NUMERICAL ANALYSIS ON SIMPLIFIED 2D MODEL OF HEART VALVE LEAFLETS DURING CARDIAC CYCLE

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Report submitted in partial fulfilment of the requirements for the award of the degree of Bachelor of Mechanical Engineering

Faculty of Mechanical Engineering
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Specially dedicated to

My beloved family and those who have guided and inspired me

Throughout my journey of learning

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ABSTRACT

Nowadays, the increasing numbers of heart diseases cases is very worrying although the medication technologies are always improving and moving forward. In this study, the objectives are to investigate the effect of blood flow velocity and leaflet displacement by using different shape of simplified two dimensional heart valve leaflets in the diastolic and systolic condition. Five different shapes of mitral valve leaflets and aortic valve leaflets were created and the simulation was performed by using ADINA-Fluid Structure Interaction. From the result obtained, triangle shape of leaflet showed it had the highest of blood velocity changes and leaflets displacement changes in a period time of one second when compare to the other four shapes whereas the square shape had the lowest performances. The relationship obtained for blood velocity flow and leaflet's displacement changes is same for both mitral valve and aortic valve. The velocity of flow and leaflet's displacement changes for triangle shape in diastolic condition is 68.54 mm/s and 2.171 mm while at systolic condition is 102 mm/s and 5.168 mm respectively for mitral valve. The outcome simulation result shows that large vortex formed behind the leaflet and leaflet deformed when the blood flow into left ventricle is agreed with the result in literature. In conclusion, five different shapes two-dimensional model of mitral valve and aortic valve has been developed and ellipse shape of valve leaflets is predicted to be the most suitable shape in applying for future artificial valve designing due to its good blood velocity flow with the small changes of leaflets displacement. Ellipse shape of leaflets could be chosen as the most suitable shape among these five shapes in further study of heart valve simulation.

ABSTRAK

Pada masa kini, nombor meningkat penyakit jantung kes amat membimbangkan walaupun teknologi ubat sentiasa memperbaiki dan bergerak ke hadapan. Dalam kajian ini, objektifnya adalah untuk mengkaji kesan halaju aliran darah dan anjakan risalah dengan menggunakan bentuk yang berlainan dipermudahkan dua dimensi risalah injap jantung dalam keadaan diastolik dan sistolik. Lima bentuk yang berlainan risalah risalah injap mitral dan injap aorta telah diwujudkan dan simulasi telah dijalankan dengan menggunakan Interaksi Struktur Adina-Bendalir. Berdasarkan keputusan yang diperolehi, bentuk segitiga risalah menunjukkan ia mempunyai perubahan halaju darah dan perubahan anjakan risalah yang tertinggi dalam masa tempoh satu saat apabila berbanding dengan empat bentuk yang lain manakala bentuk persegi mempunyai prestasi terendah. Hubungan yang diperolehi bagi halaju aliran darah dan perubahan anjakan risalah adalah sama bagi kedua-dua injap mitral dan injap aorta. Halaju aliran dan perubahan anjakan risalah untuk bentuk segitiga dalam keadaan diastolik adalah 68,54 mm / s dan 2,171 mm manakala pada keadaan sistolik adalah 102 mm / s dan 5,168 mm masing-masing bagi injap mitral. Keputusan hasil simulasi menunjukkan bahawa pusaran besar dibentuk di belakang risalah dan risalah yang cacat apabila aliran darah ke dalam ventrikel kiri bersetuju dengan keputusan dalam kesusasteraan. Dalam Kesimpulannya, lima bentuk yang berlainan model dua dimensi injap mitral dan injap aorta telah dibangunkan dan bentuk elips risalah injap yang diramal menjadi bentuk yang paling sesuai dalam memohon untuk masa depan injap tiruan merekabentuk kerana halaju aliran darah yang baik dengan kecil perubahan anjakan risalah. Bentuk elips risalah boleh dipilih sebagai bentuk yang paling sesuai di kalangan kelima-lima bentuk dalam kajian lanjut simulasi injap jantung.

TABLE OF CONTENTS

CHAPTER 3 METHODOLOGY

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

A	Cross sectional area
P	Pressure
E	Young's modulus elasticity
a	Acceleration
σ	Stress
ε	Strain
m	Mass
V	Velocity
t	Time
$\dot{m}$	Mass flow rate
F	Force
Ma	Mach number
Cp	Specific heat
T	Temperature
v	Kinematic viscosity
µ	Viscosity
ρ	Density
%	Percentage

LIST OF ABBREVIATIONS

ADINA	Automatic Dynamic Incremental Nonlinear Analysis
FSI	Fluid Structure Interaction
2D	2 dimensional
UMP	University Malaysia Pahang
ALE	Arbitrary Lagrange Euler
FEA	Finite Element Analysis
MRI	Magnetic Resonance Imaging

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

This chapter will describe about the background, problem statement, objectives and scope of the study. From the background of the study, it comes out the problem statement and from the problem statement; the purpose of this study can be identified. This study will be based on the objective that have been determined and is limited by the scopes.

1.2 BACKGROUND

The human heart is a double pump enabling the pulmonary and systemic circulation of blood. It is divided into four chambers which are the right atrium, right ventricle, left atrium and left ventricle. The left and right atrium and the left and right ventricles are separated from each other by a wall of muscle called the septum. Each atrium and ventricle are equipped with a valve to ensure the blood has unidirectional flow through the heart and consequently through the body. Bicuspid valve is located at the top right side and the mitral valve located at the top left side. While the other two valves are the pulmonary valve and the aortic valve where are located at the down right side and down left side respectively.

In the course of a day, the heart contracts and expands on average 100,000 times, pumping approximately 2,000 gallons of blood to the entire body. By opening and closing in a synchronized manner, the four valves keep the blood flowing in a forward direction. The mitral and aortic valves are the common valves are the most common sites of heart valve disease, because of their location on the left side of the heart. The left chamber has a greater workload than right chamber because it needs to pump the blood to the entire body, whereas the right chambers only push blood into the lungs. Nowadays, severe dysfunction of heart valve now is increasingly replaced by prosthetic devices which are either mechanical valve or biological valve. However, thromboembolism and tissue regeneration are detrimental to the prosthetic device's functionality. Prosthetic valve which has complex geometry, motion, deformation, flows and the interactions with the wall and blood cause the simulation become challenging. The effort of seeking and making the perfect synthetic prosthesis have not been successful yet since there is no prosthesis can reliable for long-term life.

In most of the previous research study for human heart valve, there is usually same shape of the valve orifice was used in the analysis when the mitral valve was opened fully such as in Nakamura et al. (2006). Besides, from the past until now, some of Finite Element (FE) models of mitral valve have been developed without deeply focusing on the effect of fluid through the valve and ignore the effect of the left ventricle of the heart in the blood flow (Espino et al., 2006; Einstein et al., 2005; Loon et al., 2006). Furthermore, most of the research only analysed the valve with a single leaflet model in a tube (Loon et al., 2006; Amanifard et al., 2001) and until recently only got few more researches focused on the FSI model of mitral valve with two leaflets condition (Einstein et al., 2005; Espino et al., 2006 and Hisham et al., 2011).

1.3 PROBLEM STATEMENT

This project is limited to 2-Dimensional mitral valve and aortic valve model for cardiovascular dynamics with different size and shape depends on the different human body. The main focus is investigating the velocity performance of blood flow and the maximum displacement changes of the valve leaflet by manipulating the critical size and shapes of the leaflet. For 2-Dimensional mitral valve and aortic valve model, the investigation is on the correlation between the different shape of mitral valve and aortic valve with the blood flow through the left chamber. Since the shape of the mitral valves and the aortic valve is different, the effect of blood flow through these two valves will be changed and different. The change in blood flow may cause the heart need more workload to pump the blood and affect the pressure applied on the muscle wall in the heart.

In this investigation, five different shapes of the mitral valve and the aortic valve were selected to study and will simulate by using the ADINA-FSI. The behaviour of the leaflets of the mitral valve and aortic valve by different shape will be focused during the investigation. The result of blood flow velocity and valve leaflet displacement changes obtained are important for use to support the future design of the prosthetic valves.

1.4 OBJECTIVES

The main objective of this project is to investigate the displacement changes on the valve leaflet based on different shape of mitral valve leaflet and aortic valve leaflet. Besides, the effect of the blood velocity when flows through different shape of the mitral valve leaflet and aortic valve leaflet were also determined.

1.5 SCOPE

The scopes of this project are as follows:

i) Mitral model and aortic model is limited to 2-dimensional (2D)
ii) Blood assumes as Newtonian and incompressible fluid
iii) Correlation is determined using numerical modelling
iv) The flow of blood is assumed in a steady state condition

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODCUTION

In this chapter, the basic knowledge which related to the human heart valve will be described in it. A simple explanation and intro to the mitral valve and aortic have been presented. Besides, the common mitral valve disease and also for aortic valve will be defined. The treatments for the heart valve disease such as repair and replacement also will be introduced. Moreover, fluid flow theory and the fundamental engineering theories also will be described which is related to the blood flow and leaflets deformation during simulation in this study. The simulation could be explained by using certain of the formulae and equations such as governing equation. Lastly, some journals regarding to simulation study which are highly related to this study will be summarized. The idea and dimension used to applying in designing the valve leaflet have been referred back to the previous study.

2.2 MITRAL VALVE

Mitral valve is a bicuspid valve Mitral valve is located between the left atrium and left ventricle, is one of the four valves in the heart that control the blow flow through into the heart. It also used to prevent the blood flowing backwards from the left ventricle into the left atrium. Mitral valve consists of several components which included annulus, chordae tendineae, papillary muscles and two leaflets which is anterior and posterior. When one or both mitral valve leaflets are dysfunctional, the mitral valve is unable to seal tightly and could cause the mitral stenosis and regurgitation occurred (Nakamura et al., 2006).

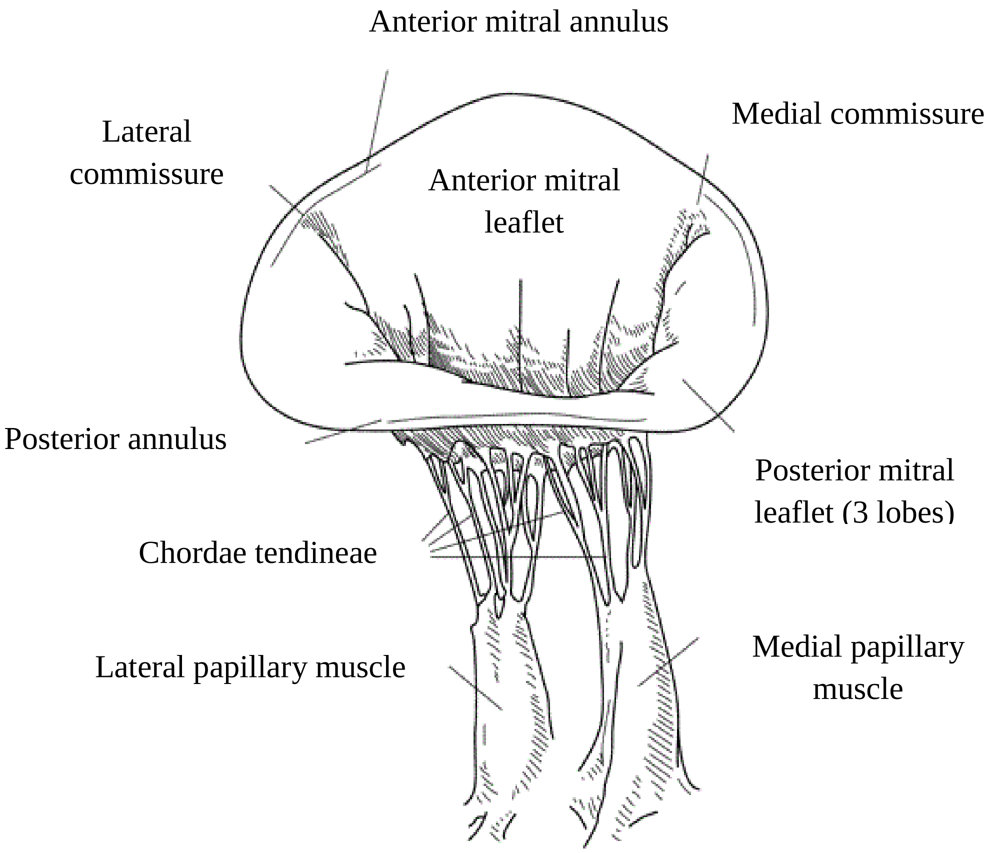


Figure 2.1: Mitral valve

Source: Otto (2003)

2.3 MITRAL VALVE DISEASES

2.3.1 Mitral Valve Stenosis

Mitral valve stenosis is the medical term and can be explained by narrow opening of the valve and prevent the valve to open properly, which will cause the blocking of the free flow of blood. Since the mitral valve is located between the left atrium and left ventricle, the narrowing opening of the valve will result an increase pressure in the left atrium. This pressure will be transmitted back to the lungs and causing the congestion of air passage-ways. In the past, mitral stenosis was usually caused by rheumatic fever, but fortunately for now, antibiotics treatment can prevent the rheumatic fever and its effect on the heart muscle and valves. The case of congenital mitral stenosis is rare. Mitral stenosis may cause by other reasons which are infective endocarditis, congenital anomalies and others causes like coronary artery disease or a heart attack. By narrowing the mitral valve opening, it will reduce the amount of blood that supposed to be supply forward to the body. It also will affect the atrium to be enlarged due to the high pressure build up in it and blood may backflow into lung resulted the lung disease (Otto Harvard Health Publications, 2012).

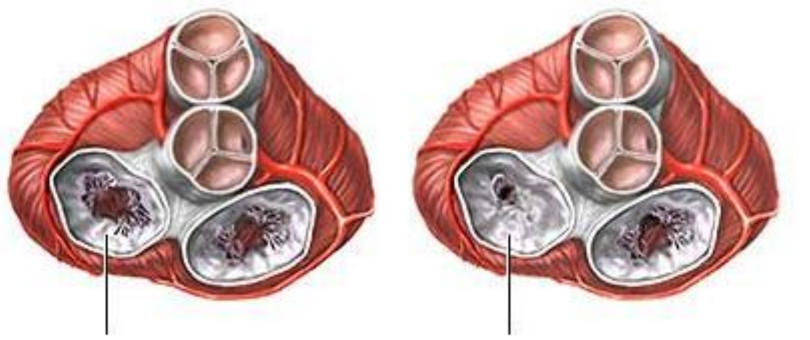


Figure 2.2: Comparison between normal and stenosis mitral valve

Source: Harvard Health Publications (2012)

2.3.2 Mitral Valve Regurgitation

Mitral valve regurgitation means the mitral valve does not close well and cause the blood back flow into the left atrium. This back flow of blood will cause the left atrium to dilate or enlarge. However, the heart is able to compensate for the valve effect and cause mitral regurgitation is difficult to detect by without present symptoms for many years. In some rare case, mitral regurgitation may be present without symptoms for many years by affected of mitral stenosis.

Mitral regurgitation is most often caused by rheumatic heart disease, which is the heart valve damage occurring when after an acute rheumatic fever. It will cause the degeneration of the valve and the muscle that control the valve to be dysfunctional. Besides, mitral valve prolapsed and heart attack is also the usual common cause. A heart attack may disrupt a portion of the heart that used to support the position of valve and result mitral insufficiency. In severity, mitral valve regurgitation can be treated through medication. If the medication did not helpful in treatment, the two open heart surgical options which are mitral valve repair or mitral valve replacement will be considered (University Virginia Health System, 2012).

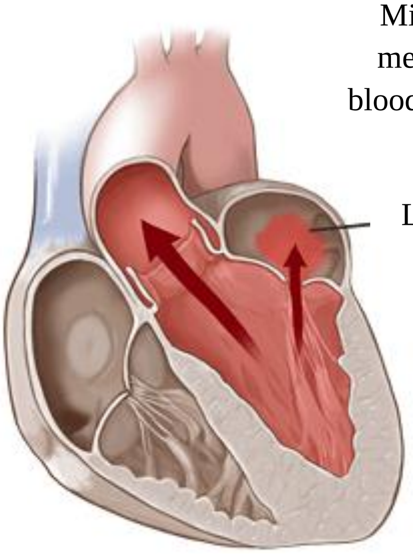


Figure 2.3: Mitral valve regurgitation

Source: University Virginia Health System (2012)

2.3.3 Mitral Valve Prolapsed

This is a common defect for heart disease and it is about 5% of the entire population has mitral prolapsed. In mitral prolapsed, the leaflet is prolapsed or may be out of its normal position to cause the valves cannot close tightly during the left atrium is emptied and left ventricle is full. It causes the blood can leak back to the left atrium and cause mitral regurgitation. In general, if there are no symptoms or the symptoms are mild, there is no treatment required (Yale School of Medicine, 2011).

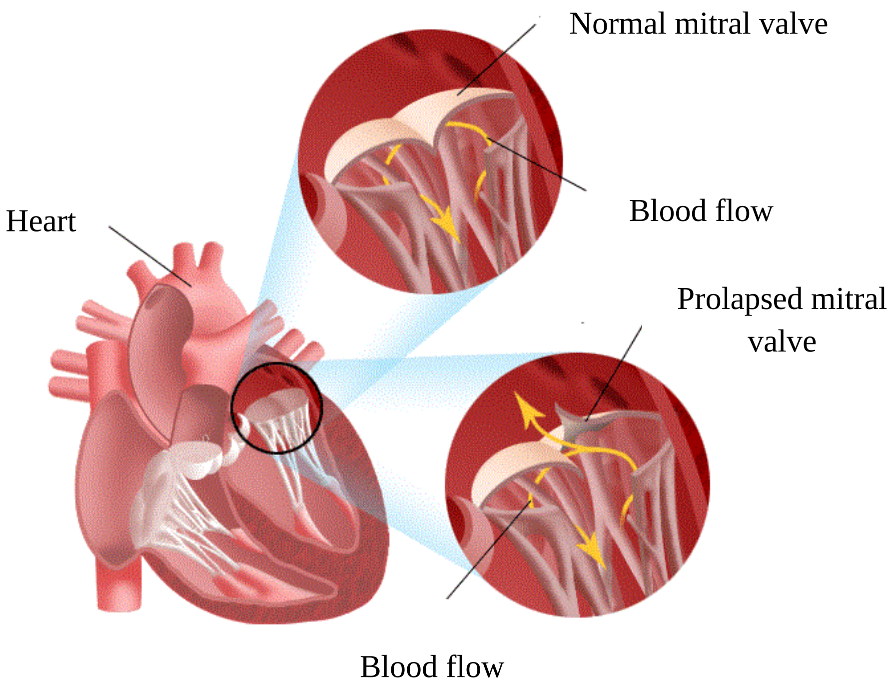


Figure 2.4: Mitral valve prolapsed

Source: Yale School of Medicine (2011)

2.4 AORTIC VALVE

Aortic valve is one of the four valves that control the blood flow form left ventricle into the aorta and pumped out to the body. Aortic valve consists of 3 half-moon-shaped pocket–like flaps of delicate tissue, as cups. Normally, these cups are perfectly aligned when the aortic valve is closed. During systole, the muscle of the left ventricle pumps the blood and the aortic valve open widely to let the blood flow freely. While during diastole, the aortic valve closes completely to prevent the blood back flow from aorta (UCLA Department of Surgery, 2004).

Figure 2.5: Aortic valve

Source: UCLA Department of Surgery (2004)

2.5 AORTIC VALVE DISEASES

2.5.1 Aortic Valve Stenosis

Aortic stenosis is a disease that same as mitral stenosis where the narrowing or obstruction in the aortic valve. The opening of aortic valves plays an important role to allow the pink oxygen-rich blood flow into aorta and get pumped out to the body. The narrowing of aortic valves will result the heart muscle must work harder to pump the blood into aorta. In most common cases, the aortic stenosis caused by aortic valve that has three leaflets or flaps has only two leaflets open instead of three leaflets during the heart pumps. In sometimes, the aortic stenosis also may cause by the aortic valve leaflets are fused together so the valve cannot open all the way or the entire aortic valve is congenital smaller than it should be (Healthwise Incorporated, 2009).

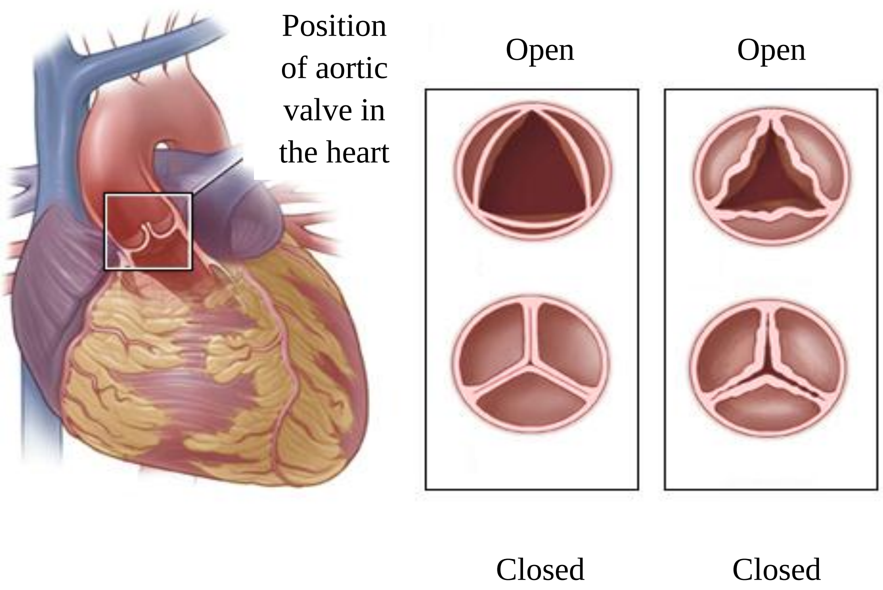


Figure 2.6: Comparison between normal and stenosis aortic valve

Source: Healthwise Incorporated (2009)

2.5.2 Aortic Valve Regurgitation

In the common case, the chronic form, aortic valve regurgitation is the consequence of the widening of the aorta region where it connects to the valve. The widening of the aorta ring will prevent the aortic valve from properly closing of the left ventricle. Besides, aortic regurgitation also may occur as the result of valve disease and rheumatic fever. Aortic valve regurgitation is same like others valve abnormalities where could produces no symptoms for many years. The symptoms like breathlessness accompanied chest pain and ankle swelling may be noticed after for many years if the condition is severe. In severe case, valve replacement may become necessary once the heart failure to operate in well (Pick, 2006).

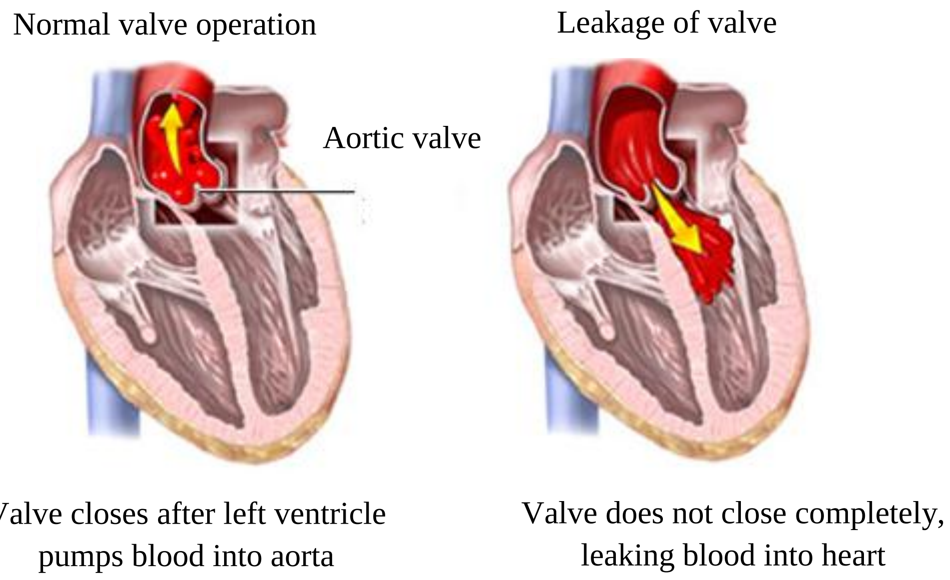


Figure 2.7: Comparison between normal and regurgitation aortic valve

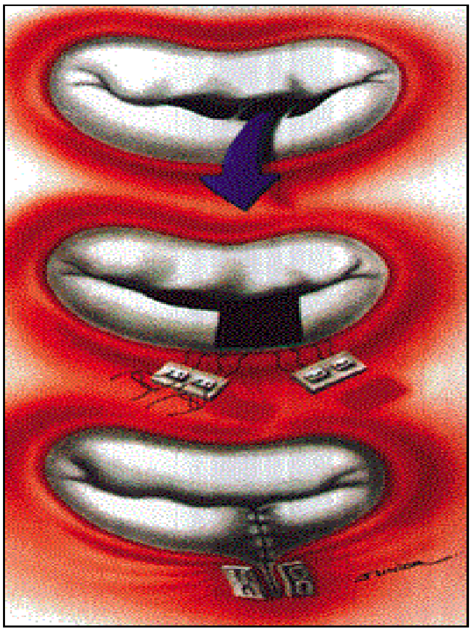
Source: Pick (2006)

2.6 VALVE REPAIRING AND REPLACEMENT

2.6.1 Mitral Valve Repair and Replacement

This operation is performed to treat the most severe cases of mitral valve like mitral prolapsed, mitral stenosis; mitral regurgitation and others valve disease. During this operation, the mitral valve is repaired or replaced through a chest incision. In the usual case, a minimally invasive approach that involves a small incision under the right breast is selected rather than traditional incision down the front of the chest that divides the entire breast bone. By this, the patient could associate will less postoperative pain with allow to heal in a short time and reduces the period of staying in hospital.

