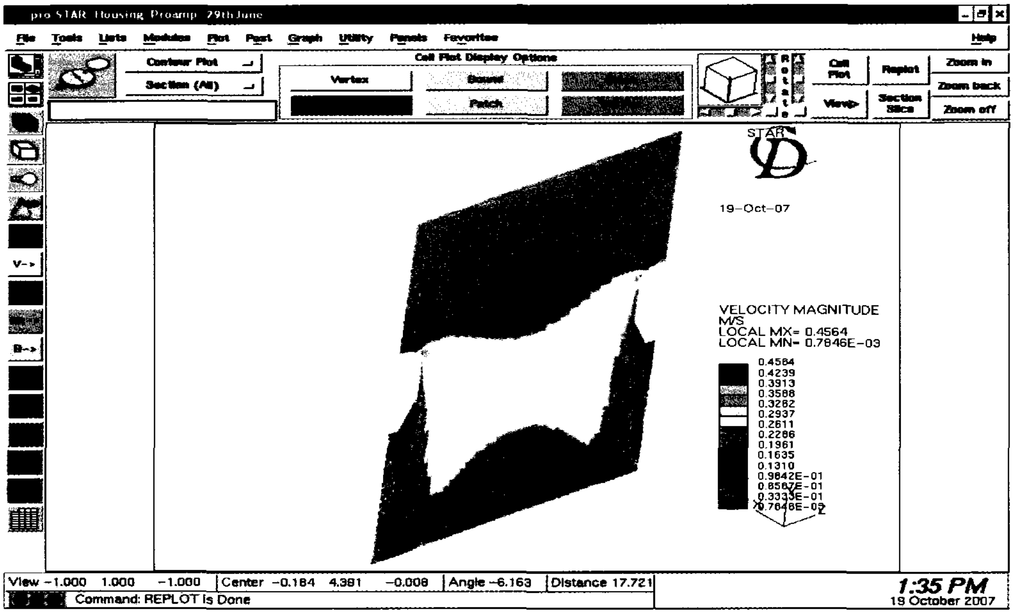
```
View 1.000 0.000 0.000 |Center -0.201 9.268 11.255 |Angle -6.163 |Distance 0.036
```

Figure 22. Generation of subsurface.



```
View 1.000   0.000   0.000   |Center -0.201   4.529   0.230   |Angle -6.163   |Distance 8.759
Command: ZOOM is Done
5:19 PM
21 October 2007
```

Figure 23. Volumetric mesh.



```
View -1.000   1.000   -1.000   |Center -0.184   4.381   -0.008   |Angle -6.163   |Distance 17.721
Command: REPLOT is Done
1:35 PM
19 October 2007
```

Figure 24. Velocity profile (section).