The decision either repairing or replacing the valve is depending on the type of damage to the mitral valve. Mitral valve repair will be chosen whenever for possible rather than valve replacement for mostly all patients with leaking of mitral and narrowed mitral valve. Repairing is more successful if there is limited damage to certain areas while replacement usually preferred for people who have widespread damage or hard, calcified mitral ring on the valve. Mitral valve repair involves removing the diseased portion of leaflets, reconstruction of the chords that control the leaflets and placement of the band or a ring to support the valve framework. Compared to valve replacement, mitral repair provides more advantages like better long-term survival, better preservation of heart function, lower risk of complication and eliminated the need for long term use of anticoagulants (Pomerantzeff et al., 1999).



Quadrangular resection of the posterior leaflet

Figure 2.8: Quadrangular resection of the posterior leaflet in patients with myxomatous degeneration

Source: Pomerantzeff et al. (1999)

Heart valve replacement involves the removal of the severely damaged valve. If a valve replacement is required, the prosthetic valve like mechanical heart valve or biological valve is used for the operation. Mechanical heart valve is constructed of metal, polymers and other material while biological valve consists of donated human or animal tissue. The damaged valve is removed by surgery and the new prosthetic valve is sewn into place. The development of blood clots in the heart may happen to those people who receive a mechanical heart replacement surgery. There are different advantages and disadvantage by using different forms of valves (Pick, 2006).

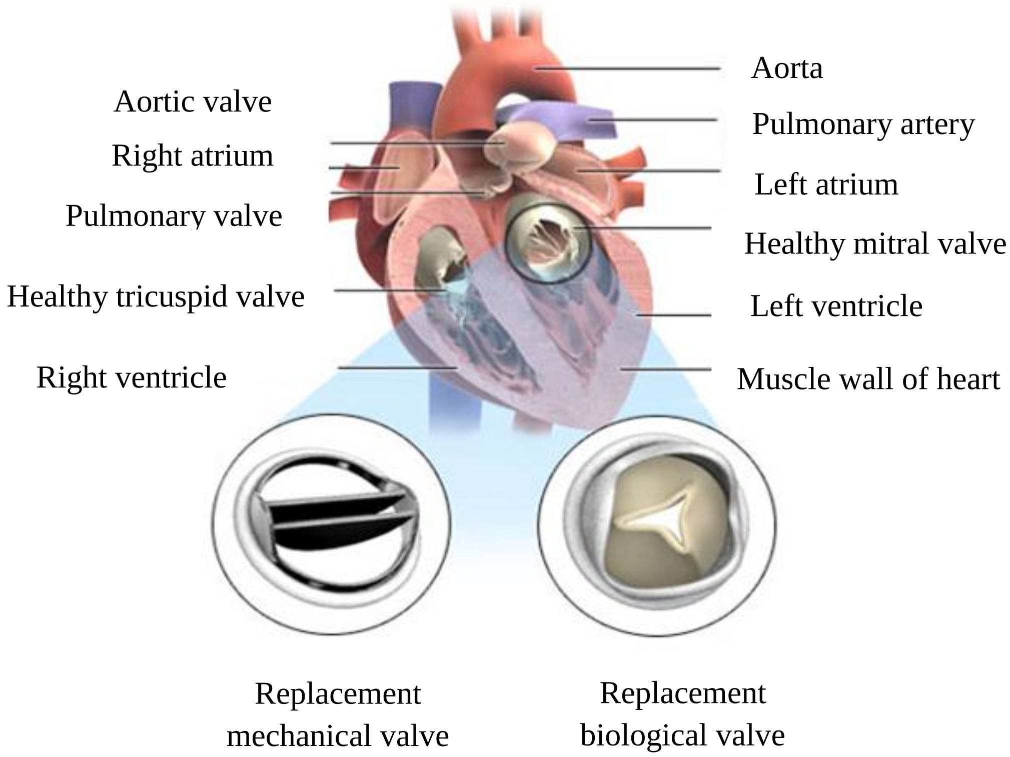


Figure 2.9: Mitral valve replacement with biological valve or mechanical valve

Source: Pick (2006)

2.6.2 Aortic Valve Repair and Replacement

Aortic valve is likely to the mitral valve which can be healing the decease by repair or replace the valve. The result of the diagnostic tests, the structure of the heart, age and other factors will consider whether the aortic valve repair or replacement is the best treatment for different people. Aortic valve usually is treated by replacement rather than repair. It is differing to the mitral valve. For aortic valve replacement, the native valve is removed and a new valve is replaced. New valve can either be mechanical or biological valve. For aortic valve repairing, two types of repairing where are bicuspid aortic valve repair and repairing of enlarged aorta was always been selected. Bicuspid aortic valve repair allows the aortic leaflet to open and close more completely while repairing of enlarging aorta prevent the leaking of blood from the aorta back into the left ventricle (Pick, 2006).

2.7 GOVERNING EQUATION

In the fluid flow theory, the equations involve that used to describe the behaviour of blood flow is governing equation. The governing equations involve are the continuity equation, energy equation and momentum equation. In usually, simulation is performed by fundamentally using the governing equation of fluid dynamics to obtain the result of iteration. These equations were derived by based on some physical laws such as Newton's second law and first law of thermodynamics (Jiyuan, 2008).

2.7.1 Continuity Equation

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{2.1}$$

In general, in a two-dimensional analysis which is performed for a channel flow that is possible to make the assumption that one of the axis directions is sufficiently large in order to remain the flow in invariant along the coordinate direction and it can be ignored. For a fluid that is assumed as an incompressible fluid, the density ρ can say is constant since there are no changes in mass and volume. A continuity equation in two dimensions for an incompressible flow could be obtained as above Equation (2.1) (Jiyuan, 2008). In 2 dimensional simulations, the velocity profiles will be represented by velocity components u and v where the u velocity component is related to x coordinate direction and v velocity components is related to y coordinate direction.

2.7.2 Momentum Equation

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -\frac{1}{p}\frac{\partial p}{\partial x} + v\frac{\partial^2 u}{\partial x^2} + v\frac{\partial^2 u}{\partial y^2} \quad (2.2)$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = -\frac{1}{p}\frac{\partial p}{\partial y} + v\frac{\partial^2 v}{\partial x^2} + v\frac{\partial^2 v}{\partial y^2} \quad (2.3)$$

For the momentum equation, in a two-dimensional case of the fluid flow where the flow is invariant along the z direction, so the variables related to z direction could be ignored. In the case that is a constant property of fluid flow where the density is constant and the body forces, the momentum equation could be invoked by the continuity equation with the inclusion of the stress-strain relationships could be reduce into below equation form. The two momentum equations shown above was derived from the concept of Newton’s second law and where v represent the kinematic viscosity of fluid, μ represent the viscosity of fluid and ρ represent the density of fluid in below Equation 2.4. Newton's second law of motion states that the sum of forces that is acting on the fluid element is equals to the product between its mass and acceleration of the element. It describes the conservation of momentum of the fluid flow and these are known as the Navier-Stokes equations (Jiyuan, 2008). The symbol u and v used in above two momentum equation represent the velocity components in the x coordinate direction and y coordinate direction while the p symbol used to explain the pressure applied. In a simulation with constant viscosity and density of fluid properties setup, its kinematic viscosity could be determined through calculation.

$$v = \frac{\mu}{\rho} \quad (2.4)$$

2.7.3 Energy Equation

$$\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \frac{k}{pC_p}\frac{\partial^2 T}{\partial x^2} + \frac{k}{pC_p}\frac{\partial^2 T}{\partial y^2} \tag{2.5}$$

The energy equation is derived based on the knowledge by referring the first law of thermodynamics. First law of thermodynamics stated that the rate of change of energy equals the sum of rate of heat addition to and the rate of work done on the fluid. For a fluid, the energy of a fluid can be related to the sum of the internal energy, kinetic energy and gravitational potential energy. In case of the fluid is incompressible fluid and the continuity equation applied, kinetic energy can be neglected and the enthalpy h can be assumed as CpT and where C_p is the specific heat and is assumed to be constant. For a two-dimension condition where the temperature, T is assumed invariant along the z direction and the thermal conductivity k is constant, the equation for the conservation of energy in two dimensions can be expressed as the equation 2.5 shown in above (Jiyuan, 2008).

2.8 FLUID FLOW THEORY

2.8.1 Newtonian Fluid

From George Keith Batchelor (2000), Newtonian fluid defined as a fluid which the stress versus strain rate curve is linear and passes through the origin. The constant of the proportionality is known as the viscosity. For Newtonian fluids, its viscosity is only depends on the temperature and pressure, not on the force exert upon on it. By this, the viscosity of the fluid can be assumed constant when constant temperature and constant pressure apply to Newtonian fluid (Batchelor, 2000).

2.8.2 Incompressible Flow

In an incompressible flow of fluid, the change of density of fluid is negligible since no mass and volume changes occurring. However, there is no fluid is truly behaviour like incompressible since the liquid will have their density increase through the existence of sufficient pressure. The fluid density changes could be neglected if the Mach number, Ma of the flow is small. This condition for incompressible flow is given by the equation below, where *V* is the fluid velocity and *a* is the speed of sound of the fluid. It is nearly impossible to obtain Ma = 0.3 in liquid flow because it will require a very high pressure. Therefore liquid flow is incompressible (Calay, 2001).

$$Ma = \frac{v}{a} < 0.3 \tag{2.7}$$

In simulation for a rigid body where the volume is unchanged and fixed all the time, the assumption of fluid flow of blood is assumed to be incompressible flow and therefore the setup value in density could be constant in whole simulation.

2.8.3 Steady State Condition

Steady state condition can be defined as a stable condition which that is no change over time. In steady state condition of heat transfer, there is no temperature variation with time. It means the temperature is remaining constant for the overtime. Steady state is a more general situation than dynamic equilibrium. In human heart valve simulation, assumption the steady state condition is preferred for neglected the effect of the small change of human body temperature.

2.9 ENGINEERING FUNDAMENTAL THEORY

2.9.1 Pressure and Stress- Force Acting Over an Area

For a force acting over an area can be defined as a term of pressure. Pressure is defined as the ratio of force over the contact surface area. The relationship between the force and the area could be represented in below Equation (2.8) (Moaveni, 2011).

$$Pressure = \frac{F}{A} = \frac{force}{area} \tag{2.8}$$

2.9.2 Newton's Second Law of Motion

In Newton's second law of motion, it could explain by using below Equation (2.9). The acceleration produced by the force acting on the body is directly proportional to the magnitude of the force for a constant mass object (Shipman, 2009).

$$Force = mass \times acceleration = ma \tag{2.9}$$

However, the acceleration could be defined as the change of velocity in a time period and could represent as below Equation (2.10).

$$Acceleration = \frac{velocity}{time} = \frac{v}{t} \tag{2.10}$$

By combining the both equations in Equation (2.9) and Equation (2.10), we could obtain new Equation (2.11) and Equation (2.12) in below.

$$Force = mass \times \frac{velocity}{time} = m \times \frac{v}{t} \tag{2.11}$$

$$Force = mass\ flow\ rate \times velocity = \dot{m} \times v \tag{2.12}$$

From above Equation (2.12), we could derive the relationship between of force, mass flow rate and velocity. The force acting on a body is directly proportional to the velocity of motion in a constant mass flow rate condition.

2.9.3 Elasticity of Material

The elasticity of the material could be defined as the property of a material by virtue of which differences in the velocity of the rebound are causing and it tends to revert to original shapes is called elasticity (Rao, 2007).

2.9.4 Stress and Strain

Stress and strain are always related in each together in engineering terms. Stress could define as internal forces which acting at the body molecules level at all points and in all directions. Besides, strain is defined as the rate of changes of displacements with related to the original dimensions of position in under deformation. Stress and strain could be explained by below Equation (2.13) and Equation (2.14) (Rao, 2007).

$$Stress, \sigma = \frac{Load}{Cross\ sectional\ area} = \frac{P}{A} \tag{2.13}$$

$$Strain, \varepsilon = \frac{Change\ in\ length}{Original\ length} = \frac{\delta l}{l} \tag{2.14}$$

2.10 BOUNDARY CONDITION

Boundary condition has an essential role in many applications of physics. The nonslip boundary condition always was assumed and used to define the behaviour of the blood inside the vessel.

For non-slip boundary condition, it was been purposed by Amanifard et al. (2001) during investigated the numerical simulation of the mitral valve opening. An assumption stated that the fluid density in the vicinity of the wall to be consistent with that of the inner fluid was made (Amanifard et al., 2011). Non-slip boundary condition stated that for viscous fluid that at a solid boundary, the fluid flow will have zero velocity relative to the solid boundary. That means the fluid velocity at all fluid–solid boundaries is equal to that of the solid boundary. Therefore, the fluid flow velocity will remain constant during flowing inside the wall and there is no velocity loss due to the fluid contact with the wall.

2.11 SIMULATION STUDY

Previous research have shown by using simulation, one can predict the movement of valve leaflet and the behaviour of human heart valve in applying in real model. Table 2.1 and Table 2.2 show the summaries of previous study for mitral valve and aortic valve respectively.

Table 2.1: Journal summaries between results simulation for mitral valve

Journal	Simulation
Al-Atabi et al. (2010)	The flow of blood caused the valve leaflets to deform in turn altering the flow of blood. The simulation predicted a large vortex behind the anterior leaflet during inflow of the blood into the left ventricle.
Hellevik et al. (2007)	The simulation results show that the initial pressure configuration in the left heart is significant for the mitral valve dynamics. It also indicates that the mitral valve flutter has important bearings on the vortex formation in the vicinity of the mitral valves.
Baccani et al. (2002)	The diastolic fluid dynamics of a model left ventricle has been analysed numerically solving the equations of motion in the axisymmetric approximation. A travelling vortex wake that is formed from the transmitral jet during the early filling acceleration phase.
Lau et al. (2010)	The results of the structural and fluid–structure interaction models have shown that the stress distribution in the closure simulation is similar in all the models, but the magnitude and closed configuration differ. Comparison of the fluid domains of the fluid–structure interaction models have shown that the ventricular geometry generates slower fluid velocity with increased vorticity compared to the tubular geometry.

Table 2.2: Journal summaries between results of simulation for aortic valve

Journal	Simulation
Ranga et al. (2007)	In this work, compliance at the sinotubular junction was seen to be an important element in creating the triangular opening seen in-vivo. Hyperelastic material properties were shown to have a significant effect on stresses and strain magnitudes and distributions.
Carmody et al. (2004)	The results show a circulatory flow being generated in the ventricle which produces a substantially axial flow through the aortic aperture. The aortic valve behaves in an essentially symmetric way under the action of this flow, so that the pressure difference across the leaflets is approximately uniform.
Hart et al. (2000)	A two-dimensional fluid-structure interaction model is presented, which allows the Reynolds number to be within the physiological range, using a fictitious domain method based on Lagrange multipliers to couple the two phases.
Hart et al. (2003)	The results presented in this paper show that the implemented fiber-reinforcement has significant impact on the stress state and kinematics of the leaflets, while the fluid dynamical behaviour is preserved when compared to non-reinforced isotropic leaflets.

2.11.1 Simulation of Blood Flow through the Mitral Valve of the Heart: A Fluid Structure Interaction Model

Based on the journal written by Espino et al. (2006), a two-dimensional FSI model of mitral valve was generated and investigated by using ALE mesh. Simple approximation of geometry was used and valve dimensions were based on measurement (Espino et al., 2006). Failure of the mitral valve of the heart can be fatal if it is not corrected surgically. Improvement in the understanding of the biomechanics of the mitral valve would aid current knowledge of the mitral valve function, its failure and possible surgical correction. Therefore, a Fluid-Structure Interaction (FSI) model of the mitral valve has been generated. The mitral valve is present in the left side of the heart, and functions normally to allow blood to flow into the left ventricle of the heart when it is filled. This valve then closes when blood is pumped out from the heart towards the body. In doing so, it prevents the regurgitation of fluid.

The FSI model of the mitral valve in Espino et al. (2006) was developed includes the walls of the left ventricle of the heart, both anterior and posterior leaflets of the valve, and the outflow tract of the aorta. Inflow boundary conditions were applied to simulate valve opening during diastole and valve closure during systole. (Espino et al., 2006) During diastole an inflow velocity was applied at the atrium and a pressure condition was applied at the apex of the heart, to apply the relevant ventricular pressures. During systole, ventricular pressure was applied from the apex of the heart, and outflow boundary conditions were applied at the aortic outlet. During systole only the stage of outflow of blood was simulated.

The properties of blood and material could be shown in below table 2.1. In the simulation, a large vortex is predicted to occur behind the anterior leaflet during inflow of blood into the left ventricle. The simulation result of the flow in this journal is good in agreement with the MRI scans in previous studies. The deformation of leaflets also agrees with the previous experimental results. In conclusion, a two-dimensional of mitral valve has successfully been developed and will use in further developments in the investigation of heart failure and surgery repair. (Espino et al., 2006)

Table 2.3: Values of parameters used to describe blood and heart valves during simulations.

Parameter	Value
Blood density (kg/m^3)	1.06×10^3
Blood viscosity (Pa.s)	2.70×10^{-3}
Leaflet density (kg/m^3)	1.06×10^3
Anterior leaflet Young's modulus (MPa)	2.0×10^6
Posterior leaflet Young's modulus (MPa)	1.0×10^6
Leaflet Poisson's ratio	0.49

Source: (Espino et al., 2006)

2.11.2 A Compliant Dynamic FEA Model of the Aortic Valve

According to the journal of Ranga et al. (2007) on the studies of a compliant dynamic FEA model of the aortic valve. The study's aim was to integrate three main keys of physiological important features into a realistic structural simulation of the aortic valve. The three main keys involved are compliance of the aortic root wall, non-linear material properties of the tissues, and dynamic loading (Ranga et al., 2007). The compliance of the root could affect to the opening and closing shape and the dynamics of the leaflet. It altered the diastolic and systolic geometries and helped to reduce the stresses on the valve. The results of the studies can provide improved knowledge in accuracy tool in the investigation valve pathologies, device design and modelling robot-issue interaction by assisting in heart surgery technologies.

In the Ranga et al. (2007) studies, the model of aortic valve is assumed to be stress-free at the initial state. Loads were gradually applied on the model up to diastolic pressure over a period of 0.5 seconds. The total time duration start from model closed, diastolic, stress configuration, two full cardiac cycles were simulated in a simulation time of 1.79 seconds (Ranga et al., 2007). The pressure difference between the aorta and left ventricle was applied on the aortic valve leaflets. For the purposes of applying the loads, three areas were defined: aortic root wall below the annulus, aortic root wall above the annulus and leaflets. The figure below shows the pressure value in the graph where applied on the aortic, left ventricle and leaflet surfaces in a function of time in the simulation.

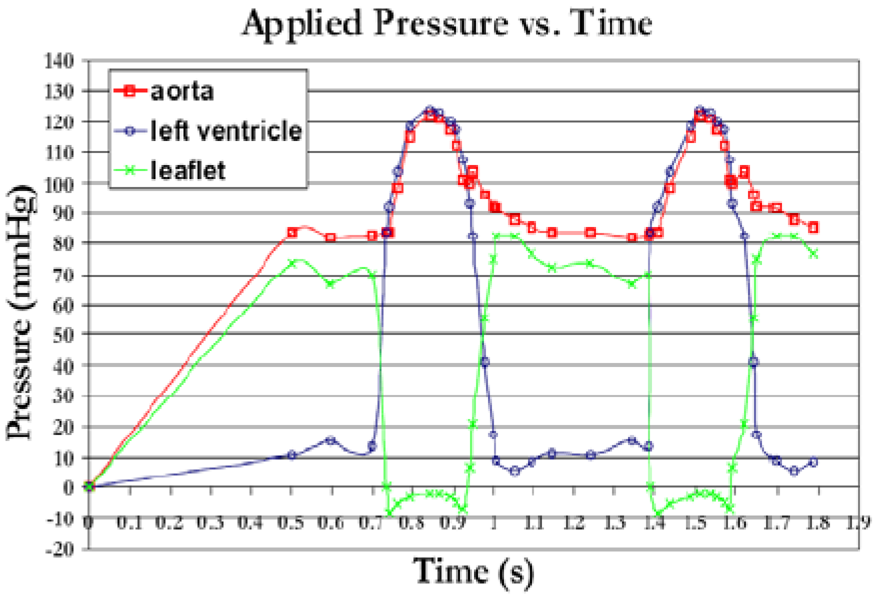


Fig. 2.10: Pressure waveforms applied on the aortic, left ventricular and leaflet surfaces as a function of time

Source: (Ranga et al., 2007).

For the material properties setup, it is found that in the research done by Ranga et al. (2007) using a linear elastic model with a Young's modulus of 2000 KPa, Poisson's ratio of 0.495 and a density of 1000 Kg/m^3 (Ranga et al., 2007). The model used is assumed as nearly incompressibility of soft tissue in leaflets. This Young's modulus chosen was showing this to be the value matching physiological conditions more closely.

From the results obtained in journal by Ranga et al. (2007), the compliance of the sinotubular junction is clearly its sequences of the deformed shape of the valve. The radial displacements in that region are tracked and the maximal displacements are seen at during peak systole, as expected, and these values correspond to expansibility of 15.2 % for the linear model (Ranga et al., 2007). By this, the compliance is clearly seen and shows to have an effect to provide an increasing in diameter at the sinotubular junction which permits the leaflets to assume their natural triangular configuration.

Furthermore, the result of stress and strain on the tissue also is yielded in simulation, which is difficult to determine in the experiment. Maximum strains and stresses were found to occur at the commissures where local at top of the attachment line between leaflets and aortic root wall during diastole, which is the moment when the leaflets pulled the most on the root wall (Ranga et al., 2007). The observations may point to the importance of the hyper elastic nature of valve tissue in distributing stress and lowering strain during the curvature reversal observed in leaflets going from a diastolic to a systolic configuration.

2.11.3 An Approach to the Simulation of Fluid Structure Interaction in the Aortic Valve

In the research of journal by Carmody et al. (2006), the simulation on the behaviour of the aortic valve has been research as recent famous topic. This is because the need for flow and stress data to support the design of prosthetic valves in the absence of viable measurement methods; and because the complexity of the geometry, motion, deformation and flows and their interactions make the simulation a major challenge. Moreover, the development of numerical methods in recently for modelling fluid–solid interaction (FSI) has allowed the blood flow to be modelled as well as the material of the valve, This will improve the more reality compare the simulation with actual since there is strong interaction between the leaflets of the valve and the blood flow during the opening and closing of the valve. However, the opening and closing of the valve are dynamic events involving the large motion of thin leaflets driven by the blood flow derived from the pumping action of the left ventricle.

In this study, a pair of finite element models has been employed by Carmody et al. (2006) to study the interaction of blood flow with the operation of the aortic valve. A three-dimensional model of the left ventricle with applied wall displacements has been used to generate data for the spatially and time-varying blood velocity profile across the aortic aperture. These data have been used as the inlet loading conditions in a three-dimensional model of the aortic valve and its surrounding structures. Both models involve fluid structure interaction and simulate the cardiac cycle as a dynamic event (Carmody et al., 2006).

The results showed in journal shows a circulatory flow being generated in the ventricle which produces a substantially axial flow through the aortic aperture. The aortic valve shows in an essentially symmetric way under the action of the flow. The pressure difference across the leaflets is approximately uniform (Carmody et al., 2006). The results of this study support the use of spatially uniform but temporally variable pressure distributions across the leaflets in dry or structural models of aortic valves. In conclusion, this study caused an advance through its use of truly three-dimensional geometry, spatially non-uniform loading conditions for the valve leaflets and the successful modelling of progressive contact of the leaflets in a fluid environment.

CHAPTER 3

METHODOLOGY

3.1 INTRODUCTION

This chapter will describe the detail of the methodology used in this study. By modelling and simulation the left chamber of the heart, which is included the mitral valve and the aortic valve. There are five different shapes of valve leaflet for mitral valve and aortic valve were designed based on certain acceptable dimension. The dimension of the mitral valve, aortic valve and left ventricle used in modelling was referred to the previous study. Besides, the parameters used to setup the simulation of the fluid and structure was based on the literature. The whole FSI simulation was performed by using ADINA-FSI software. During the diastolic and systolic setup, the simulation was performed in a time period of 1 second and independent parameters like the flow and pressure variables was applied to the mitral valve and aortic valve. The interaction between the fluid and the leaflets was bringing forth the outcome of expected results.

3.2 EXPERIMENT SETUP

3.2.1 Design and Parameters Collection

The idea to design the mitral valve were connected together with the left ventricle was obtained from the journal by Mushtak Al-Atabi, Daniel M. Espino and David W.L. Hukins from School of Engineering, Taylor's University College with their journal title's *"Computer and Experimental Modelling of Blood Flow through the Mitral Valve of the Heart"*. Besides, for the design of the aortic valve, the idea is mainly obtained from the journal written by B Knierbein, N. Rosarius, A. Unger, H. Reul and G. Rau from the Helmholtz-Institute for Biomedical Engineering at Aachen University of Technology, Germany with their journal title's "CAD-design, stress analysis and in vitro evaluation of three leaflet blood-pump valves".

Besides the above two journals, there are some parameters data obtained from the others journals which are *"Numerical Simulation of the Mitral Valve Opening Using Smoothed Particle Hydrodynamics"* by Nima Amanifard, Behnam Rahbar, Muhammad Hesan and *"Collagen fibers reduce stresses and stabilize motion of aortic valve leaflets during systole"* by J. De Hart, G.W.M. Peters, P.J.G. Schreurs, F.P.T. Baaijens from Department of Mechanical Engineering, Eindhoven University of Technology, Netherlands.

3.2.2 Parameters Setup

Table 3.1: Parameters setup

Parameters	Value
Normal diastolic Pressure, mmHg	80
Normal systolic Pressure, mmHg	120
Blood density, kg/m^3	1.06×10^3
Blood viscosity, Pa.s	2.70×10^{-3}
Mitral valve leaflet Poisson's ratio	0.49
Aortic valve leaflet Poisson's ratio	0.45
Normal Mitral valve area, cm^2	4.0-5.0
Normal Aortic valve area, cm^2	3.0-4.0
Mitral valve leaflet Young's modulus, Pa	2.0×10^6
Aortic valve leaflet Young's modulus, Pa	2.0×10^6

Source: Al-Atabi et al (2010); Hart et al (2003) and Ranga et al (2007)

3.3 FSI SIMULATION

3.3.1 Model Overview

In this project, a simple two-dimensional FSI model of mitral valve and aortic valve was run in simulation. For mitral valve, it is connected together with left ventricle in this project whereas aortic valve is without connected with left ventricle. Five simple shapes of leaflets are designed as the leaflets of mitral valve and aortic valve. Both mitral valve and aortic valve are used the same design for the shapes of leaflets. By this, five different of 2D FSI model was generated by using ADINA-STRUCTURE/CFD and simulated in ADINA-FSI. In ADINA-FSI, to generate the fluid flow, basic parameters like pressure applied and fluid initial properties was setup and 2D fluid is apply to determine the variation of the variables in the study. Non-slip boundary condition, steady-state condition and Newtonian flow were assumed to the fluid on the fluid-structure boundary. This will ensure that the fluid flow velocity will remain constant during flowing inside the moving wall and there is no velocity loss due to the fluid contact with the wall. Besides, the viscosity of the fluid will remain unchanged for constant pressure and temperature since Newtonian flow and steady state condition was assumed. The stress distribution and fluid dynamics are determined simultaneously by using moving Arbitrary Lagrange Euler (ALE) mesh. During simulations, medium meshing size was used during developing the models.

3.3.2 Geometry and Modelling Of the Models

In this project, the models were designed where the mitral valve was connected together with the left ventricle while aortic valve is not. A simple of left ventricle was made as an ellipse in shape with the major axis of 70 mm and minor axis of 24 mm. The vessel that contains the mitral valve and connected to the left ventricle was designed as a 40 mm in width and 30 mm in length. For the mitral valve, its dimension of leaflet was approximately 20 mm long and 0.7 mm thick. Five different shapes of mitral valve leaflets were shown in below figure 3.1 (a), (b), (c), (d) and (e).

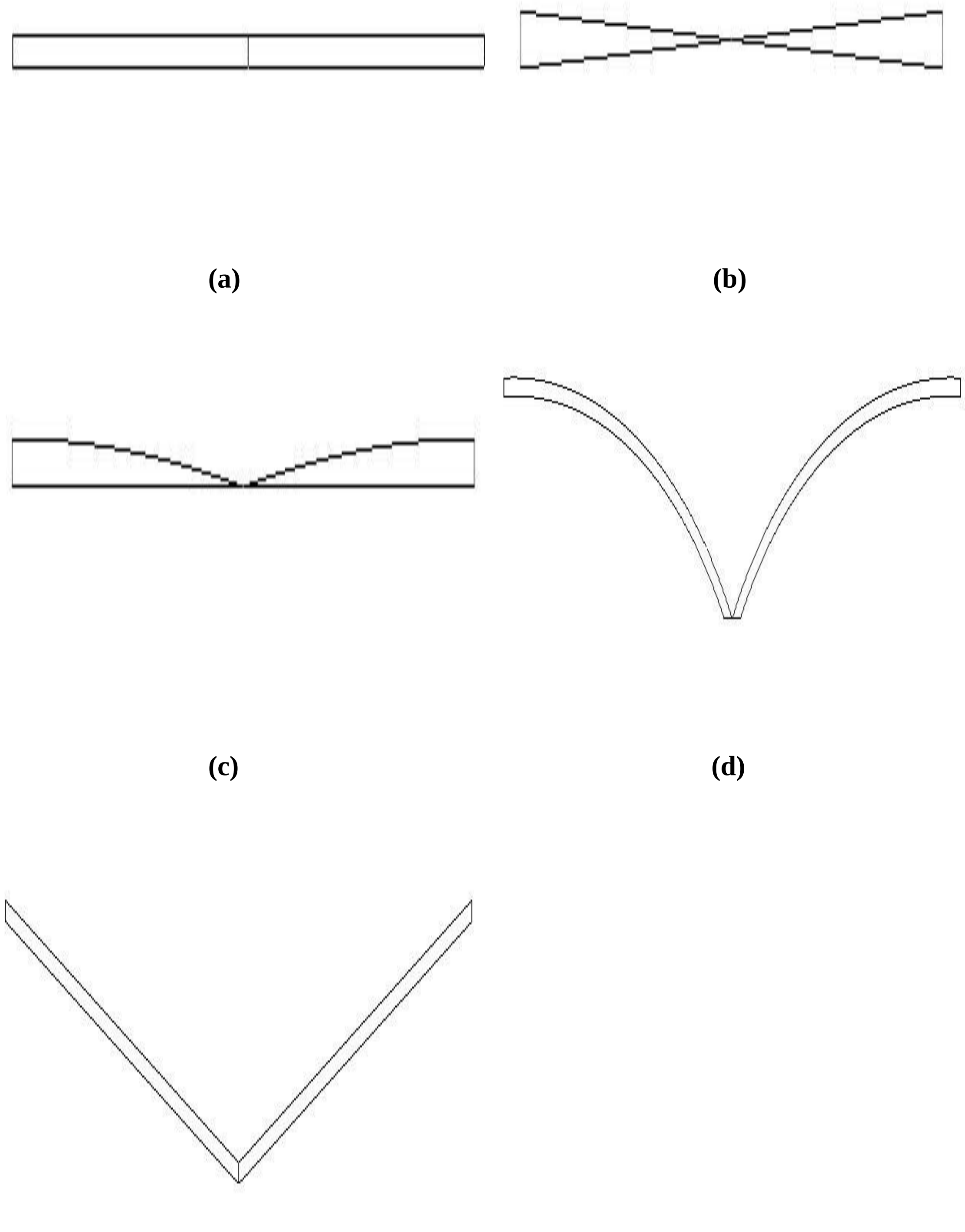
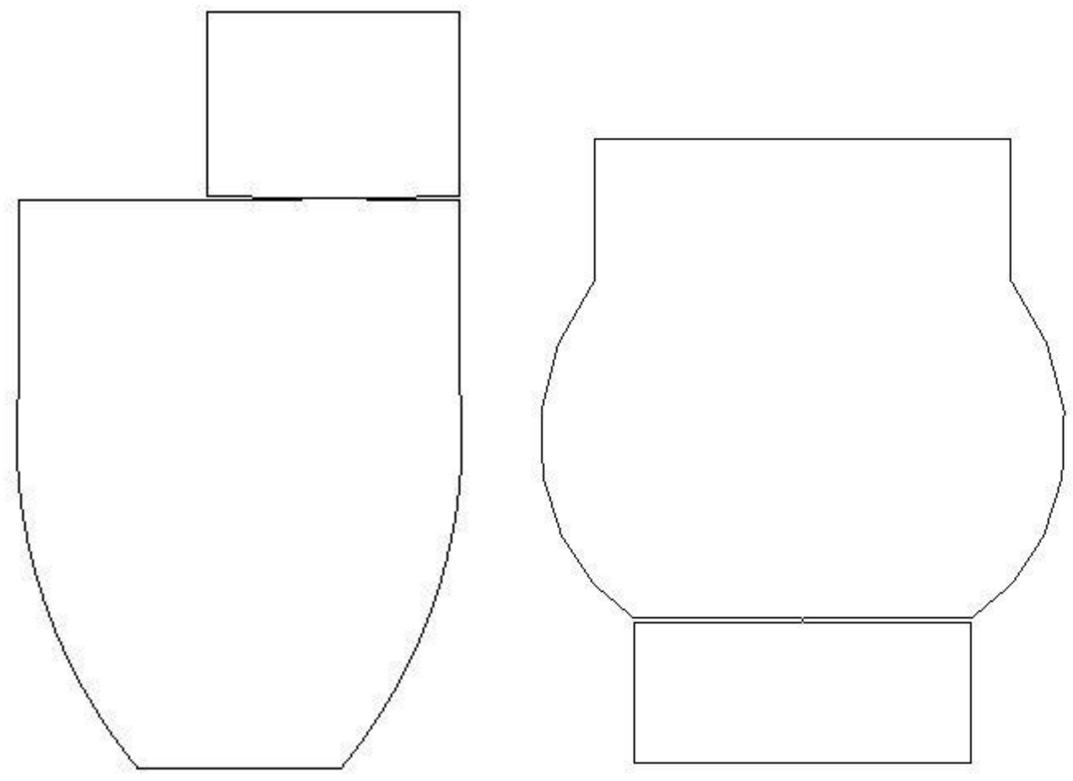


Figure 3.1: Valve leaflet (a). Leaflets with triangle shape, (b). Leaflet with square shape, (c). Leaflet with half-hemisphere shape, (d). Leaflet with ellipse shape, (e). Leaflet with V-shape

By the way, for the aortic valve model, the leaflet dimension of the aortic valve is different to the mitral valve. Aortic valve leaflets were designed as approximately 12 mm in length and 0.3 mm in its thickness. It was connected to a 24 mm width of the vessel. The five different shapes of aortic leaflets were employed the same shape designing with the mitral valves in during the simulation run. It was shown in above figures 3.1.

Both design and dimensions of mitral valve, aortic valve and left ventricle was being proven before and showed a successful preliminary design in developing the realistic model. The figure 3.2 (a) in below shown the model of mitral valve connected to the left ventricle in ADINA-FSI. While the figure 3.2 (b) shows the model of aortic valve without connecting with the left ventricle in ADINA-FSI.



(a) **(b)**

Figure 3.2: Model in ADINA-FSI (a). Mitral valve with left ventricle, (b). Aortic valve without left ventricle.

3.3.3 Parameters and Boundary Condition

The preliminary setup in the simulation was determined the parameters of blood and both valve leaflets by referring to the Table 3.1. During applying the diastolic and systolic condition to the mitral valve and aortic valve leaflets, a normal traction was enforced at the atrium side to make a pressure difference between the left ventricle and the atrium for mitral valve while left ventricle and left aorta for aortic valve. This will cause the condition of fluid flowing through the mitral valve and aortic valve occurred. For the simulation on aortic valve, there is same setup in fluid properties that used as in mitral valve simulation.

3.4 NUMERICAL SIMULATIONS

In this project, the drawing of the heart valve was considered as a rigid body. The heart model will remain in its original shape and deformation is neglected during running in the simulation. The simulation mainly to investigate the effect of the displacement changes on the leaflets and the blood flow velocity by validate the parameters in the period of one second. A pressure difference between the inlet and outlet was enforced with the Neumann boundary condition. A difference value of normal traction was used to acquire the fluid flow through the different shapes of leaflets in the simulation. The simulation for different shapes of the leaflets was performed and the result was carried out within 5 minutes for each. The constant value for the initially parameters setups during the simulation was the blood density $\rho = 1.06 \times 10^3$ kgm^{-3} and absolute viscosity $\mu = 2.07 \times 10^{-3}$ Pa.s. For mitral valve and aortic valve, it has its own Young's Modulus and Poisson ratio value. Table 3.2 in below shown the initially simulation setup in ADINA-FSI for the fluid and structure properties.

Table 3.2: ADINA-FSI Simulation setup

Structure (valve leaflet)		
	Mitral valve	**Aortic valve**
Poisson Ratio	0.49	0.45
Young's Modulus, MPa	2.0×10^{6}	2.0×10^{-2}
Fluid (human blood)		
Viscosity, μ (Pa.s)	2.07×10^{-3}	
Blood Density, ρ (kgm^{-3})	1.06×10^{3}	

Source: Al-Atabi et al (2010); Hart et al (2003) and Ranga et al (2007)

3.5 MESHING

Meshing process used to be the one of most important step to determine the accuracy of result obtained in simulation. In our study, Arbitrary Lagrange Euler (ALE) mesh was used during the setup in simulation**.** Hart et al (2003) stated that to solve the multidimensional such as two-dimensional numerical simulation problems which involved fluid dynamics and nonlinear solid mechanics, it always required coping with strong distortions of the continuum under consideration while allowing for a clear delineation of fluid–fluid, solid–solid, or fluid–structure interfaces.

In the ALE explanation, the nodes in the computational mesh could be moved either with the continuum in normal Lagrangian fashion or be held fixed in Eulerian method. In Lagrangian method, it stated that each individual node in the computational mesh follows the associated material particle during movements, which usually apply in the structural mechanism. The disadvantage for Lagrangian method is it unable to apply during large distortions of the computational domain without depends on redo meshing operations. Furthermore, Eulerian method is widely applied in fluid dynamics where the mesh is fixed and continuum moves with respect to the grid. It is different with Lagrangian method where it could handle with large distortions in the continuum motion.

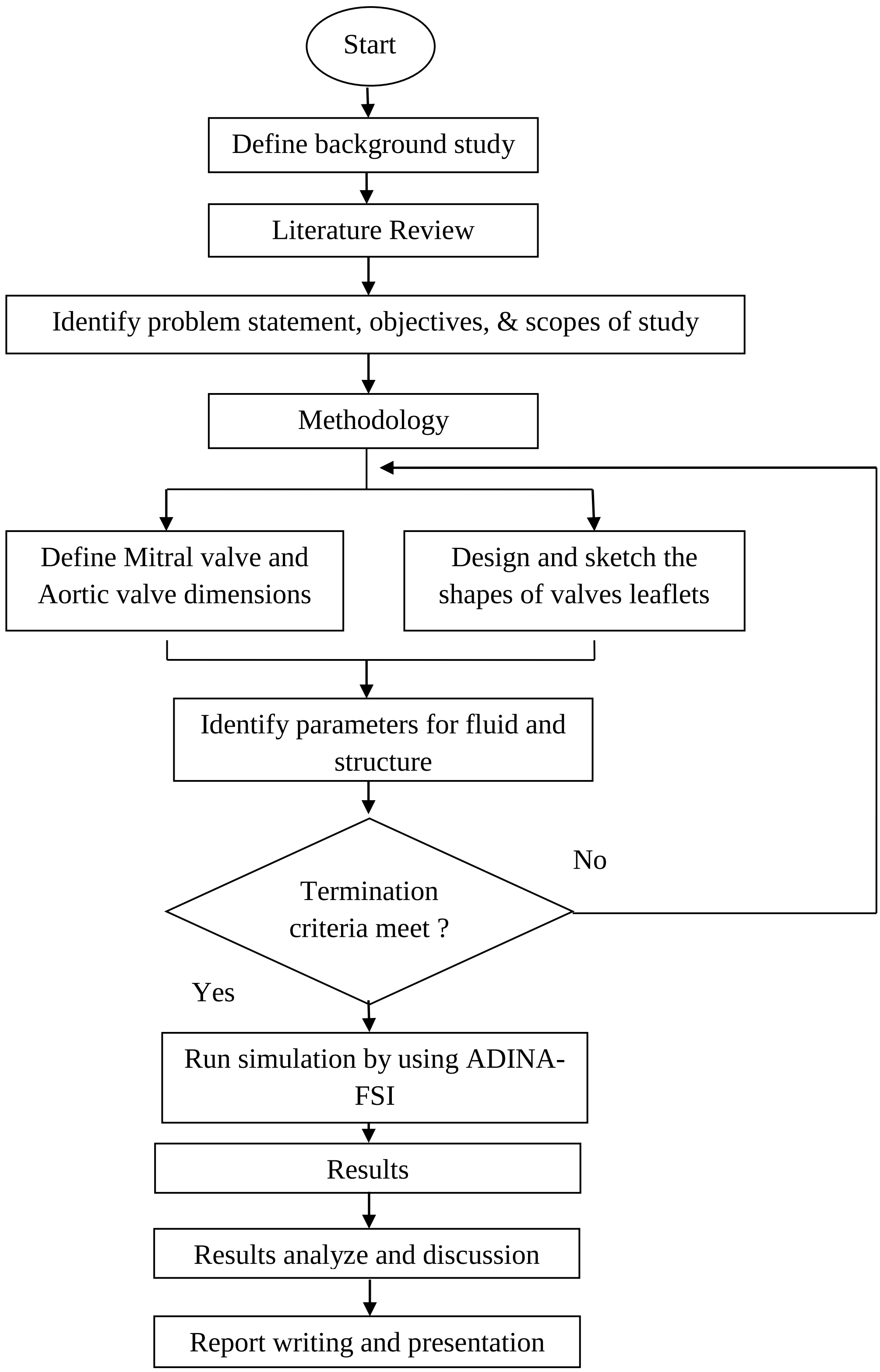


Figure 3.3: Flow Chart of Project

3.6 THE FLOW PROCESS OF THE PROJECT

This project was started by understanding and studied for the back ground journals which were related to the title. By go through a lot of literature review summaries; the focus area and direction of the title could be defined. From this, it comes out the idea and the direction of the objectives, problem statement and scopes for this study. After determined and define the paths for the investigation of the study, it continued by study the way for performing the investigation by methodology. From the previous study, the dimension of the mitral valve and aortic valve is determined. Then, five different shapes of valve were been designed and sketching by applying the dimension obtained from previous study. Besides of sketching, the properties of the valve structure and fluid flow also were been determined and studied. After a complete discussion and analysed to the initial value and design setup, the simulation was performed by using ADINA-FSI. The outcome results were been collected and analysed. Discussion and conclusion have been made based on result obtained. Finally, report writing and presentation have been performed to show the whole progress of this study.

3.7 PRE-SETUP IN ADINA-FSI FOR STRUCTURE PART

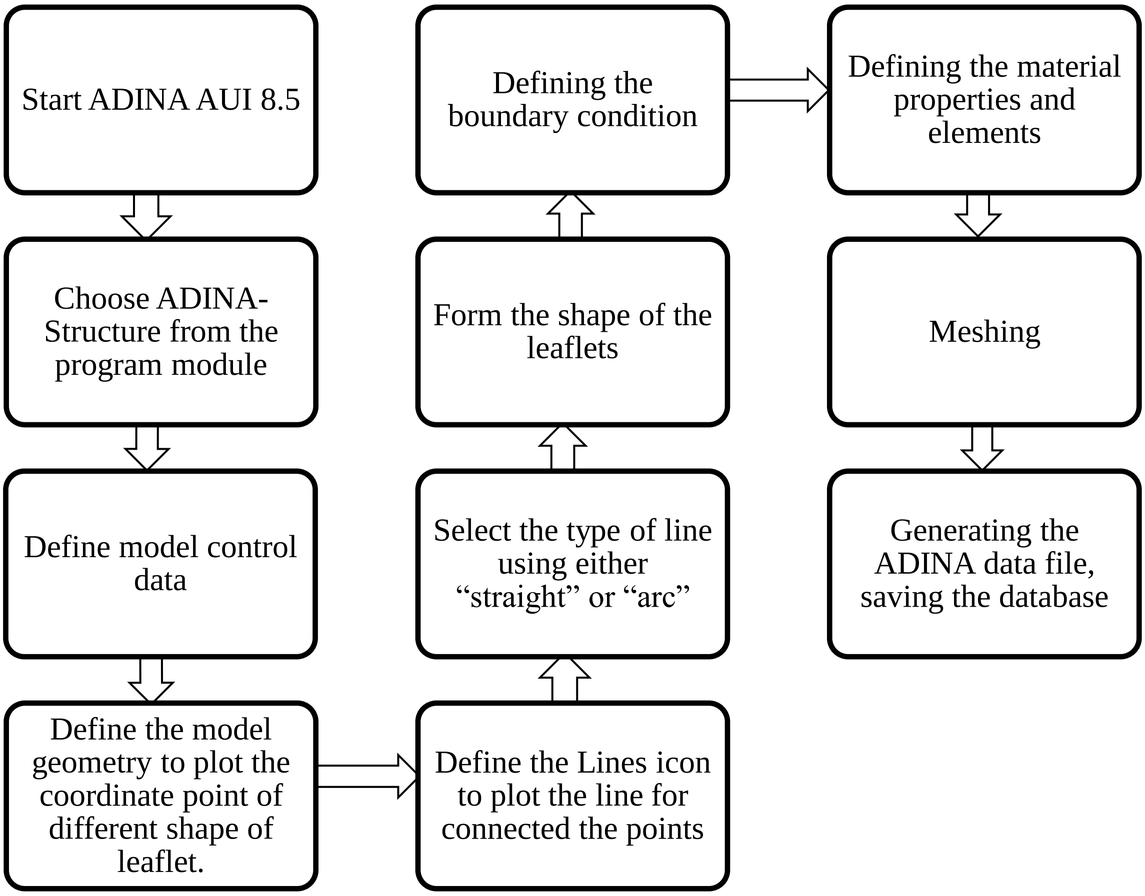


Figure 3.4: The flow process to setup in ADINA-FSI for structure part

The steps for running the simulation in ADINA could be divided into 2 partitions, which are the structure part and the fluid part. In FSI, it involved with the combination of interaction between the structure and fluid. From this, in ADINA-FSI, we will create the fluid database and structure database separately. In pre-setup for structure part, we initially opened the ADINA-FSI software with the program module into ADINA-Structure mode. Then, the setup for model control data such as setup the FSI mode, analysis assumption was assumed and master degrees of freedom will be setup. Next, the model geometry of the leaflet was been defined by entering the coordinate and the shape of the leaflet could be connected by the line and define the surface to form the shape of the leaflet. The next step after finished drawing the shape was defined the boundary condition of the drawing. Fix wall boundary and FSI boundary condition was applied. After this, material properties for the leaflet could be defined by key in the value of the Young's modulus and Poisson's ratio. Next, it followed by performed the elements defining by defining the type of leaflet into 2D solid type. After that, meshing process was continued after the element was defined, by subdivided the structure with division lines and generated the mesh surface. Finally, the drawing was saved into ADINA data file and it was completed for structure part.