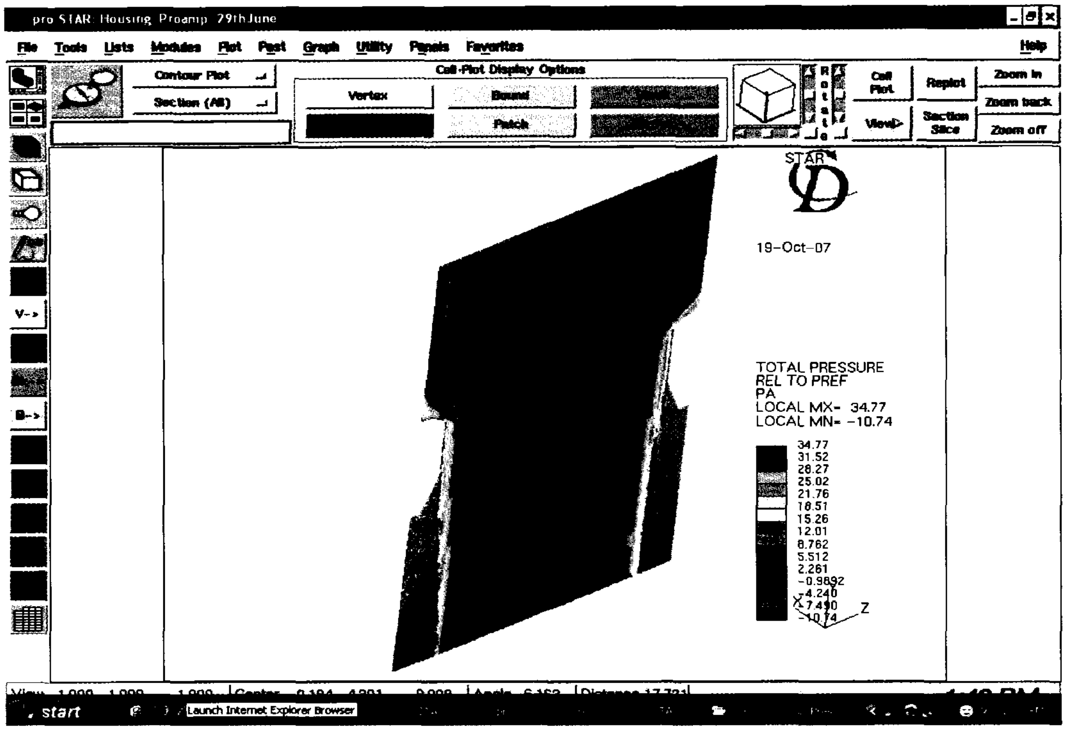


Figure 25. Pressure profile (section)

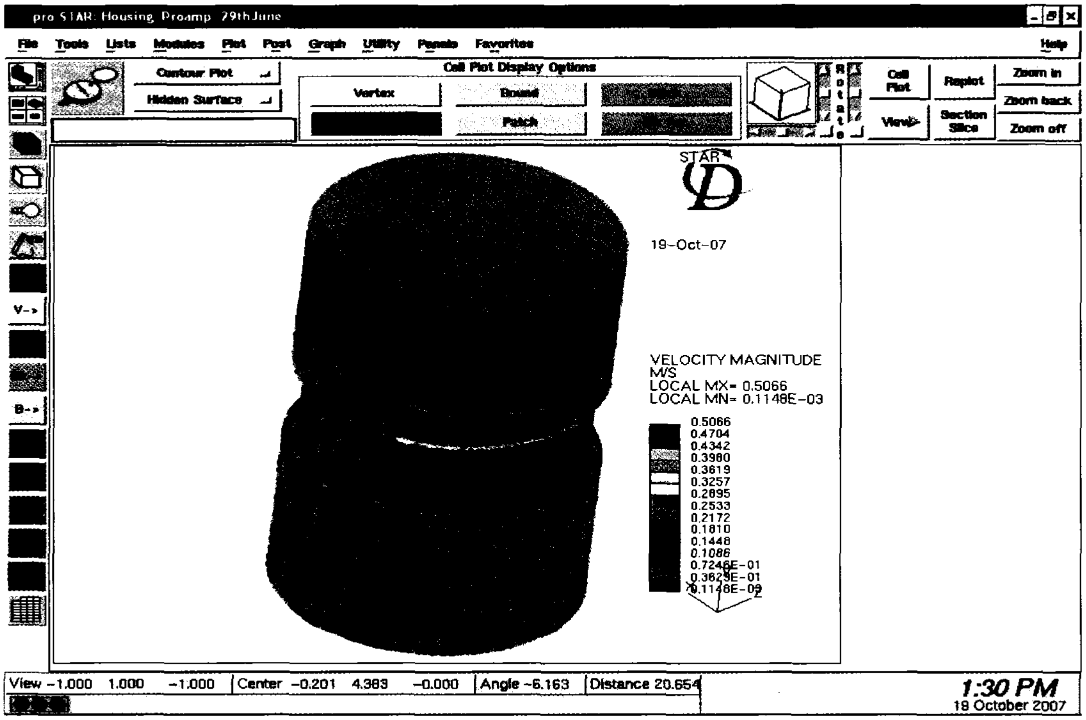
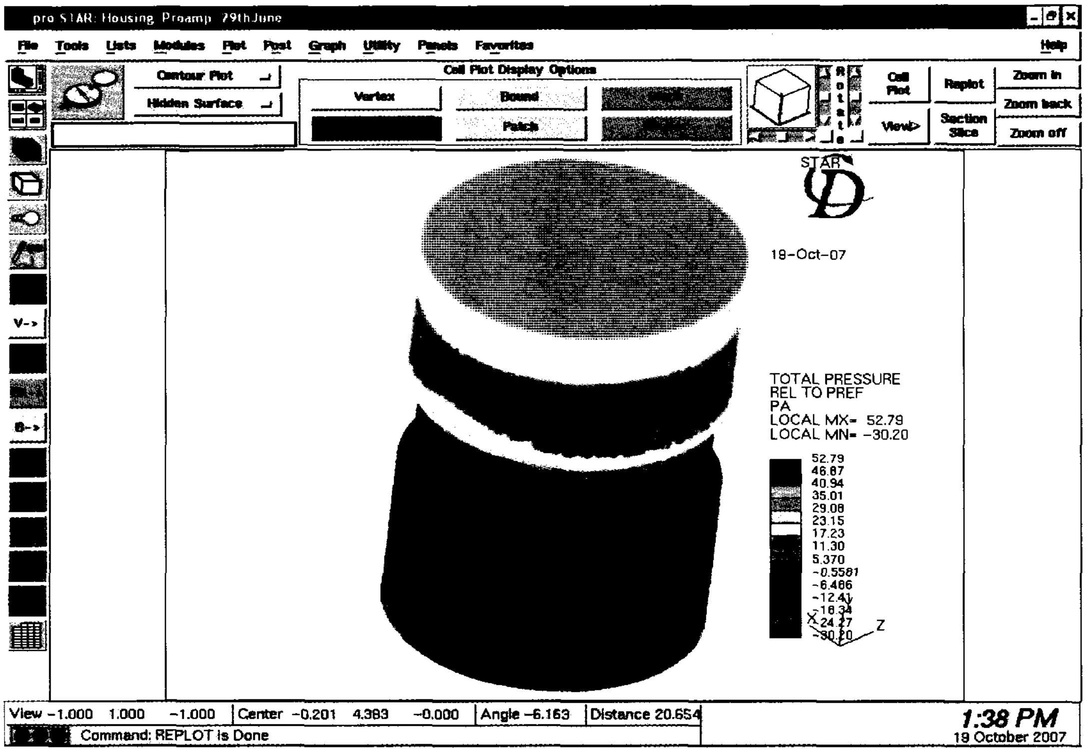