3.8 PRE-SETUP IN ADINA-FSI FOR FLUID PART

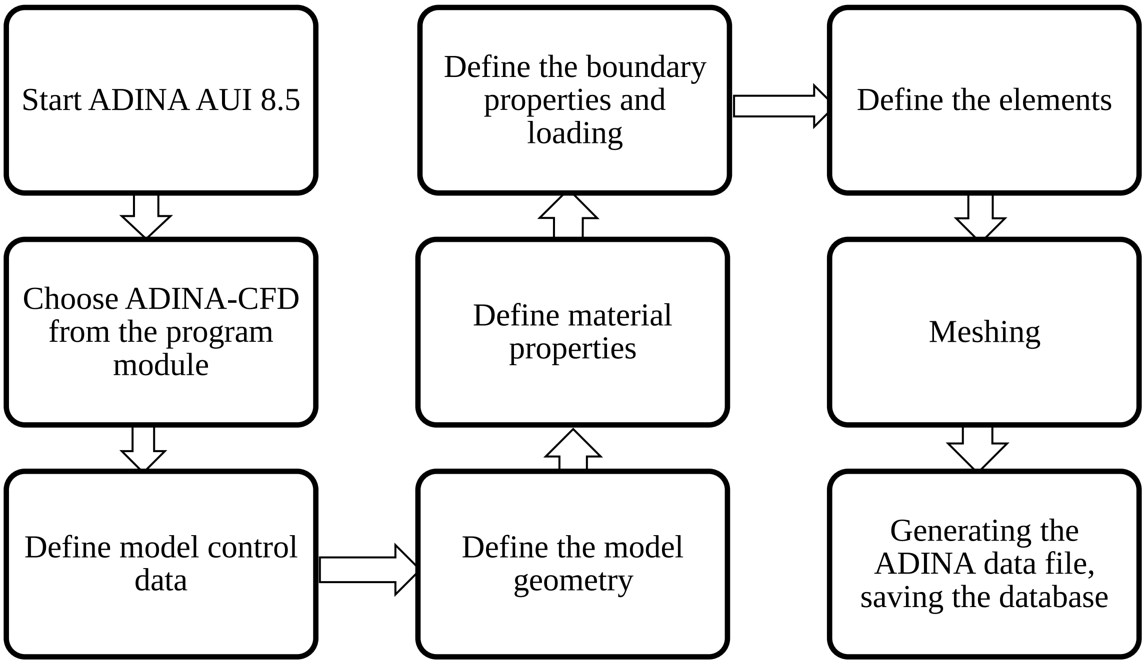


Figure 3.5: The flow process to setup in ADINA-FSI for fluid part

In the pre-preparation for fluid simulation, the steps involved were nearly same as the steps involved in previous setup for structure part. The steps were started with opened the ADINA-CFD module and defined the model control data. Then FSI analysis was chosen, flow assumption was assumed, time steps and time function was determined. Next, model geometry was defined by key in the coordinate for the model design. By connecting the point with lines and defined the surface, the complete shape of the design could be viewed. The next step was proceeded by defined the material properties such as density and viscosity of the fluid. After this, it proceeded by defining the boundary condition with no-slip boundary condition and FSI boundary condition. A loading that functions as the normal traction was setup for applied the pressure difference between left atrium and left ventricle. Then, it continued by defined the element group and adding the type of 2D fluid. Meshing was continued after define the element group by subdividing the line by a surface per surface. Quadrilateral type of mesh was applied due to the numbers of nodes for simple design of model can provide better quality solutions. It reduced false diffusion when the mesh was aligned with the flow. Meshing was performing after all surface subdivisions were done. Finally, after finished the meshing step, the drawing could be saved into ADINA-CFD database file.

CHAPTER 4

RESULT AND DISCUSSION

4.1 INTRODUCTION

In this chapter, the simulation result obtained for mitral valve and aortic valve based on the initial setup will be presented and discussed. In the initial setup for normal diastolic stage, mitral valve and aortic valve is applied with the blood pressure of 80 mmhg whereas for normal systolic stage 120 mmhg blood pressures are applied. The result of velocity of blood versus time, displacement changes of leaflets versus time, force versus time and the elasticity changes due to the blood pressure effect versus time was shown in below. These results for mitral valve and aortic were obtained by manipulated the shapes of valve leaflets. In the end, the finding the most suitable shape of leaflet for the design of the prosthesis valve in future through the relationship of result obtained was been be defined. The correlation of velocity of blood and displacement changes of leaflet with the different shapes of leaflets will be determined.

4.2 VALIDATION AND VERIFICATION

In simulation, model and result need to verification and validation (V&V) is essential parts of the model development process if models and results to be accepted and used to support decision making. Verification is done used to ensure the model is programmed correctly, algorithms have been implemented properly and the model and results does not contain errors, oversights, or bugs. However, there are no computational model will ever be fully verified and guaranteeing 100 % of error-free implementation. Besides, for validation, it ensure ensures that the model meets its intended requirements in terms of the methods employed and the results obtained. The ultimate goal of model validation is to make the model useful in the sense that the model addresses the right problem, provides accurate information about the system being modelled, and to makes the model actually used.

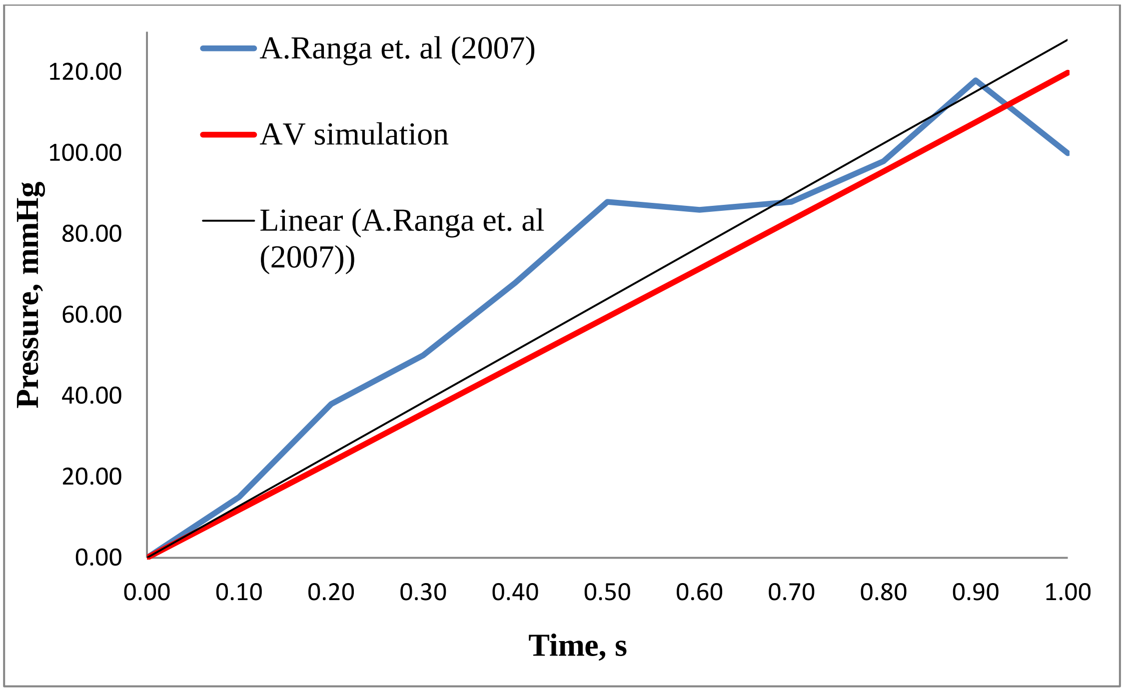


Figure 4.1: Comparison the pressure applied between aortic valve model and previous study

The above figure 4.1 shows the comparison of the pressure applied to the aortic valve model in this study's simulation with the model with Ranga et al. (2007). Ranga et al. (2007) showed the pressure value applied to the aortic valve is in increasing behaviour in their simulation study. By comparing the result with the previous study, the pressure applied is increased when the time instant is increased. The result shows that at the time instant of 0.1 second and 0.8 second, the pressure result of simulation was nearly same in value with previous study in Ranga et al. (2007). The pressure used in both simulation studies is applied in the range of normal systolic condition which is below 120 mmHg.

4.3 SIMULATION RESULT FOR MITRAL VALVE

4.3.1 Blood Flow Velocity for Mitral Valve at Normal Diastolic Stage (Blood Pressure = 80 mmhg)

i) Square Shape Leaflets

Figure B-1 until B-5 shown in appendix B represents the changes of blood flow velocity when flowing through the square shape of mitral valve leaflets in duration of 1.0 second. From the figure B-1 where the time instant is 0.2 second, the blood is flowing in a velocity value of 0.00454205 mm/s. Then at the time instant is 0.6 second shown in figure B-3, the velocity of the blood flow is 0.0688452 mm/s. At figure B-5, the highest velocity of the blood flow is achieved at a value of 1.05776 mm/s at the time instant of 1.0 second is due to highest pressure was applied at that moment. The pressure used to apply in pushing the blood flows can be determined from the background colour in the image. The different background colour means the different pressure condition between the left atrium and left ventricle. The different pressure is applied in the simulation by increasing proportionally from initially until the end of 1.0 second duration. This increment of the pressure applied over the time will purposely to result the deformation of valve leaflet.

ii) Triangle Shape Leaflets

Appendix B of Figure B-6 until B-10 shows the changes of blood flow velocity when flowing through the triangle shape of mitral valve leaflets for the duration of 1.0 second. In figure B-6 when the time instant is 0.2 second, the blood is flowing at a velocity value of 11.49 mm/s. Then at the time instant of 0.6 second shown in figure B-8, the velocity of blood flow is 27.42 mm/s. In figure B-10, the highest velocity of the blood flow is achieved where the value is 68.54 mm/s at the time instant of 1.0 second. The pressure used to apply in pushing the blood flows can be determined from the background colour in the image. The different background colour means the different pressure condition between the left atrium and left ventricle.

iii) Half-Hemisphere Shape Leaflets

For the half-hemisphere shape of mitral valve leaflets, the changes of blood flow velocity when flowing through it in 1.0 second of duration is shown in Figure B-11 until B-15 at appendix B. From the figure B-11 where the time instant is 0.2 second, the blood is flowing in a velocity value of 9.00613 mm/s. Then at the time instant is 0.6 second shown in figure B-13, the velocity of blood flow is 22.9785 mm/s. At figure B-15, the highest velocity of the blood is achieved at a value of 33.8938 mm/s at the time instant of 1.0 second. The pressure used to apply to push the blood flows can be determined from the background colour in the image. The different background colour means the different pressure condition between the left atrium and left ventricle.

iv) Ellipse Shape Leaflets

The changes of blood flow velocity when flowing through the ellipse shape of mitral valve leaflets in 1.0 second of duration is shown in Figure B-16 until B-20 at appendix B. From the figure B-16 where the time instant is 0.2 second, the blood is flowing in a velocity value of 7.1002 mm/s. Then at the time instant is 0.6 second shown in figure B-18, the velocity of blood flow is 32.27 mm/s. At figure B-20, the highest velocity of the blood is achieved at a value of 65.5252 mm/s at the time instant of 1.0 second. The pressure used to apply to push the blood flows can be determined from the background colour in the image. The different background colour means the different pressure condition between the left atrium and left ventricle.

v) V-Shape Leaflets

Meanwhile the Figure B-21 until B-25 shown in appendix B represents the changes of blood velocity when flowing through the V-shape of mitral valve leaflets in 1.0 second of duration. From the figure B-21 where the time instant is 0.2 second, the blood is flowing in a velocity value of 1.655 mm/s. Then at the time instant is 0.6 second shown in figure B-23, the velocity of blood flow is 28.76 mm/s. At figure B-25, the highest velocity of the blood is achieved at a value of 65.8478 mm/s at the time instant of 1.0 second. The pressure used to apply to push the blood flows can be determined from the background colour in the image. The different background colour means the different pressure condition between the left atrium and left ventricle.

4.3.2 Blood Flow Velocity for Mitral Valve at Normal Systolic Stage (Blood Pressure = 120 mmhg)

i) Square Shape Leaflets

Figure B-26 until B-30 shown in appendix B represents the changes of blood flow velocity when flowing through the square shape of mitral valve leaflets in duration of 1.0 second. From the figure B-26 where the time instant is 0.2 second, the blood is flowing in a velocity value of 0.004951 mm/s. Then at the time instant is 0.6 second shown in figure B-28, the velocity of the blood flow is 0.6181 mm/s. At figure B-30, the highest velocity of the blood flow is achieved at a value of 6.521 mm/s at the time instant of 1.0 second. The pressure used to apply in pushing the blood flows can be determined from the background colour in the image. The different background colour means the different pressure condition between the left atrium and left ventricle.

ii) Triangle Shape Leaflets

Appendix B of Figure B-31 until B-35 shows the changes of blood flow velocity when flowing through the triangle shape of mitral valve leaflets for the duration of 1.0 second. In figure B-31 when the time instant is 0.2 second, the blood is flowing at a velocity value of 15.70 mm/s. Then at the time instant of 0.6 second shown in figure B-33, the velocity of blood flow is 55.99 mm/s. In figure B-35, the highest velocity of the blood flow is achieved where the value is 102 mm/s at the time instant of 1.0 second. The pressure used to apply in pushing the blood flows can be determined from the background colour in the image. The different background colour means the different pressure condition between the left atrium and left ventricle.

iii) Half-Hemisphere Shape Leaflets

For the half-hemisphere shape of mitral valve leaflets, the changes of blood flow velocity when flowing through it in 1.0 second of duration is shown in Figure B-36 until B-40 at appendix B. From the figure B-36 where the time instant is 0.2 second, the blood is flowing in a velocity value of 12.87 mm/s. Then at the time instant is 0.6 second shown in figure B-38, the velocity of blood flow is 30.88 mm/s. At figure B-15, the highest velocity of the blood is achieved at a value of 46.23 mm/s at the time instant of 1.0 second. The pressure used to apply to push the blood flows can be determined from the background colour in the image. The different background colour means the different pressure condition between the left atrium and left ventricle.

iv) Ellipse Shape Leaflets

The changes of blood flow velocity when flowing through the ellipse shape of mitral valve leaflets in 1.0 second of duration is shown in Figure B-41 until B-45 at appendix B. From the figure B-41 where the time instant is 0.2 second, the blood is flowing in a velocity value of 13.8 mm/s. Then at the time instant is 0.6 second shown in figure B-43, the velocity of blood flow is 59.78 mm/s. At figure B-45, the highest velocity of the blood is achieved at a value of 94.46 mm/s at the time instant of 1.0 second. The pressure used to apply to push the blood flows can be determined from the background colour in the image. The different background colour means the different pressure condition between the left atrium and left ventricle.

v) V-Shape Leaflets

Meanwhile the Figure B-46 until B-50 shown in appendix B represents the changes of blood velocity when flowing through the V-shape of mitral valve leaflets in 1.0 second of duration. From the figure B-46 where the time instant is 0.2 second, the blood is flowing in a velocity value of 4.576 mm/s. Then at the time instant is 0.6 second shown in figure B-48, the velocity of blood flow is 57.2 mm/s. At figure B-50, the highest velocity of the blood is achieved at a value of 91.1 mm/s at the time instant of 1.0 second. The pressure used to apply to push the blood flows can be determined from the background colour in the image. The different background colour means the different pressure condition between the left atrium and left ventricle.

4.3.3 Velocity of Blood Flow for Mitral Valve at Normal Diastolic Stage (80 mmhg) and Normal Systolic Stage (120 mmhg)

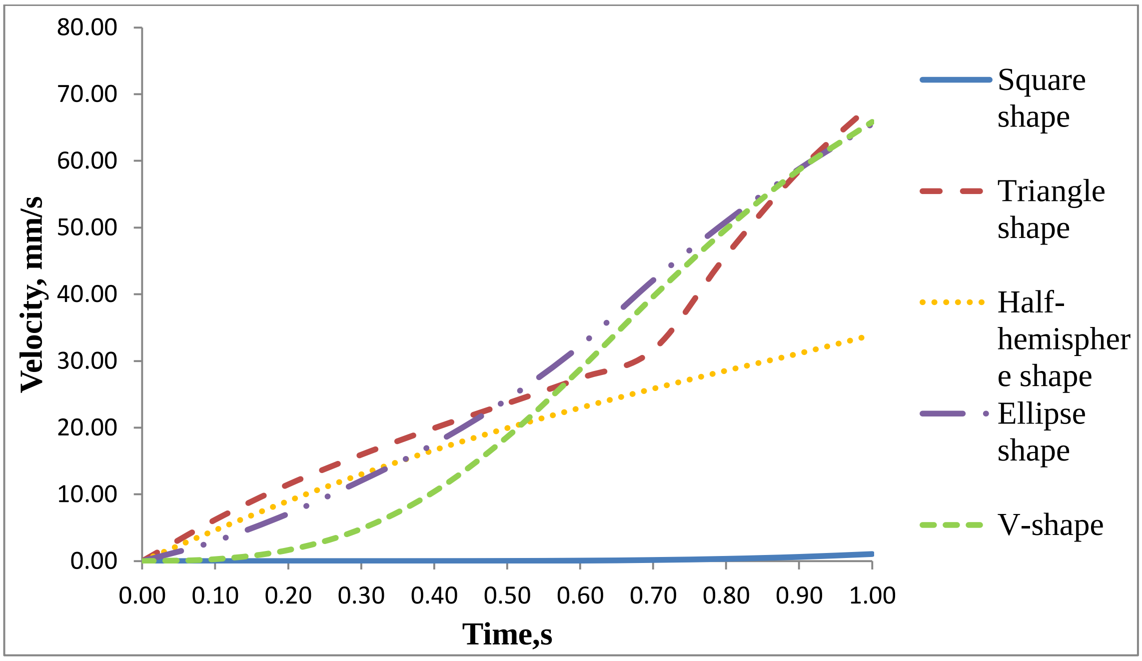


Figure 4.2: Velocity of blood flow for different shapes versus time at Normal Diastolic stage (80mmhg)

In Figure 4.2, the graph of velocity (mm) versus time (second) in diastole condition with different shape of mitral leaflets was plotted. From the result obtained, triangle shape has the highest velocity performance which is around 68.54 mm/s compares to others four shapes. The velocity performance is following by the V-shape and ellipse shape which have a value of 65.84 mm/s and 65.52 mm/s respectively. Besides, half-hemisphere has a velocity value of 33.89 mm/s. Square shape has the lowest velocity performance where is only 1.05 mm/s and this occurred may hugely related to its displacement change during opening. Small displacement changes in opening may block the path of blood to flow. By compare with the maximum and minimum value obtained, there are nearly 98.5 percentage of value difference in velocity changes between the triangle shape and square shape.

Besides, the triangle shape, V-shape and ellipse shape shows that it is only a small difference of velocity changes among these three shapes. There are only approximately 3.93 percentage in difference for triangle shape to V-shape whereas 4.41 percentage to the ellipse shape. In fact, triangle shape, V-shape and ellipse shape are perform well in velocity changes when compare to the square shape and half-hemisphere shape during normal diastole condition for mitral valve model.

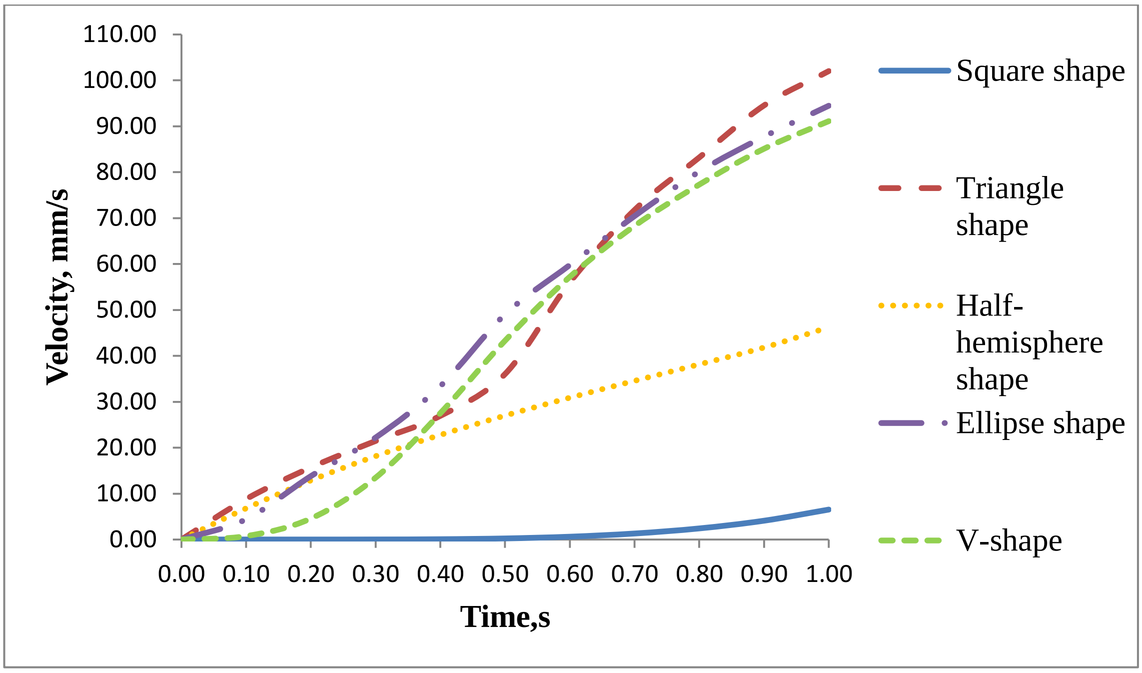


Figure 4.3: Velocity of blood flow for different shapes versus time at Normal Systolic stage (120mmhg)

In Figure 4.3, the graph of velocity (mm/s) versus time (second) in systole condition with different shape of mitral leaflets was plotted. From the result obtained, triangle shape has the highest velocity performance which is around 102 mm/s compares to others four shapes. The velocity performance is following by the V-shape and ellipse shape which have a value of 94.5 mm/s and 91.1 mm/s respectively. Next, half-hemisphere shape has a value of 46.22 mm/s of velocity. Square shape has the lowest velocity performance where is 6.52 mm/s and this occurred may hugely related to its displacement change during opening. Small displacement changes in opening may block the path of blood to flow. By compare with the maximum and minimum value obtained, there are nearly 93.6 percentage of value difference in velocity changes between the triangle shape and square shape.

Besides, the ellipse shape shows that it is only a small difference of velocity changes when compare to the triangle shape. There are only approximately 7.39 percentage in difference for ellipse shape to triangle shape whereas 3.55 percentage to the V-shape. In fact, ellipse shape, V-shape and triangle shape are perform well in velocity changes when compare to the square shape and half-hemisphere shape during systole condition for mitral valve model.

Furthermore, the velocity result obtained from simulation show that triangle shape obtained the highest velocity while square shape obtained the lowest velocity. The result of the velocity of fluid obtained could be related to the displacement changes of the leaflets. The opening of the leaflets will influence the fluid flow velocity. In this simulation, the velocity result obtained shows the value of velocity in the condition of constant pressure is applied varies with time. Therefore, the results of velocity shown could be explained by using Newton's second law of motion where force is equal to the mass times velocity of the motion. In Newton's second law of motion, it could explain where the acceleration produced by the force acting on the body is directly proportional to the magnitude of the force for a constant mass object (Shipman, 2009). Acceleration is used to define as the change of rate for velocity motion. By this, the concept in Newton's second law of motion could derive into another form of relationship. It shows the relationship of the velocity motion of the body is directly proportional to the motive force applied on it.

In the fundamental of pressure law, pressure is equals to force divided by surface area. The surface area mentioned here is pointed to the cross section area of the blood flow during the valve opening. In order to get a higher cross section area, the behaviour of the leaflets displacement changes should be higher. Thus, the blood flow cross section area is directly proportional to the displacements changes of leaflets. Higher displacements changes will lead to higher crossing surface area of blood flow. At the condition where constant pressure and mass is applied, a conclusion that the changes of blood velocity are related with the changes in leaflets displacement could be made. Hence, higher displacement in leaflets opening will result in the fluid to flow at higher velocity.

4.3.4 The Leaflet's Displacement for Mitral Valve at Normal Diastolic Stage (Blood Pressure = 80 mmhg)

i) Square Shape Leaflets

Figure B-51 until B-55 shown in appendix B represents the displacement changes of square shape leaflet under deformation in duration of 1.0 second. From the figure B-51 where the time instant is 0.2 second, the displacement change of the leaflet is 0.2205 mm. Then at the time instant is 0.6 second shown in figure B-53, the displacement changes of the leaflet are increased to 0.66145 mm. At figure B-55, the change of leaflet displacement is reached to the maximum value which has a value of 1.103 mm at the time instant of 1.0 second is due to highest pressure was applied at that moment. The pressure used to apply in pushing the blood flows can be determined from the background colour in the image. The different background colour means the different pressure condition between the left atrium and left ventricle. The different pressure is applied in the simulation by increasing proportionally from initially until the end of 1.0 second duration. This increment of the pressure applied over the time will purposely to result the deformation of valve leaflet.

ii) Triangle Shape Leaflets

Appendix B of Figure B-56 until B-60 shows the displacement changes of triangle shape leaflet under deformation for the duration of 1.0 second. In figure B-56 when the time instant is 0.2 second, the leaflet displacement change is 0.7428 mm. Then at the time instant of 0.6 second shown in figure B-58, the leaflet displacement changes are increased to 2.171 mm. In figure B-60, the change of displacement is reached to the maximum with a value of 3.544 mm at the time instant of 1.0 second. The pressure used to apply in pushing the blood flows can be determined from the background colour in the image. The different background colour means the different pressure condition between the left atrium and left ventricle.

iii) Half-Hemisphere Shape Leaflets

For the half-hemisphere shape of mitral valve leaflets, the displacement change of leaflet under deformation in 1.0 second of duration is shown in Figure B-60 until B-65 at appendix B. From the figure B-60 where the time instant is 0.2 second, the leaflet displacement change is 0.3177 mm. Then at the time instant is 0.6 second shown in figure B-63, the leaflet displacement changes are increased to 0.9472 mm. At figure B-65, the change of leaflet displacement is reached to the maximum with a value of 1.588 mm. at the time instant of 1.0 second. The pressure used to apply to push the blood flows can be determined from the background colour in the image. The different background colour means the different pressure condition between the left atrium and left ventricle.

iv) Ellipse Shape Leaflets

The leaflet displacement change of ellipse shape leaflet under deformation in 1.0 second of duration is shown in Figure B-66 until B-70 at appendix B. From the figure B-66 where the time instant is 0.2 second, the leaflet displacement change is 0.3201 mm. Then at the time instant is 0.6 second shown in figure B-68, the leaflet displacement changes are increased to 0.9551 mm. At figure B-70, the change of leaflet displacement is reached to the maximum with a value of 1.582 mm at the time instant of 1.0 second. The pressure used to apply to push the blood flows can be determined from the background colour in the image. The different background colour means the different pressure condition between the left atrium and left ventricle.

v) V-Shape Leaflets

Meanwhile the Figure B-71 until B-75 shown in appendix B represents the displacement changes of V-shape leaflet under deformation in 1.0 second of duration. From the figure B-46 where the time instant is 0.2 second, the leaflet displacement change is 0.3099 mm. Then at the time instant is 0.6 second shown in figure B-48, the leaflet displacement changes are increased to 0.9391 mm. At figure B-50, the change of leaflet displacement is reached to the maximum with a value of 1.555 mm at the time instant of 1.0 second. The pressure used to apply to push the blood flows can be determined from the background colour in the image. The different background colour means the different pressure condition between the left atrium and left ventricle.

4.3.5 The Leaflet's Displacement for Mitral Valve at Normal Systolic Stage (Blood Pressure = 120 mmhg)

i) Square Shape Leaflets

Figure B-76 until B-80 shown in appendix B represents the displacement changes of square shape leaflet under deformation in duration of 1.0 second. From the figure B-76 where the time instant is 0.2 second, the displacement change of the leaflet is 0.3294 mm. Then at the time instant is 0.6 second shown in figure B-78, the displacement changes of the leaflet are increased to 1.242 mm. At figure B-80, the change of leaflet displacement is reached to the maximum value which has a value of 1.65 mm at the time instant of 1.0 second is due to highest pressure was applied at that moment. The pressure used to apply in pushing the blood flows can be determined from the background colour in the image. The different background colour means the different pressure condition between the left atrium and left ventricle. The different pressure is applied in the simulation by increasing proportionally from initially until the end of 1.0 second duration. This increment of the pressure applied over the time will purposely to result the deformation of valve leaflet.

ii) Triangle Shape Leaflets

Appendix B of Figure B-81 until B-85 shows the displacement changes of triangle shape leaflet under deformation for the duration of 1.0 second. In figure B-81 when the time instant is 0.2 second, the leaflet displacement change is 1.084 mm. Then at the time instant of 0.6 second shown in figure B-83, the leaflet displacement changes are increased to 3.142 mm. In figure B-85, the change of displacement is reached to the maximum with a value of 5.168 mm at the time instant of 1.0 second. The pressure used to apply in pushing the blood flows can be determined from the background colour in the image. The different background colour means the different pressure condition between the left atrium and left ventricle.

iii) Half-Hemisphere Shape Leaflets

For the half-hemisphere shape of mitral valve leaflets, the displacement change of leaflet under deformation in 1.0 second of duration is shown in Figure B-86 until B-90 at appendix B. From the figure B-86 where the time instant is 0.2 second, the leaflet displacement change is 0.4206 mm. Then at the time instant is 0.6 second shown in figure B-88, the leaflet displacement changes are increased to 1.399 mm. At figure B-90, the change of leaflet displacement is reached to the maximum with a value of 2.352 mm at the time instant of 1.0 second. The pressure used to apply to push the blood flows can be determined from the background colour in the image. The different background colour means the different pressure condition between the left atrium and left ventricle.

iv) Ellipse Shape Leaflets

The leaflet displacement change of ellipse shape leaflet under deformation in 1.0 second of duration is shown in Figure B-91 until B-95 at appendix B. From the figure B-91 where the time instant is 0.2 second, the leaflet displacement change is 0.5322 mm. Then at the time instant is 0.6 second shown in figure B-93, the leaflet displacement changes are increased to 1.452 mm. At figure B-95, the change of leaflet displacement is reached to the maximum with a value of 2.346 mm at the time instant of 1.0 second. The pressure used to apply to push the blood flows can be determined from the background colour in the image. The different background colour means the different pressure condition between the left atrium and left ventricle.

v) V-Shape Leaflets

Meanwhile the Figure B-96 until B-100 shown in appendix B represents the displacement changes of V-shape leaflet under deformation in 1.0 second of duration. From the figure B-96 where the time instant is 0.2 second, the leaflet displacement change is 0.4571 mm. Then at the time instant is 0.6 second shown in figure B-98, the leaflet displacement changes are increased to 1.38 mm. At figure B-100, the change of leaflet displacement is reached to the maximum with a value of 2.285 mm at the time instant of 1.0 second. The pressure used to apply to push the blood flows can be determined from the background colour in the image. The different background colour means the different pressure condition between the left atrium and left ventricle.

4.3.6 Displacement Changes of Leaflets for Mitral Valve at Normal Diastolic Stage (80mmhg) and Normal Systolic Stage (120 mmhg)

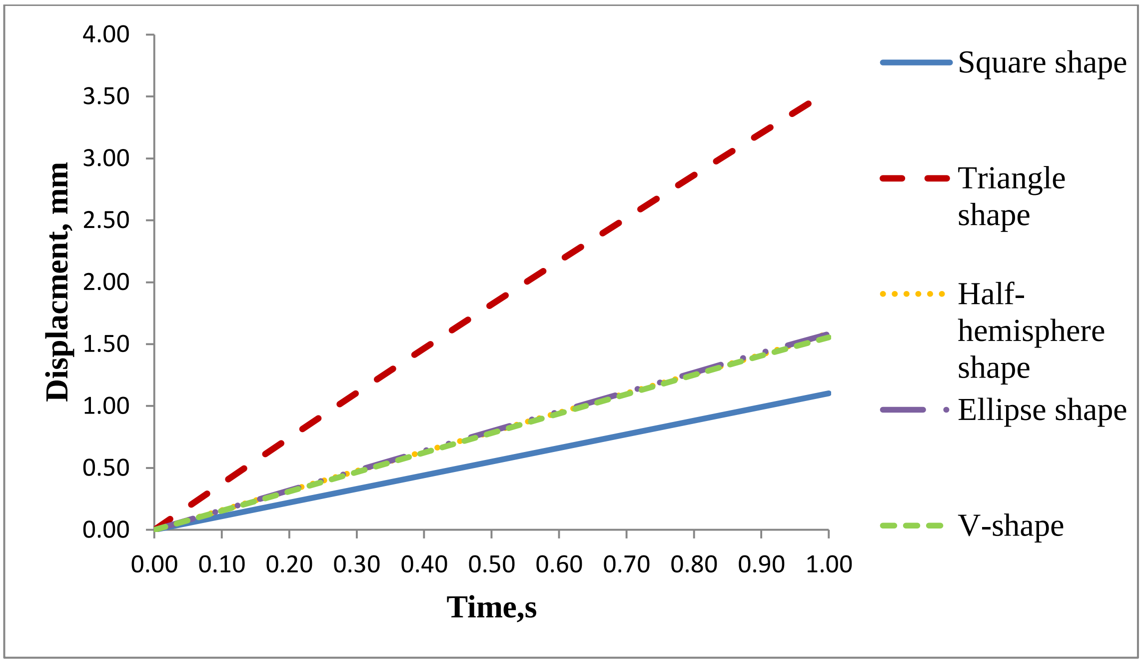


Figure 4.4: Displacement changes of leaflets for different shape versus time at Normal Diastolic stage (80mmhg)

Figure 4.4 shown in above represented the result of displacement (mm) versus time (second) in diastole condition with five different shapes of mitral leaflets. It shows that the displacement of leaflet is directly proportional to the time since the value of normal traction applied on the leaflets is increasing during the time period is increasing. The triangle shape of leaflet has the highest value of displacement change in diastole condition which is around 3.54 mm whereas the square shape of leaflet has the lowest value around 1.11 mm of displacement change. There is an approximately 68 percentage of difference between the maximum and the minimum displacement changes. Besides, half-hemisphere shape, ellipse shape and V-shape show that these three shapes have almost same in value for the displacement changes which is 1.587 mm , 1.582 mm and 1.554 mm respectively. There is only approximately 0.341 percentage of difference between half-hemisphere with ellipse shape and nearly 2.6 percentage different compare to V-shape.

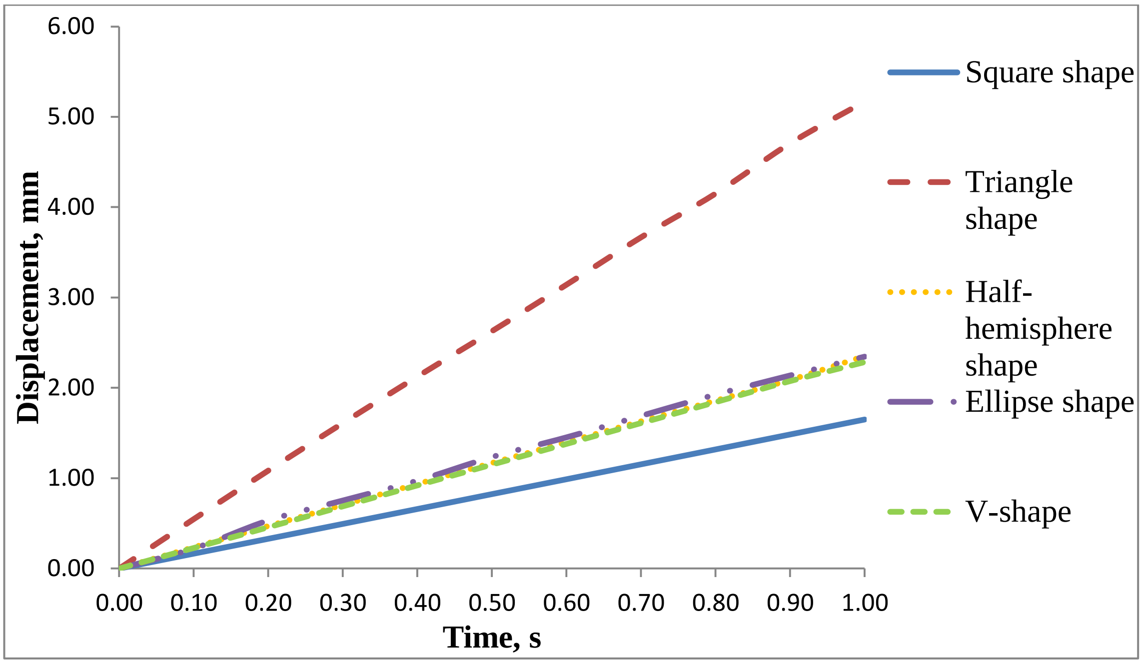


Figure 4.5: Displacement changes of leaflets for different shapes versus time at Normal Systolic stage (120 mmhg)

Figure 4.5 shown in above represented the result of displacement (mm) versus time (second) in systole condition with five different shapes of mitral leaflets. It shows that the displacement of leaflet is directly proportional to the time since the value of normal traction applied on the leaflets is increasing during the time period is increasing. The triangle shape of leaflet has the highest value of displacement change in systolic condition which is around 5.17 mm whereas the square shape of leaflet has the lowest value around 1.65 mm of displacement change. There is an approximately 68 percentage of difference between the maximum and the minimum displacement changes. Besides, half-hemisphere shape, ellipse shape and V-shape show that these three shapes have almost same in value for the displacement changes which is 2.35 mm , 2.34 mm and 2.28 mm respectively. There is only approximately 0.265 percentage of difference between half-hemisphere with ellipse shape and nearly 2.82 percentage in different to V-shape.

For the displacement changes of the leaflets, triangle shape show the maximum displacement changes while square shapes show the minimum displacement changes. This phenomenon occurred is due to the changes in pattern of the shape. The thickness of the square shape leaflet is thicker than triangle shape leaflet where the blood flows through the centre of valve. Therefore, it is easier for triangle shape rather than for square shape to form a large changes in displacement at leaflets. Displacement of the leaflet could be related with the deformation due to bending stress. Bending stress defined as the normal stress that is induced at a point in a body subjected to loads that cause it to bend. When a load is applied perpendicular to the length of a beam with two supports on each end, bending moments are induced in the beam. In this simulation, the leaflet used behaved like a beam when the blood flow through the valve leaflet will result the deformation of leaflet. During calculation of the bending stress experienced on a beam, one of the main factors that influenced the value of bending stress is the length of perpendicular distance to the neutral axis. The length of perpendicular distance to the neutral axis is the same as the height or thickness of beam. From the formulae in Roylance (2000), the relationship between the bending stress is directly proportional to the value of the height. For square shape, its thickness is larger than triangle shape. So the square shape can resists more bending stress compare to the triangle shape. Bending stress is the stress required to cause the deformation of leaflet to occur. At a condition where constant pressure is applied, the leaflet displacement changes of triangle shape is larger than the square shape since the stress experienced is same while the capability to resist to be bending is different. Square shape has a large capability to resist bending and deformation causing it to have a lower result in displacement changes.

Besides, ellipse shape, half-hemisphere shape and V-shape also show a similar value in the leaflet displacement changes. This situation could be explained because they possess a nearly same shape in design. The upper boundary of the half-hemisphere shape has the same behaviour with ellipse shape because of the curve shape. The shape of half-hemisphere leaflet is the same as the ellipse shape which have a curved shape on its upper boundary. The curve shape boundary relationship could be explained by using curved beam. Curved shape boundary is more resistant towards bending and deformation. Therefore the ellipse shape only has a small value in leaflet displacement changes compare to the V-shape because of V-shape owns linear shape boundary. Although both V-shape and ellipse shape are extending onto the left ventricle when compare to the other three shapes of leaflet in which the other three shapes are placed horizontal at the entrance to the left ventricle. However, the different shape of the upper layer and the lower layer of leaflet result in difference displacement changes of the leaflets.

4.3.7 Force versus Displacement for Mitral Valve at Normal Diastolic Stage (80 mmhg) and Normal Systolic Stage (120 mmhg)

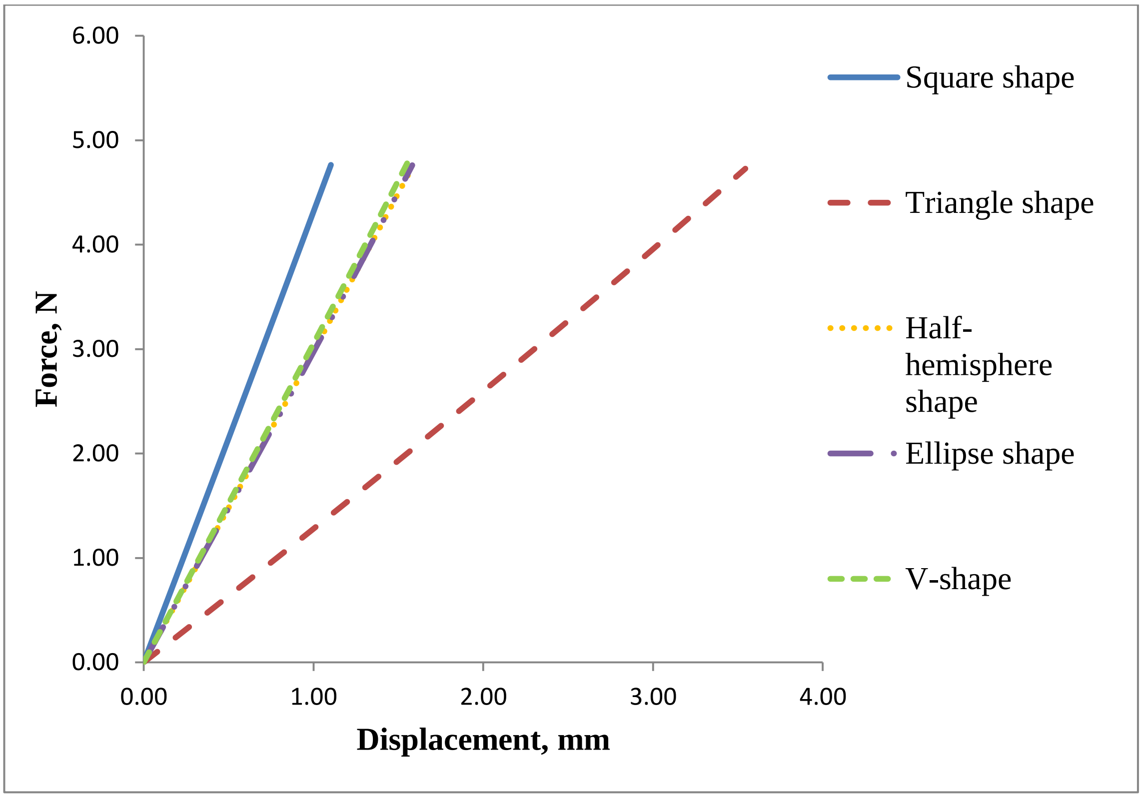


Figure 4.6: Force versus displacement for different shapes of mitral valve at Normal Diastolic stage (80 mmhg)

Figure 4.6 shows the relationship between the forces (N) with the displacement (mm) for the five different shapes of leaflets in normal diastolic condition. It shows that the force applied is directly proportional to the displacement of leaflet. Higher normal traction applied on the leaflets, leaflet is more in opening and higher displacement result obtained. When a certain amount of force is applied, triangle shape shows that it has the highest displacement. The value of force applied is in a range of 4.72 N until 4.79 N. The force value is calculated by applied the fundamental of pressure theory where pressure is equal to the force times the area. By applied a constant area for the normal valve opening with the value of 4.5 cm^2, the force applied on the leaflets could be calculated. Besides, the half-hemisphere shape, V-shape and ellipse shape show that these three shapes have nearly same in displacement changes if same amount force is applied. Square shape shows that it has the hardest the have displacement changes by compare to the others four shapes.

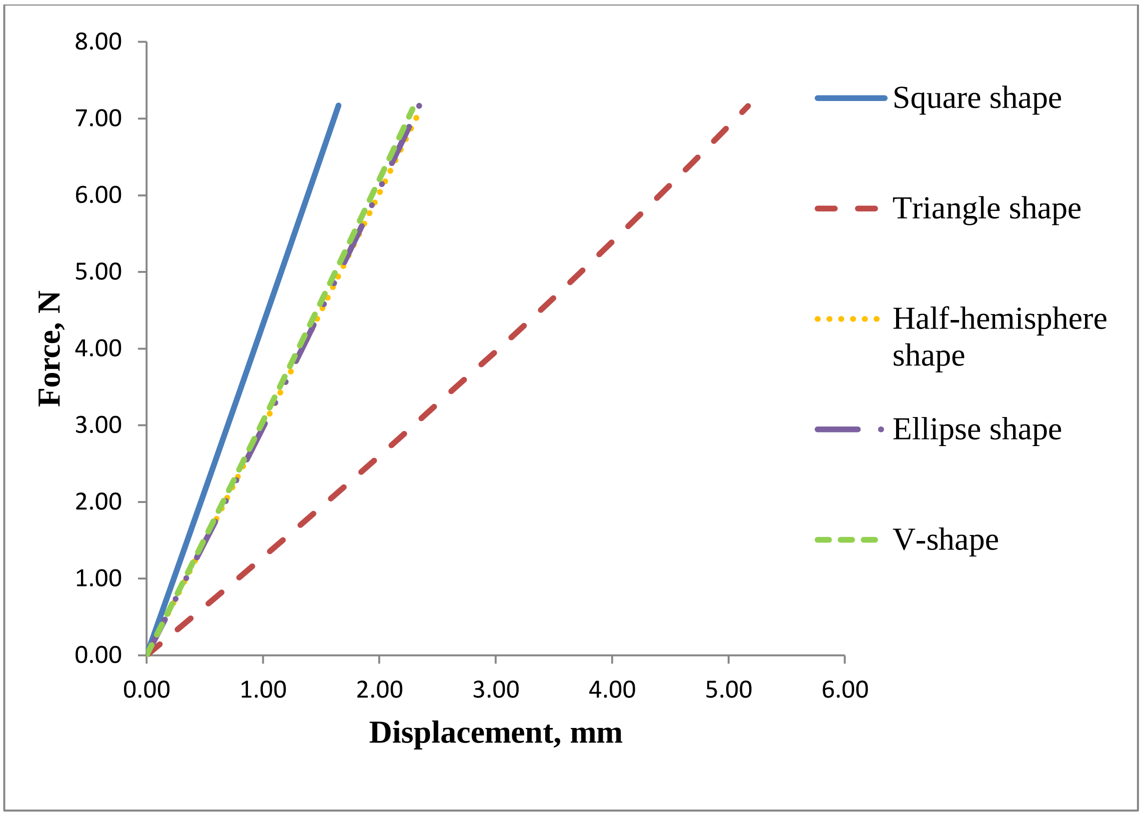


Figure 4.7: Force versus displacement for different shapes of mitral valve at Normal Systolic stage (120 mmhg)

The relationship for the five different shapes of leaflet between the force (N) and displacement (mm) is shown in above Figure 4.7. The result shown is represented the blood condition under the normal systole condition where 120 mmhg is applied at the condition. The result of relation obtained is same as the relationship obtained for diastole condition where when higher normal traction applied on the leaflets, leaflet is more in opening and higher displacement result obtained. Square shape still possessed the hardest to displacement changes whereas the triangle shape is the simplest shape. Ellipse shape, half-hemisphere shape and V-shape these three shapes of leaflet are behave in same behaviour for the displacement changes. When a certain amount of force is applied, triangle shape shows that it has the highest displacement. The value of force applied is in a range of 7.11 N until 7.17 N. The force value is calculated by applied the fundamental of pressure theory where pressure is equal to the force times the area. By applied a constant area for the normal valve opening with the value of 4.5 cm^2, the force applied on the leaflets could be calculated.