Figure 26. Velocity profile.



```
View -1.000   1.000    -1.000  |Center  -0.201   4.383    -0.000  |Angle -6.163  |Distance 20.654
Command: REPLOT is Done
```

1:38 PM
19 October 2007

Figure 27. Pressure profile.

REFERENCES

REFERENCES

[1] Flangan, T C., Pandit, A., 2003, "Living Artificial Heart Valve Alternatives: A Review." European Cells & Materials, 6, pp. 28-45.

[2] Akutsu, T., Giguchi, D., 2001, "Flow Analysis of the Bileaflet Mechanical Prosthetic Heart Valves using Laser.Doppler Anemometer: Effect of the Valve Designs and Installed Orientations to the Flow Inside the Simulated Left Ventricle." The Japanese Society for Artificial Organs, 4, pp. 113-125.

[3] Yoganathan, A P., Zhaoming, He, Jones, S C, 2004, "Fluid Mechanics of Heart Valves." Annual Review of Biomedical Engineering, 6, pp. 331-362

[4] Yuan Q., Xu L., Nqoi B K., 2003, "Dynamic Impact Stress Analysis of a Bileaflet Mechanical Heart Valve." Journal of Heart Valve Disease, 12, pp. 102-109.

[5] Kelly, S G D.,2002 "Computational Fluid Dynamics Insights in the Design of Mechanical Heart Valves", International Society for Artificial Organs, 26, (7), pp. 608-613.

[6] Star-Cd User Manual.

[7] Ideas Help Guide.