Furthermore, from the result obtained in the graph of force versus displacement, its shows that square shape require higher force to make a displacement changes compare to triangle shape. The value of forces required is obtained by applying a multiple constant normal cross section area times with the pressure applied. For a constant cross section area, it is highly depends on the displacements changes of the leaflets. Since square shape leaflet's behaviour is difficult to have changes in displacement, therefore it needs a lot of force in order to have higher displacements changes for constant normal cross section area and constant pressure situation. The constant pressure mentioned is the normal systolic stage where 120 mmhg is applied and the constant normal cross section area is 4.5 cm^2 (Espino et al., 2006). Triangle shape which is easily deforms and change in leaflet displacement required a small value of force to achieve the constant normal cross section area. For the other three shapes which is V-shape, ellipse shape and half-hemisphere shape, since they are almost same in performance of displacement result, therefore the force required to obtain nearly same cross section area will also almost the same in value.

4.3.8 Result of Stress versus Strain for Different Shapes of Mitral Valve at Normal Diastolic Stage (80 mmhg) and Normal Systolic Stage (120 mmhg)

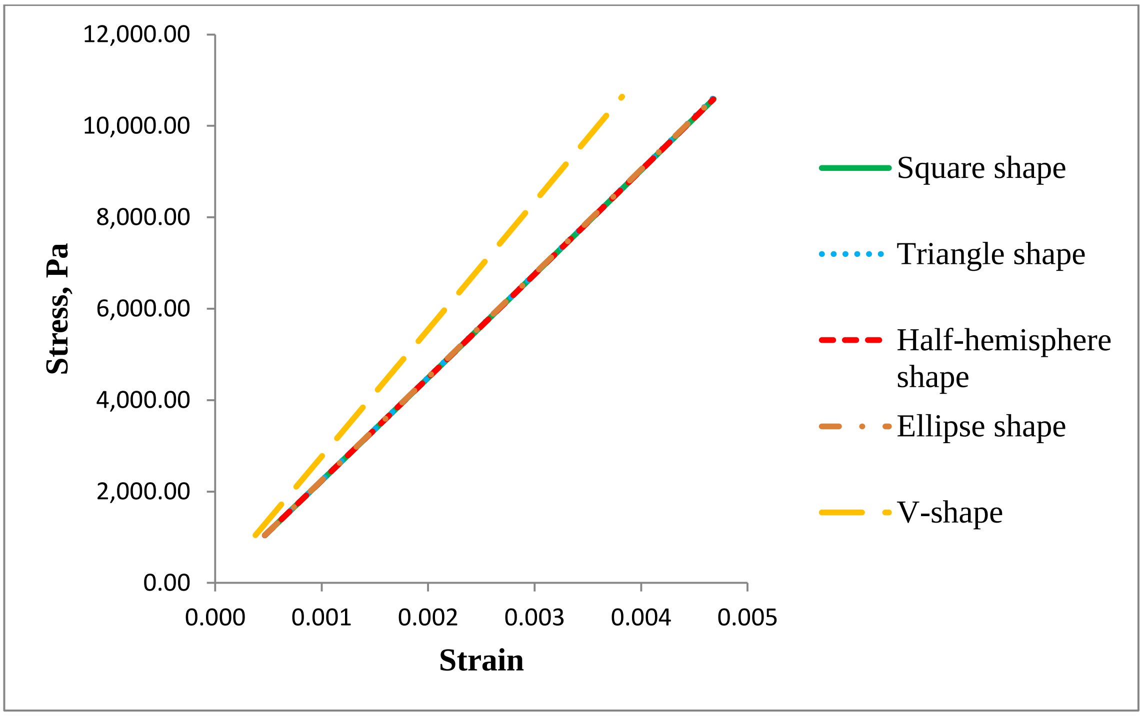


Figure 4.8: Stress versus strain for different shapes of mitral valve at Normal Diastolic Stage (80 mmhg)

Figure 4.8 shown in above represent the graph of stress (Pa) versus strain for different shape of mitral valve at normal diastole condition. From the graph, square shape, triangle shape, half-hemisphere shape and ellipse shape shows that these four shapes having a nearly value in strain during blood pressure applied is 80mmhg, which is 0.004682, 0.00469, 0.004678 and 0.004671 respectively. However, V-shape is slightly less in strain changes during the same stress is applied on it. V-shape has the strain value of 0.003822 which is lower than the others four shapes. The difference of strain between the maximum strain and the minimum strain obtained is around 22.71 %.

The stress versus strain for these five different shapes obtained the same trend. Stress divide by strain is always related to the elasticity value that used during the initial setup in simulation. The value of strain of leaflets is directly proportional to the stress applied on the leaflet for these five shapes. Through the calculation that divides the stress by strain in diastole condition, the value of elasticity was successfully obtained which is almost near to the value of the setup initial. During initial setup of the simulation, the elasticity of valve leaflet was set to a value of 2 MPa. The value of elasticity for square shape, triangle shape, half-hemisphere shape, ellipse shape and V-shape are 2.261 MPa, 2.268 MPa, 2.261 MPa, 2,265 MPa and 2.784 MPa respectively. V-shape had the highest difference in elasticity value obtained when compare to the exact value, which is around 39.2 %.

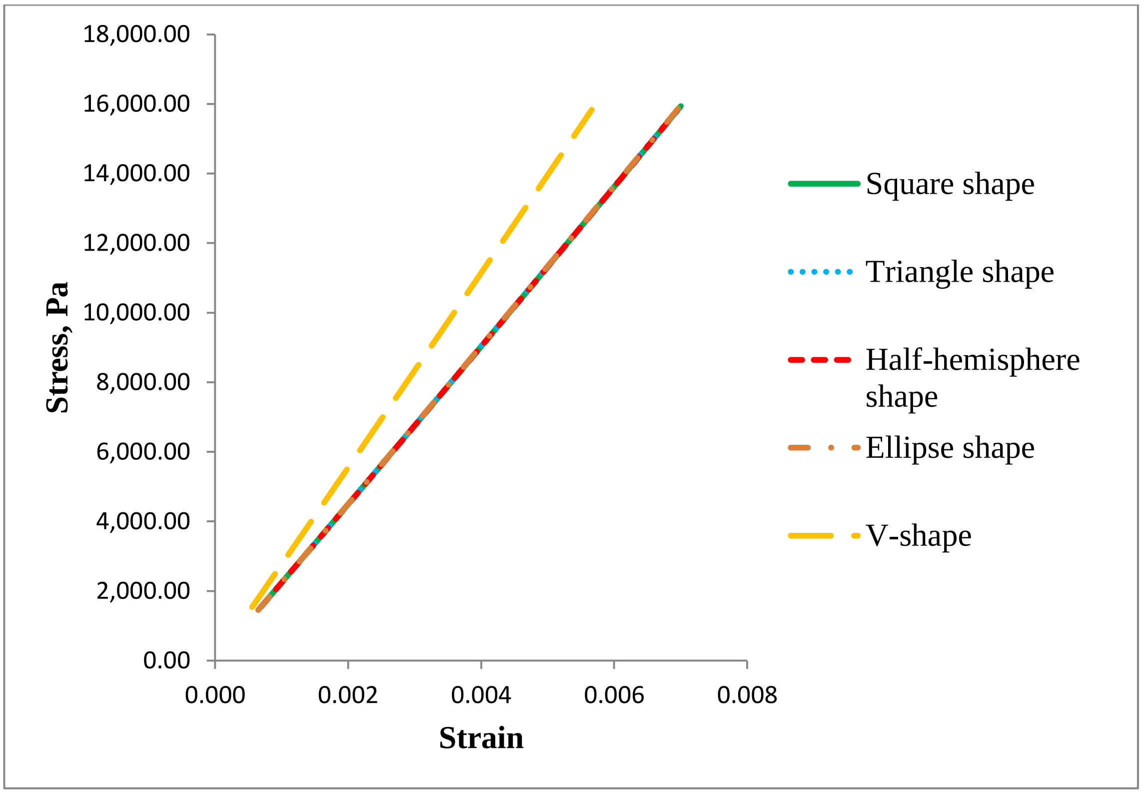


Figure 4.9: Stress versus strain for different shapes of mitral valve at Normal Systolic Stage (120 mmhg)

Figure 4.9 shown in above represent the graph of stress (Pa) versus strain for different shape of mitral valve at normal systole condition. From the graph, square shape, triangle shape, half-hemisphere shape and ellipse shape shows that these four shapes having a nearly value in strain during blood pressure applied is 120mmhg, which is 0.007002, 0.006988, 0.006949, and 0.006999 respectively. However, V-shape is slightly less in strain changes during the same stress is applied on it. V-shape has the strain value of 0.005662 which is lower than the others four shapes. The difference of strain between the maximum strain and the minimum strain obtained is around 23.67 %.

Moreover, the stress versus strain for these five shapes is obtained a same in trend. Stress divide by strain is always related to the elasticity value that used during the initial setup in simulation. The value of strain of leaflets in directly proportional to the stress applied on the leaflet for these five shapes. Through the calculation that divide the stress with strain in diastole condition, we success to obtain the value of elasticity which is almost near to the value that we setup initial. At the initial setup during simulation, the elasticity of valve leaflet was setup in a value of 2 MPa. The value of elasticity for square shape, triangle shape, half-hemisphere shape, ellipse shape and V-shape are 2.276 MPa, 2.278 MPa, 2.276 MPa, 2,279 MPa and 2.796 MPa respectively. V-shape had the highest difference in elasticity value obtained when compare to the exact value, which has around 39.8 %.

4.4 SIMULATION RESULT FOR AORTIC VALVE

4.4.1 Blood Flow Velocity for Aortic Valve at Normal Diastolic Stage (Blood Pressure = 80 mmhg)

i) Square Shape Leaflets

Figure B-101 until B-105 shown in appendix B represents the changes of blood flow velocity when flowing through the square shape of aortic valve leaflets in duration of 1.0 second. From the figure B-101 where the time instant is 0.2 second, the blood is flowing in a velocity value of 0.022165 mm/s. Then at the time instant is 0.6 second shown in figure B-103, the velocity of the blood flow is 0.7331mm/s. At figure B-105, the highest velocity of the blood flow is achieved at a value of 5.059 mm/s at the time instant of 1.0 second is due to highest pressure was applied at that moment. The pressure used to apply in pushing the blood flows can be determined from the background colour in the image. The different background colour means the different pressure condition applied in aortic valve. The different pressure is applied in the simulation by increasing proportionally from initially until the end of 1.0 second duration. This increment of the pressure applied over the time will purposely to result the deformation of valve leaflet.

ii) Triangle Shape Leaflets

Appendix B of Figure B-106 until B-110 shows the changes of blood flow velocity when flowing through the triangle shape of aortic valve leaflets for the duration of 1.0 second. In figure B-106 when the time instant is 0.2 second, the blood is flowing at a velocity value of 8.891 mm/s. Then at the time instant of 0.6 second shown in figure B-108, the velocity of blood flow is 32.87 mm/s. In figure B-110, the highest velocity of the blood flow is achieved where the value is 64.85 mm/s at the time instant of 1.0 second. The pressure used to apply in pushing the blood flows can be determined from the background colour in the image. The different background colour means the different pressure condition in the aortic valve.

iii) Half-Hemisphere Shape Leaflets

For the half-hemisphere shape of aortic valve leaflets, the changes of blood flow velocity when flowing through it in 1.0 second of duration is shown in Figure B-111 until B-115 at appendix B. From the figure B-111 where the time instant is 0.2 second, the blood is flowing in a velocity value of 8.621 mm/s. Then at the time instant is 0.6 second shown in figure B-113, the velocity of blood flow is 20.41 mm/s. At figure B-115, the highest velocity of the blood is achieved at a value of 29.74 mm/s at the time instant of 1.0 second. The pressure used to apply to push the blood flows can be determined from the background colour in the image. The different background colour means the different pressure condition in aortic valve.

iv) Ellipse Shape Leaflets

The changes of blood flow velocity when flowing through the ellipse shape of aortic valve leaflets in 1.0 second of duration is shown in Figure B-116 until B-120 at appendix B. From the figure B-116 where the time instant is 0.2 second, the blood is flowing in a velocity value of 4.337 mm/s. Then at the time instant is 0.6 second shown in figure B-118, the velocity of blood flow is 30.67 mm/s. At figure B-120, the highest velocity of the blood is achieved at a value of 54.43 mm/s at the time instant of 1.0 second. The pressure used to apply to push the blood flows can be determined from the background colour in the image. The different background colour means the different pressure condition in the aortic valve.

v) V-Shape Leaflets

Meanwhile the Figure B-121 until B-125 shown in appendix B represents the changes of blood velocity when flowing through the V-shape of aortic valve leaflets in 1.0 second of duration. From the figure B-121 where the time instant is 0.2 second, the blood is flowing in a velocity value of 3.585 mm/s. Then at the time instant is 0.6 second shown in figure B-123, the velocity of blood flow is 33.23 mm/s.. At figure B-125, the highest velocity of the blood is achieved at a value of 49.19 mm/s at the time instant of 1.0 second. The pressure used to apply to push the blood flows can be determined from the background colour in the image. The different background colour means the different pressure condition in the aortic valve.

4.4.2 Blood Flow Velocity for Aortic Valve at Normal Systolic Stage (Blood Pressure = 120 mmhg)

i) Square Shape Leaflets

Figure B-126 until B-130 shown in appendix B represents the changes of blood flow velocity when flowing through the square shape of aortic valve leaflets in duration of 1.0 second. From the figure B-126 where the time instant is 0.2 second, the blood is flowing in a velocity value of 0.0679 mm/s. Then at the time instant is 0.6 second shown in figure B-128, the velocity of the blood flow is 3.244 mm/s. At figure B-130, the highest velocity of the blood flow is achieved at a value of 25.84 mm/s at the time instant of 1.0 second is due to highest pressure was applied at that moment. The pressure used to apply in pushing the blood flows can be determined from the background colour in the image. The different background colour means the different pressure condition applied in aortic valve. The different pressure is applied in the simulation by increasing proportionally from initially until the end of 1.0 second duration. This increment of the pressure applied over the time will purposely to result the deformation of valve leaflet.

ii) Triangle Shape Leaflets

Appendix B of Figure B-131 until B-135 shows the changes of blood flow velocity when flowing through the triangle shape of aortic valve leaflets for the duration of 1.0 second. In figure B-131when the time instant is 0.2 second, the blood is flowing at a velocity value of 13.98 mm/s. Then at the time instant of 0.6 second shown in figure B-133, the velocity of blood flow is 64.82 mm/s. In figure B-135, the highest velocity of the blood flow is achieved where the value is 92.36 mm/s at the time instant of 1.0 second. The pressure used to apply in pushing the blood flows can be determined from the background colour in the image. The different background colour means the different pressure condition in the aortic valve.

iii) Half-Hemisphere Shape Leaflets

For the half-hemisphere shape of aortic valve leaflets, the changes of blood flow velocity when flowing through it in 1.0 second of duration is shown in Figure B-136 until B-140 at appendix B. From the figure B-136 where the time instant is 0.2 second, the blood is flowing in a velocity value of 12.07 mm/s. Then at the time instant is 0.6 second shown in figure B-138, the velocity of blood flow is 27.12 mm/s. At figure B-140, the highest velocity of the blood is achieved at a value of 62.86 mm/s at the time instant of 1.0 second. The pressure used to apply to push the blood flows can be determined from the background colour in the image. The different background colour means the different pressure condition in aortic valve.

iv) Ellipse Shape Leaflets

The changes of blood flow velocity when flowing through the ellipse shape of aortic valve leaflets in 1.0 second of duration is shown in Figure B-141 until B-145 at appendix B. From the figure B-141 where the time instant is 0.2 second, the blood is flowing in a velocity value of 10.23 mm/s. Then at the time instant is 0.6 second shown in figure B-143, the velocity of blood flow is 51.69 mm/s.

At figure B-145, the highest velocity of the blood is achieved at a value of 77.05 mm/s at the time instant of 1.0 second. The pressure used to apply to push the blood flows can be determined from the background colour in the image. The different background colour means the different pressure condition in the aortic valve.

v) V-Shape Leaflets

Meanwhile the Figure B-146until B-150 shown in appendix B represents the changes of blood velocity when flowing through the V-shape of aortic valve leaflets in 1.0 second of duration. From the figure B-146 where the time instant is 0.2 second, the blood is flowing in a velocity value of 12.29 mm/s. Then at the time instant is 0.6 second shown in figure B-148, the velocity of blood flow is 48.65 mm/s. At figure B-150, the highest velocity of the blood is achieved at a value of 67.35 mm/s at the time instant of 1.0 second. The pressure used to apply to push the blood flows can be determined from the background colour in the image. The different background colour means the different pressure condition in the aortic valve.

4.4.3 Velocity of Blood Flow for Aortic Valve at Normal Diastolic Stage (80 mmhg) and Normal Systolic Stage (120 mmhg)

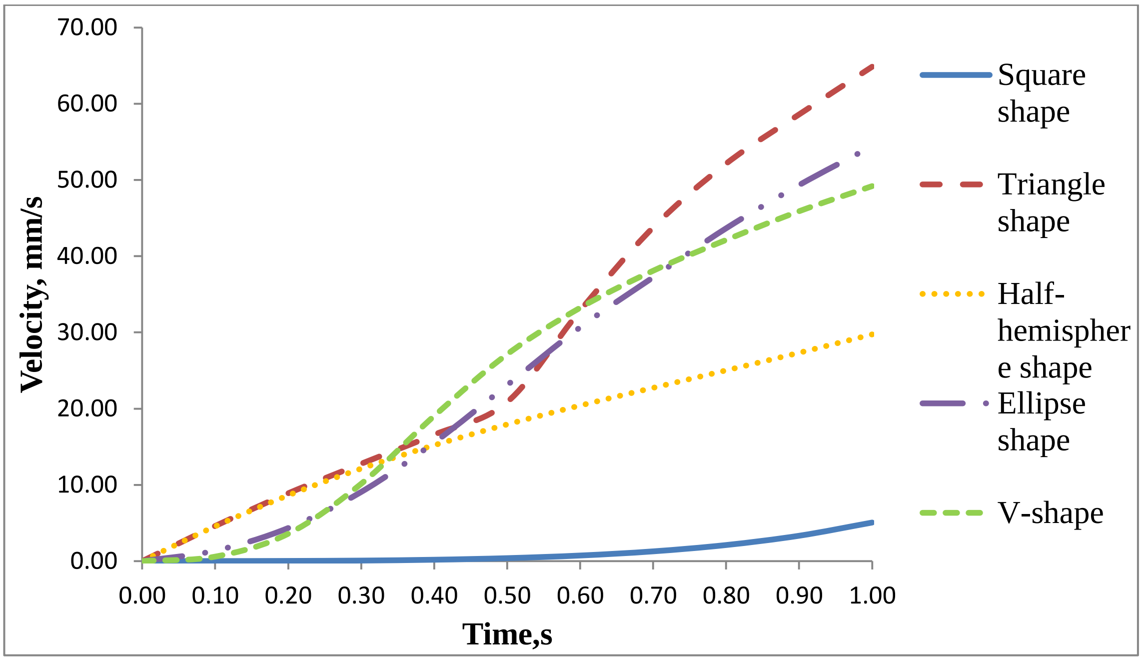


Figure 4.10: Velocity of blood flow for different shapes versus time at Normal Diastolic stage (80 mmhg)

In Figure 4.10, the graph of velocity (mm) versus time (second) in diastole condition with different shape of aortic leaflets was plotted. From the result obtained, triangle shape has the highest velocity performance which is around 64.85 mm/s compares to others four shapes. The velocity performance is following by the ellipse shape and V-shape which have a value of 54.43 mm/s and 49.19 mm/s respectively. Besides, half-hemisphere has a velocity value of 20.74 mm/s. Square shape has the lowest velocity performance where is only 5.05863 mm/s and this occurred may hugely related to its displacement change during opening. Small displacement changes in opening may block the path of blood to flow. By compare with the maximum and minimum value obtained, there are nearly 92.2 percentage of value difference in velocity changes between the triangle shape and square shape.

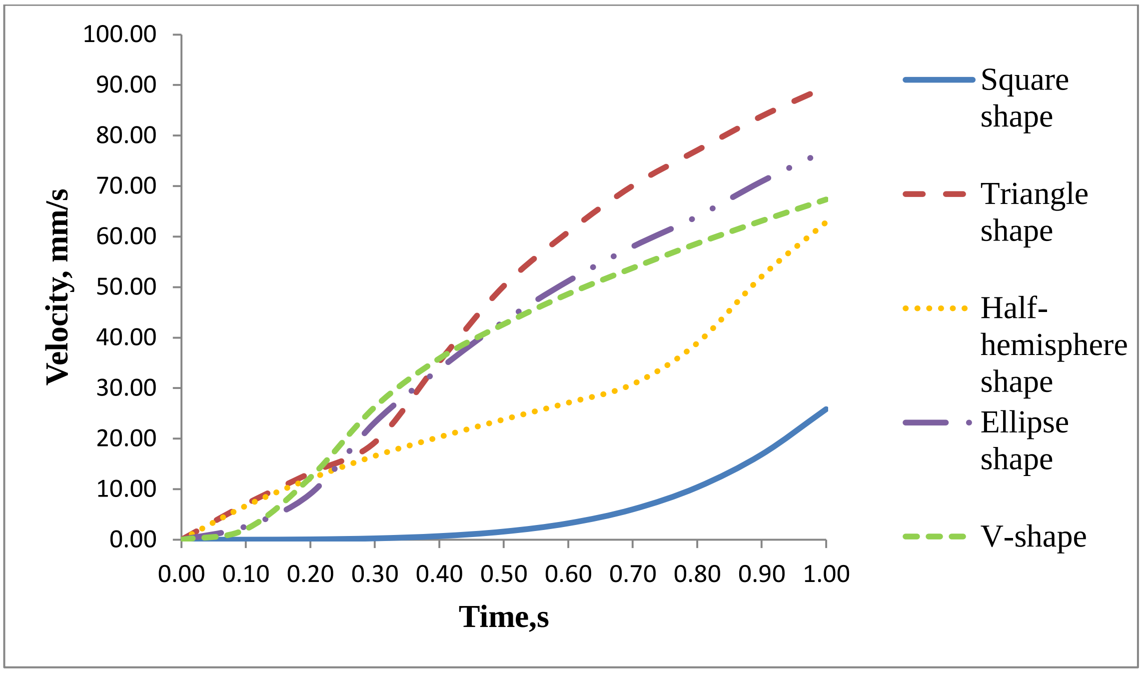


Figure 4.11: Velocity of blood flow for different shapes versus time at Normal Systolic stage (120 mmhg)

In Figure 4.11, the graph of velocity (mm/s) versus time (second) in systole condition with different shape of aortic leaflets was plotted. From the result obtained, triangle shape has the highest velocity performance which is around 89.65 mm/s compares to others four shapes. The velocity performance is following by the ellipse shape and V-shape which have a value of 77.06 mm/s and 67.35 mm/s respectively. Next, half-hemisphere shape has a value of 62.85 mm/s of velocity. Square shape has the lowest velocity performance where is 25.8406 mm/s and this occurred may hugely related to its displacement change during opening. Small displacement changes in opening may block the path of blood to flow. By compare with the maximum and minimum value obtained, there are nearly 71.2 percentage of value difference in velocity changes between the triangle shape and square shape.

Furthermore, the velocity result obtained from simulation show that triangle shape obtained the highest velocity while square shape obtained the lowest velocity. The result of the velocity of fluid obtained could be related to the displacement changes of the leaflets. The opening of the leaflets will influence the fluid flow velocity. In this simulation, the velocity result obtained shows the value of velocity in the condition of constant pressure is applied varies with time. Therefore, the results of velocity shown could be explained by using Newton's second law of motion where force is equal to the mass times velocity of the motion. In Newton's second law of motion, it could explain where the acceleration produced by the force acting on the body is directly proportional to the magnitude of the force for a constant mass object (Shipman, 2009). Acceleration is used to define as the change of rate for velocity motion. By this, the concept in Newton's second law of motion could derive into another form of relationship. It shows the relationship of the velocity motion of the body is directly proportional to the motive force applied on it.

In the fundamental of pressure law, pressure is equals to force divided by surface area. The surface area mentioned here is pointed to the cross section area of the blood flow during the valve opening. In order to get a higher cross section area, the behaviour of the leaflets displacement changes should be higher. Thus, the blood flow cross section area is directly proportional to the displacements changes of leaflets. Higher displacements changes will lead to higher crossing surface area of blood flow. At the condition where constant pressure and mass is applied, a conclusion that the changes of blood velocity are related with the changes in leaflets displacement could be made. Hence, higher displacement in leaflets opening will result in the fluid to flow at higher velocity.

4.4.4 The Leaflet's Displacement for Aortic Valve at Normal Diastolic Stage (Blood Pressure = 80 mmhg)

i) Square Shape Leaflets

Figure B-151 until B-155 shown in appendix B represents the displacement changes of square shape leaflet under deformation in duration of 1.0 second. From the figure B-151 where the time instant is 0.2 second, the displacement change of the leaflet is 0.2772 mm. Then at the time instant is 0.6 second shown in figure B-153, the displacement changes of the leaflet are increased to 0.8322 mm. At figure B-155, the change of leaflet displacement is reached to the maximum value which has a value of 1.389 mm at the time instant of 1.0 second is due to highest pressure was applied at that moment. The pressure used to apply in pushing the blood flows can be determined from the background colour in the image. The different background colour means the different pressure condition in the aortic valve. The different pressure is applied in the simulation by increasing proportionally from initially until the end of 1.0 second duration. This increment of the pressure applied over the time will purposely to result the deformation of valve leaflet.

ii) Triangle Shape Leaflets

Appendix B of Figure B-156 until B-160 shows the displacement changes of triangle shape leaflet under deformation for the duration of 1.0 second. In figure B-156 when the time instant is 0.2 second, the leaflet displacement change is 0.9124 mm. Then at the time instant of 0.6 second shown in figure B-158, the leaflet displacement changes are increased to 2.563 mm. In figure B-160, the change of displacement is reached to the maximum with a value of 3.844 mm at the time instant of 1.0 second. The pressure used to apply in pushing the blood flows can be determined from the background colour in the image. The different background colour means the different pressure condition in the aortic valve.

iii) Half-Hemisphere Shape Leaflets

For the half-hemisphere shape of aortic valve leaflets, the displacement change of leaflet under deformation in 1.0 second of duration is shown in Figure B-161 until B-165 at appendix B. From the figure B-161 where the time instant is 0.2 second, the leaflet displacement change is 0.3887 mm. Then at the time instant is 0.6 second shown in figure B-163, the leaflet displacement changes are increased to 1.147 mm. At figure B-165, the change of leaflet displacement is reached to the maximum with a value of 1.885 mm at the time instant of 1.0 second. The pressure used to apply to push the blood flows can be determined from the background colour in the image. The different background colour means the different pressure condition in the aortic.

iv) Ellipse Shape Leaflets

The leaflet displacement change of ellipse shape leaflet under deformation in 1.0 second of duration is shown in Figure B-166 until B-170 at appendix B. From the figure B-166 where the time instant is 0.2 second, the leaflet displacement change is 0.4417 mm. Then at the time instant is 0.6 second shown in figure B-168, the leaflet displacement changes are increased to 1.296 mm. At figure B-170, the change of leaflet displacement is reached to the maximum with a value of 2.025 mm at the time instant of 1.0 second. The pressure used to apply to push the blood flows can be determined from the background colour in the image. The different background colour means the different pressure condition in the aortic valve.

v) V-Shape Leaflets

Meanwhile the Figure B-171until B-175 shown in appendix B represents the displacement changes of V-shape leaflet under deformation in 1.0 second of duration. From the figure B-171 where the time instant is 0.2 second, the leaflet displacement change is 0.5592 mm. Then at the time instant is 0.6 second shown in figure B-173, the leaflet displacement changes are increased to 1.624 mm. At figure B-175, the change of leaflet displacement is reached to the maximum with a value of 2.439 mm at the time instant of 1.0 second. The pressure used to apply to push the blood flows can be determined from the background colour in the image. The different background colour means the different pressure condition in aortic valve.

4.4.5 The Leaflet's Displacement for Aortic Valve at Normal Systolic Stage (Blood Pressure = 120 mmhg)

i) Square Shape Leaflets

Figure B-176 until B-180 shown in appendix B represents the displacement changes of square shape leaflet under deformation in duration of 1.0 second. From the figure B-176 where the time instant is 0.2 second, the displacement change of the leaflet is 0.4133 mm. Then at the time instant is 0.6 second shown in figure B-178, the displacement changes of the leaflet are increased to 1.242 mm. At figure B-180, the change of leaflet displacement is reached to the maximum value which has a value of 2.084 mm at the time instant of 1.0 second is due to highest pressure was applied at that moment. The pressure used to apply in pushing the blood flows can be determined from the background colour in the image. The different background colour means the different pressure condition in the aortic valve. The different pressure is applied in the simulation by increasing proportionally from initially until the end of 1.0 second duration. This increment of the pressure applied over the time will purposely to result the deformation of valve leaflet.

ii) Triangle Shape Leaflets

Appendix B of Figure B-181 until B-185 shows the displacement changes of triangle shape leaflet under deformation for the duration of 1.0 second. In figure B-181 when the time instant is 0.2 second, the leaflet displacement change is 1.483 mm. Then at the time instant of 0.6 second shown in figure B-183, the leaflet displacement changes are increased to 3.801 mm. In figure B-185, the change of displacement is reached to the maximum with a value of 5.325 mm at the time instant of 1.0 second. The pressure used to apply in pushing the blood flows can be determined from the background colour in the image. The different background colour means the different pressure condition in the aortic valve.

iii) Half-Hemisphere Shape Leaflets

For the half-hemisphere shape of aortic valve leaflets, the displacement change of leaflet under deformation in 1.0 second of duration is shown in Figure B-186 until B-190 at appendix B. From the figure B-186 where the time instant is 0.2 second, the leaflet displacement change is 0.5772 mm. Then at the time instant is 0.6 second shown in figure B-188, the leaflet displacement changes are increased to 1.688 mm. At figure B-190, the change of leaflet displacement is reached to the maximum with a value of 2.753 mm at the time instant of 1.0 second. The pressure used to apply to push the blood flows can be determined from the background colour in the image. The different background colour means the different pressure condition in the aortic.

iv) Ellipse Shape Leaflets

The leaflet displacement change of ellipse shape leaflet under deformation in 1.0 second of duration is shown in Figure B-191 until B-195 at appendix B. From the figure B-191 where the time instant is 0.2 second, the leaflet displacement change is 0.7101 mm. Then at the time instant is 0.6 second shown in figure B-193, the leaflet displacement changes are increased to 1.847 mm. At figure B-195, the change of leaflet displacement is reached to the maximum with a value of 2.826 mm at the time instant of 1.0 second. The pressure used to apply to push the blood flows can be determined from the background colour in the image. The different background colour means the different pressure condition in the aortic valve.

v) V-Shape Leaflets

Meanwhile the Figure B-196 until B-200 shown in appendix B represents the displacement changes of V-shape leaflet under deformation in 1.0 second of duration. From the figure B-196 where the time instant is 0.2 second, the leaflet displacement change is 0.9199 mm. Then at the time instant is 0.6 second shown in figure B-198, the leaflet displacement changes are increased to 2.402 mm. At figure B-200, the change of leaflet displacement is reached to the maximum with a value of 3.575 mm at the time instant of 1.0 second. The pressure used to apply to push the blood flows can be determined from the background colour in the image. The different background colour means the different pressure condition in aortic valve.

4.4.6 Displacement Changes of Leaflets for Aortic Valve at Normal Diastolic Stage (80 mmhg) and Normal Systolic Stage (120 mmhg)

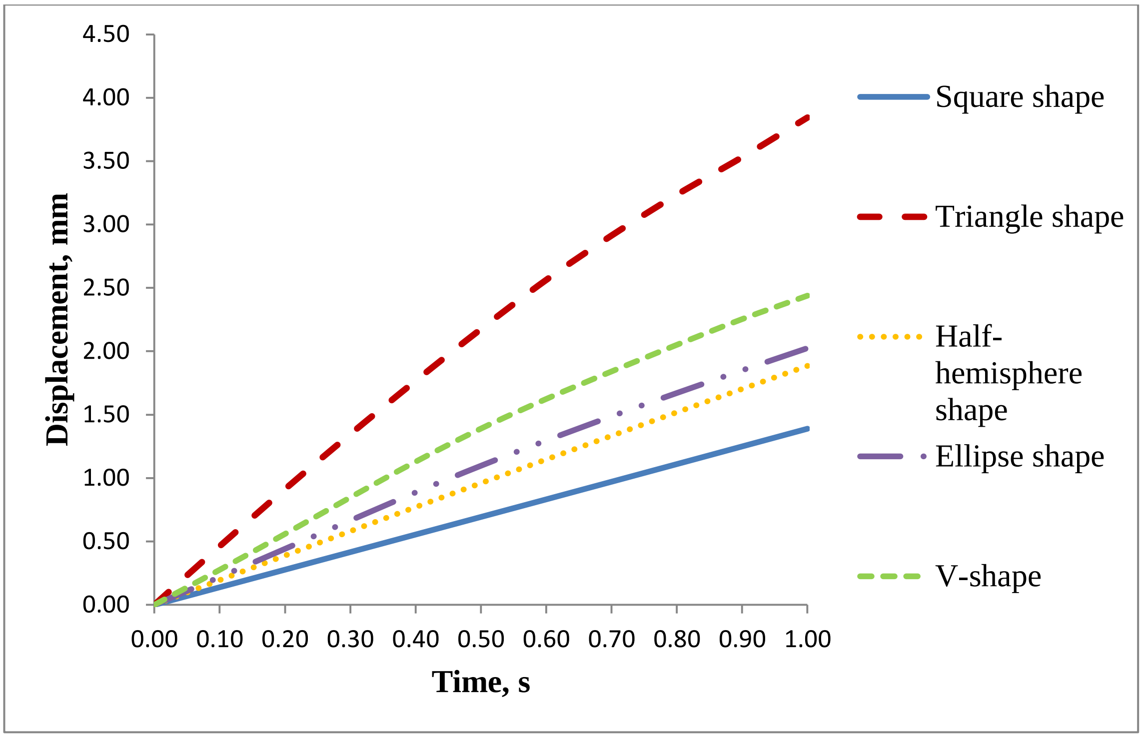


Figure 4.12: Displacement changes of leaflets for different shape versus time at Normal Diastolic stage (80 mmhg)

Figure 4.12 shown in above represented the result of displacement (mm) versus time (second) in diastole condition with five different shapes of aortic leaflets. It shows that the displacement of leaflet is directly proportional to the time since the value of normal traction applied on the leaflets is increasing during the time period is increasing. The triangle shape of leaflet has the highest value of displacement change in diastole condition which is around 3.844 mm whereas the square shape of leaflet has the lowest value around 1.38923 mm of displacement change. There is an approximately 64 percentage of difference between the maximum and the minimum displacement changes.

Besides the triangle shape, it is followed by shape V-shape, ellipse shape and half-hemisphere for the displacement changes and which is 2.439 mm, 2.025 mm and 1.885 mm respectively.

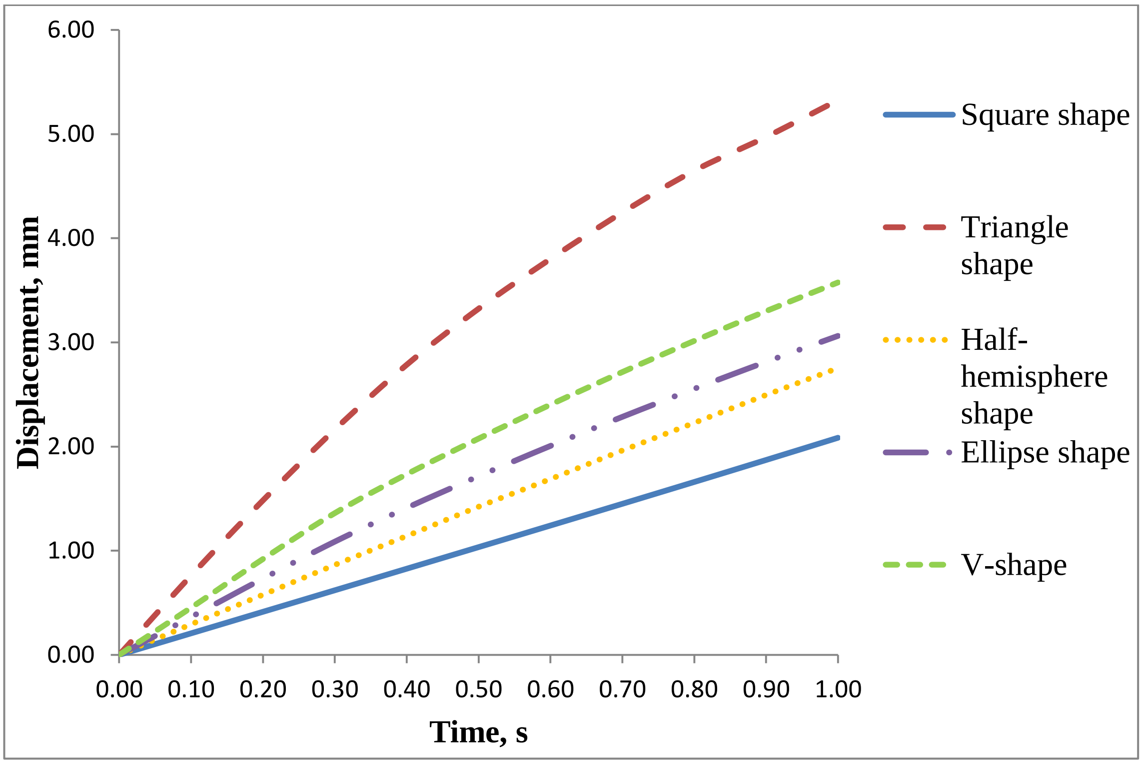


Figure 4.13: Displacement changes of leaflets for different shapes versus time at Normal Systolic stage (120 mmhg)

Fig 4.13 shown in above represented the result of displacement (mm) versus time (second) in systole condition with five different shapes of aortic leaflets. It shows that the displacement of leaflet is directly proportional to the time since the value of normal traction applied on the leaflets is increasing during the time period is increasing. The triangle shape of leaflet has the highest value of displacement change in systolic condition which is around 5.325 mm whereas the square shape of leaflet has the lowest value around 2.08393 mm of displacement change. There is an approximately 61 percentage of difference between the maximum and the minimum displacement changes.

Besides the triangle shape and square shape, the displacement changes is followed by V-shape, ellipse shape and half-hemisphere shape which is 3.575 mm , 3.062 mm and 2.753 mm respectively. There is approximately 14.3 percentage of difference between V-shape with ellipse shape and nearly 23 percentage different to half-hemisphere.

For the displacement result obtained for aortic valve with five different shape, the result for the maximum and minimum is same as mitral valve where triangle shape have the highest displacement changes while square shape have the lowest changes. The reasons to explain this phenomenon occurred is same as occur in mitral valve where the thickness of the end of leaflets is not same by compare with square shape and triangle shape. However, the displacement changes for half-hemisphere shape, ellipse shape and V-shape is not nearly same in value as in the mitral valve. V-shape show higher changes than ellipse shape and after ellipse shape is followed by half-hemisphere shape.

4.4.7 Force versus Displacement for Aortic Valve at Normal Diastolic Stage (80 mmhg) and Normal Systolic Stage (120 mmhg)

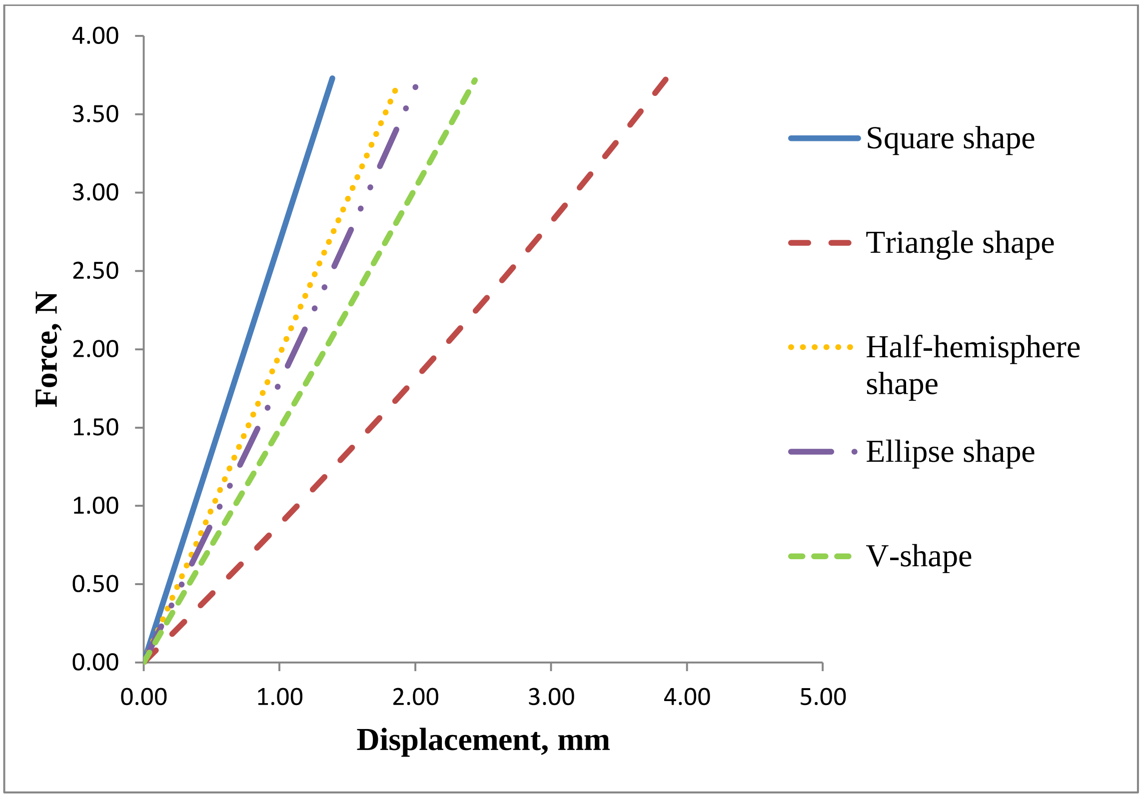


Figure 4.14: Force versus displacement for different shapes of aortic valve at Normal Diastolic stage (80 mmhg)

Figure 4.14 shows the relationship between the forces (N) with the displacement (mm) for the five different shapes of aortic valve leaflets in normal diastolic condition. It shows that the force applied is directly proportional to the displacement of leaflet. Higher normal traction applied on the leaflets, leaflet is more in opening and higher displacement result obtained. When a certain amount of force is applied, triangle shape shows that it has the highest displacement. The value of force applied is in a range of 3.71 N until 3.73 N. The force value is calculated by applied the fundamental of pressure theory where pressure is equal to the force times the area. By applied a constant area for the normal valve opening with the value of 4.5 cm^2, the force applied on the leaflets could be calculated. Besides the triangle shape, it follow by half-hemisphere shape, ellipse shape and V-shape show orderly in displacement changes if same amount force is applied. Square shape shows that it has the hardest the have displacement changes by compare to these others four shapes.

Furthermore, from the result obtained in graph for force versus displacement, its shows that square shape required higher force to make a displacement changes compare to triangle shape required smaller force. The value of force required is obtained by applied a constant normal cross section area by multiple with the pressure applied. In a constant cross section area, it is highly depends on the displacements changes of the leaflets. Since square shape leaflet's behaviour is difficult to have changes in displacement, therefore is needs a lot of force applying to make it have higher displacements changes and so do having to the constant normal cross section area at a constant pressure situation. The constant pressure mentioned is the normal diastolic stage where 80 mmhg is applied and the constant normal cross section area is 3.5 cm^2 is referred from Gaasch et al (2012). Triangle shape which is easily to deform and changes in displacement of leaflet required a small value of force to achieve the constant normal cross section area. For the others three shapes which is V-shape, ellipse shape and half-hemisphere shape, since they are almost same in performance in displacement result, therefore to obtain in nearly same cross section area the force required will also almost same in value.

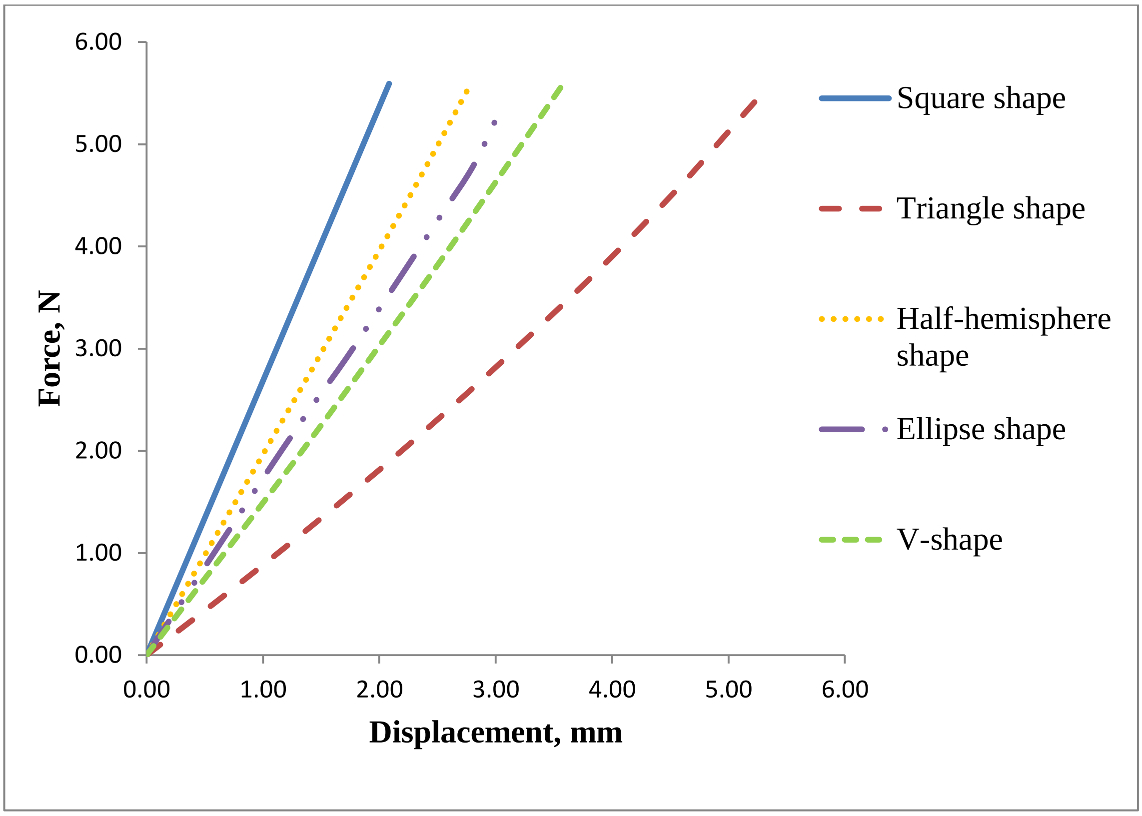


Figure 4.15: Force versus displacement for different shapes of aortic valve at Normal Systolic stage (120 mmhg)

The relationship for the five different shapes of leaflet between the force (N) and displacement (mm) is shown in above Figure 4.15. The result shown is represented the blood condition under the normal systole condition where 120 mmhg is applied at the condition. The result of relation obtained is same as the relationship obtained for diastole condition. Square shape still possessed the hardest to displacement changes whereas the triangle shape is the simplest shape. Behind the square shape, it follow by half-hemisphere shape, ellipse shape and V-shape orderly for the difficulty of displacement changes. Higher normal traction applied on the leaflets, leaflet is more in opening and higher displacement result obtained. When a certain amount of force is applied, triangle shape shows that it has the highest displacement. The value of force applied is in a range of 5.39 N until 5.59 N. The force value is calculated by applied the fundamental of pressure theory where pressure is equal to the force times the area. By applied a constant area for the normal valve opening with the value of 4.5 cm^2, the force applied on the leaflets could be calculated. Besides the triangle shape, it follow by half-hemisphere shape, ellipse shape and V-shape show orderly in displacement changes if same amount force is applied. Square shape shows that it has the hardest the have displacement changes by compare to these others four shapes.

Furthermore, from the result obtained in graph for force versus displacement, its shows that square shape required higher force to make a displacement changes compare to triangle shape required smaller force. The value of force required is obtained by applied a constant normal cross section area by multiple with the pressure applied. In a constant cross section area, it is highly depends on the displacements changes of the leaflets. Since square shape leaflet's behaviour is difficult to have changes in displacement, therefore is needs a lot of force applying to make it have higher displacements changes and so do having to the constant normal cross section area at a constant pressure situation. The constant pressure mentioned is the normal systolic stage where 120 mmhg is applied and the constant normal cross section area is 3.5 cm^2 which is referred from Gaasch et al (2012). Triangle shape which is easily to deform and changes in displacement of leaflet required a small value of force to achieve the constant normal cross section area. For the others three shapes which is V-shape, ellipse shape and half-hemisphere shape, since they are almost same in performance in displacement result, therefore to obtain in nearly same cross section area the force required will also almost same in value.

4.4.8 Result of Stress versus Strain for Different Shapes of Aortic Valve at Normal Diastolic Stage (80 mmhg) and Normal Systolic Stage (120 mmhg)

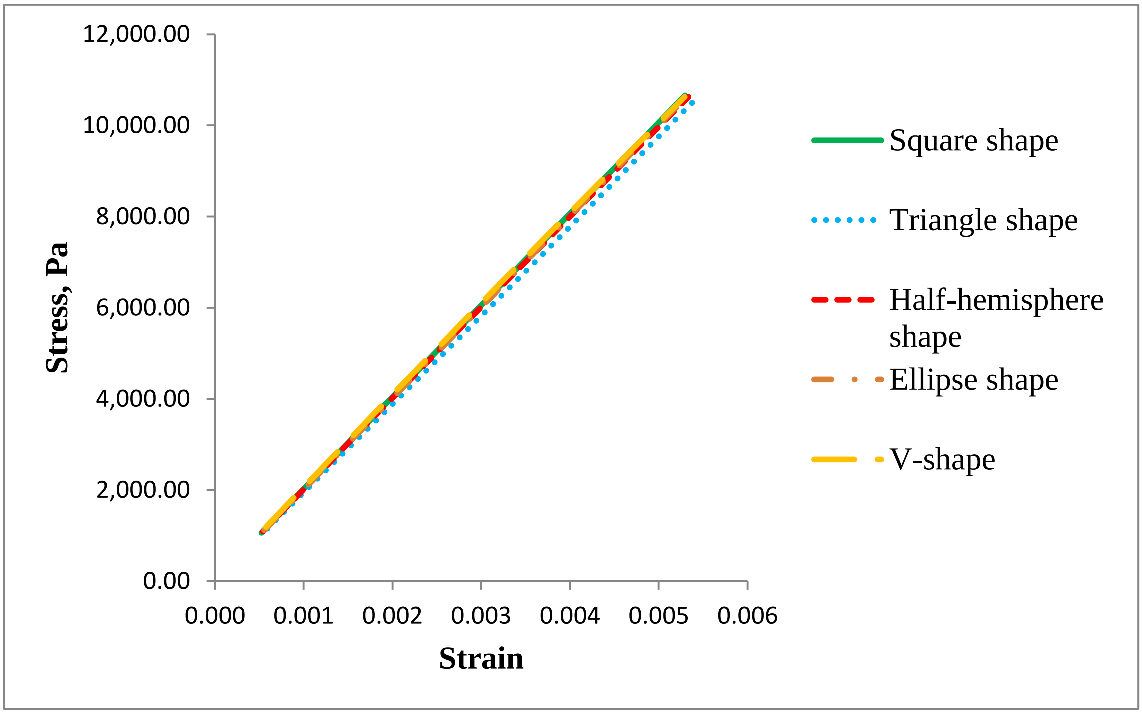


Figure 4.16: Stress versus strain for different shapes of aortic valve at Normal Diastolic Stage (80 mmhg)

Figure 4.16 shown in above represent the graph of stress (Pa) versus strain for different shape of aortic valve at normal diastole condition. From the graph, square shape, triangle shape, half-hemisphere shape, ellipse shape and V-shape shows that these five shapes having a nearly value in strain during blood pressure applied is 80 mmhg, which is 0.005297, 0.005449, 0.005335, 0.005317 and 0.005293 respectively. In addition, the stress versus strain result obtained in aortic valve for these five shapes is same in trend and almost same in value when same amount of pressure is applied. The value of strain of leaflets in directly proportional to the stress applied on the leaflet. However, there are slightly different when compare with the obtained in mitral valve where the V-shape has slightly difference compare to the others four shape in mitral valve. In aortic, V-shape is performing as the others four shapes.

When applied the concept of elasticity, the divide of stress to the strain is related equal as the elasticity. At the initial setup during simulation, the elasticity of valve leaflet was setup in a value of 2 MPa. Through the calculation that divide the stress with strain for diastole condition, we success to obtain the value of elasticity which is almost near to the value that we setup initial. The value of elasticity for square shape, triangle shape, half-hemisphere shape, ellipse shape and V-shape are 2.012 MPa, 1.952 MPa, 1.991 MPa, 1.999 MPa and 2.007 MPa respectively. Triangle shape had the highest difference in elasticity value obtained when compare to the exact value, which has around 2.46 % in difference. This result could prove that the velocity and displacement result obtained is verified at the condition of elasticity value that we setup.

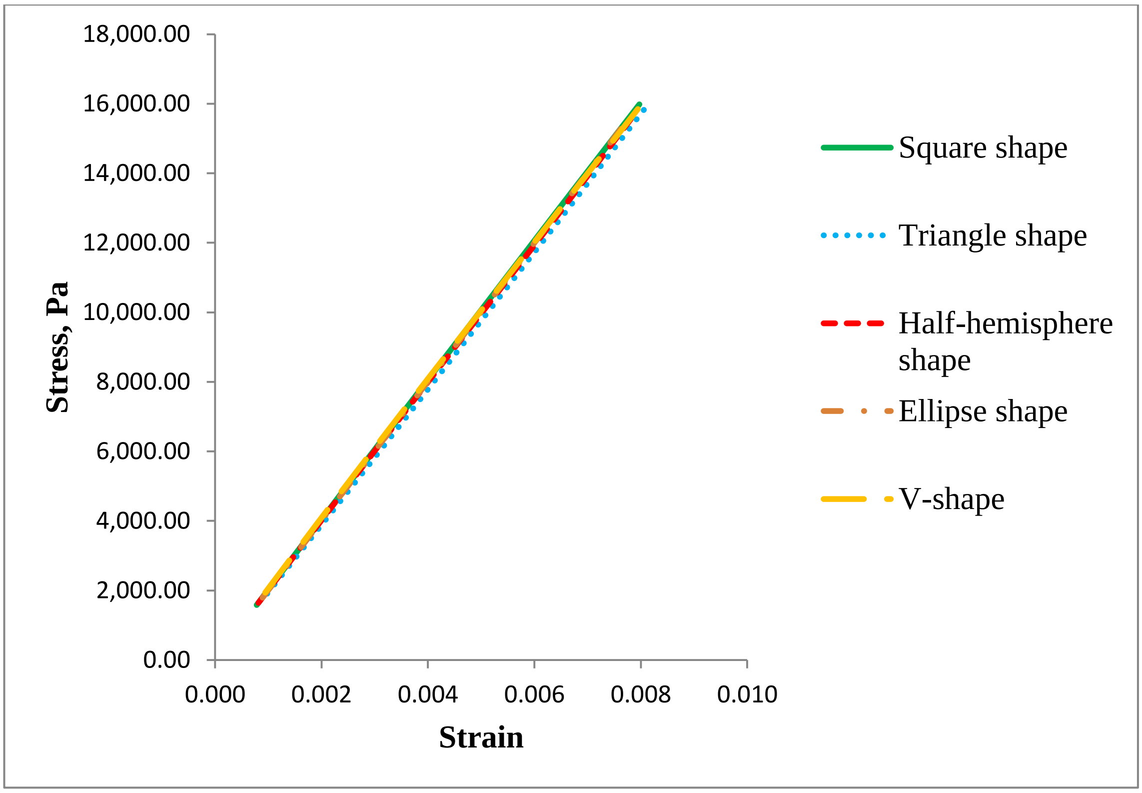


Figure 4.17: Stress versus strain for different shapes of aortic valve at Normal Systolic Stage (120 mmhg)

Figure 4.17 shown in above represent the graph of stress (Pa) versus strain for different shape of aortic valve at normal systole condition. From the graph, square shape, triangle shape, half-hemisphere shape, ellipse shape and V-shape shows that these five shapes having a nearly value in strain during blood pressure applied is 120 mmhg, which is 0.007973, 0.008065, 0.007923, 0.007684 and 0.008001 respectively. In addition, the stress versus strain result obtained in aortic valve for these five shapes is same in trend and almost same in value when same amount of pressure is applied. The value of strain of leaflets in directly proportional to the stress applied on the leaflet. The relationship of result for aortic valve obtained in systole condition is same as in diastole condition. There are also no differences for V-shape when compare to the others four shapes and not like the occurred in mitral valve. In aortic, V-shape is performing as the others four shapes performances.

When applied the concept of elasticity, the divide of stress to the strain is related equal as the elasticity. At the initial setup during simulation, the elasticity of valve leaflet was setup in a value of 2 MPa. Through the calculation that divide the stress with strain in systole condition, we success to obtain the value of elasticity which is almost near to the value that we setup initial. The value of elasticity for square shape, triangle shape, half-hemisphere shape, ellipse shape and V-shape are 2.004 MPa, 1.964 MPa, 1.992 MPa, 2.004 MPa and 1.994 MPa respectively. Triangle shape had the highest difference in elasticity value obtained when compare to the exact value, which has around 1.83 % in difference. This result could prove that the velocity and displacement result obtained is verified at the condition of elasticity value that we setup.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 INTRODUCTION

In this chapter, a conclusion is made by summaries the whole part of this paper study and recommendation in future in order to improve the knowledge obtained from this study will also be explained. By referring the conclusions made in this study, it is related to the objectives targeted initially. Besides that, by referring with the recommendation to this study, scopes and limitation of this study can be improve and enriched in future.

5.2 CONCLUSIONS

In conclusion, FSI simulation on five different shapes of mitral valve and aortic valve which are square shape, triangle shape, half-hemisphere shape, ellipse shape and V-shape was presented this paper. The simulations incorporated the dynamic interaction of blood flow with the leaflet locomotion in the left side of heart, which is mitral valve and aortic valve. The simulation on the mitral valve and aortic valve is performed in separately. For mitral valve, the simulation is performed together with the left ventricle whereas aortic valve is without connected with left ventricle. An explicit coupling procedure was been implanted for the rigid body motion of the mitral valves and blood flow by divide into structure part and fluid part.

All of these five shapes have shown that its own performance result of velocity and displacement result for mitral valve and aortic valve. In critical for mitral valve, triangle shape showed the maximum performance in velocity of blood flow and displacement changes of leaflet whereas square shape showed the minimum performance during 1.0 second of time period. In normal diastolic condition, triangle shape obtained a FSI result of 68.54 mm/s in blood flow velocity and 2.171 mm of leaflets displacement change. While for square shape, it has a FSI result of blood flow velocity and leaflets displacement changes of 1.05776 mm/s and 1.103 mm respectively. In normal systolic condition, the relationship obtained for velocity and displacement changes by the variation of shape is same as normal diastolic condition where triangle shape still owns the highest performances whereas square shape still possessed the minimum performances. From the result obtained, in normal systolic condition triangle shape have a value of 102 mm/s in blood flow velocity and 5.168 mm changes in leaflet displacement while for square shape have a value of 6.521 mm/s in blood flow velocity and 1.242 mm changes in leaflet displacement.

There are same relationship of result obtained in aortic valve when compare with the mitral valve. In general, the trend of relationship between the leaflet with the displacement and velocity performance found in aortic valve is nearly same as found in mitral valve. Triangle shape still showed the maximum performance in velocity of blood flow and displacement changes of leaflet whereas square shape showed the minimum performance. In normal diastolic condition, triangle shape obtained a FSI result of 64.85 mm/s in blood flow velocity and 3.844 mm of leaflets displacement change during 1.0 second of time period. While for square shape, it has a FSI result of blood flow velocity and leaflets displacement changes of 5.05863 mm/s and 1.38923 mm respectively. In the systolic condition, the relationship obtained for velocity and displacement changes by the variation of shape is same as normal diastolic condition where triangle shape still owns the highest performances whereas square shape still possessed the minimum performances during 1.0 second of time period. From the result obtained, in normal systolic condition triangle shape have a value of 89.65 mm/s in blood flow velocity and 5.325 mm changes in leaflet displacement while for square shape have a value of 25.8406 mm/s in blood flow velocity and 2.08393 mm changes in leaflet displacement.

From the FSI result finding in this study, triangle shape has the maximum value in velocity of blood flow and also the leaflets displacement changes. However, in applying the result into reality application cannot just depends on the velocity and displacement result. In general, the prosthesis designs are more preferred in choosing the shape of valve which will result an average value of blood flow velocity and leaflet displacement changes. The high result in blood flow velocity could cause the damage in the left ventricle's muscle while high leaflets displacement changes may also cause the blood backflow occurred. Therefore, triangle shape and square shape is not quite suitable in applying for the design in future prosthetic valve. By this, ellipse shape showed that it has an average performance in velocity of blood flow and leaflets displacement changes which is suitable in applying in future prosthesis design. Ellipse shape is better performance in velocity of blood flow and leaflets displacement changes when compare with the half-hemisphere shape and V-shape.

5.3 RECOMMENDATIONS

In future, to apply the result for the real design in prosthetic valve could not just only depend on the velocity and displacement result. In general, higher velocity of the flow is more prefer since it will bring effect to the ejection efficiency of the left ventricle to the aorta and the whole body. But, the quantity volume of blood flow into the left ventricle could not be too large because it could hurt the muscle of the left ventricle by the increasing pressure inside the left ventricle. It may also cause the mitral valve to be prolapsed too.

For the displacement changes, there are necessary to say that a higher displacement change is better although it will make effect to the velocity of the flow. Sometimes, leaflets which possess a higher displacement changes may be difficult to close properly after the blood is fulfil the left ventricle. This cause the back flow of blood is occurred. Therefore, by control the velocity of flow and displacement changes of leaflet, there are still a lot of reasons and factors must be consider before apply the design of shape into the real life application.

By this, in future further study, the model of the different shape could be applied in three-dimensional model for a more nearly flow and near to reality result could be obtained. By related the different of the shapes of leaflet together investigated with the other medical important issue before apply in real design.

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APPENDIX A

SIMULATION PROCEDURES

1. ADINA-FSI

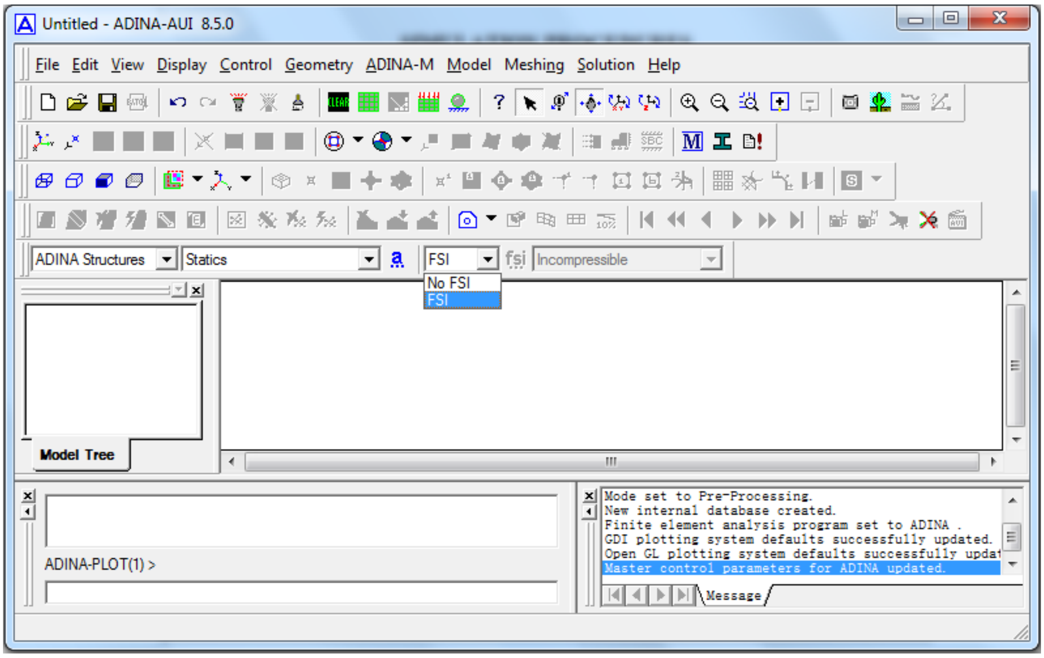

Figure A-1: FSI structure setting

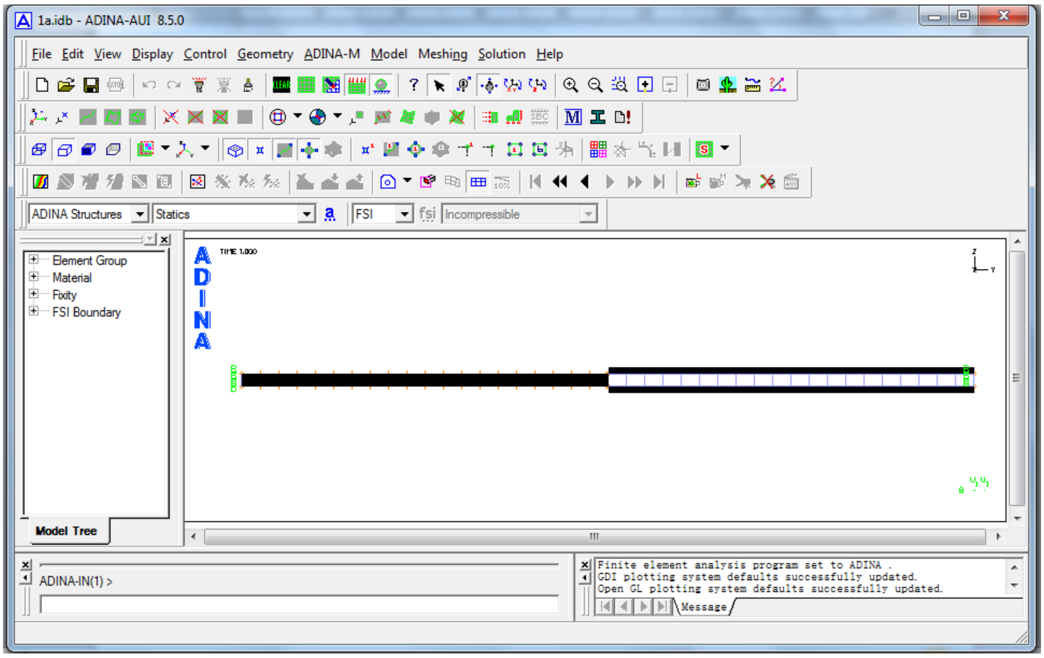

Figure A-2: Design 2D structure (mitral valve)

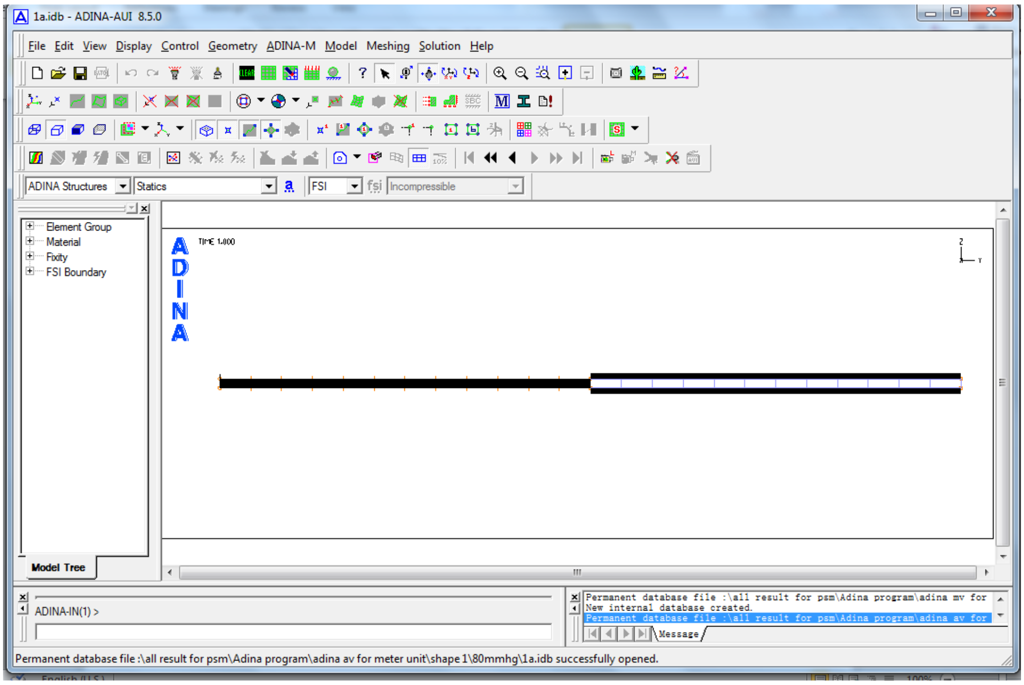

Figure A-3: Design 2D structure (aortic valve)

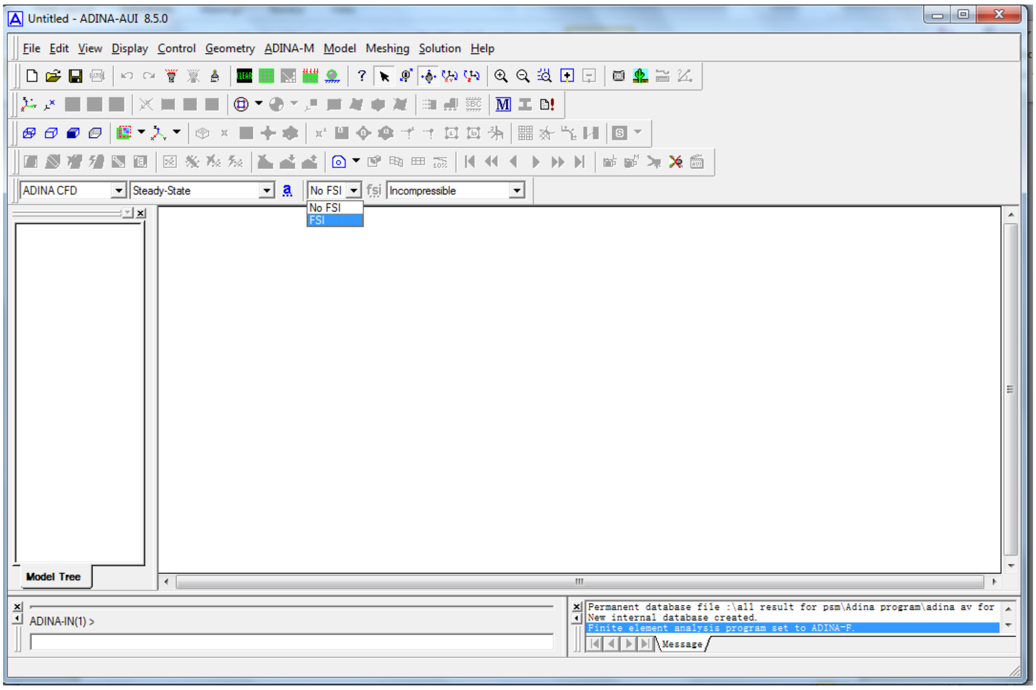

Figure A-4: FSI fluids setting

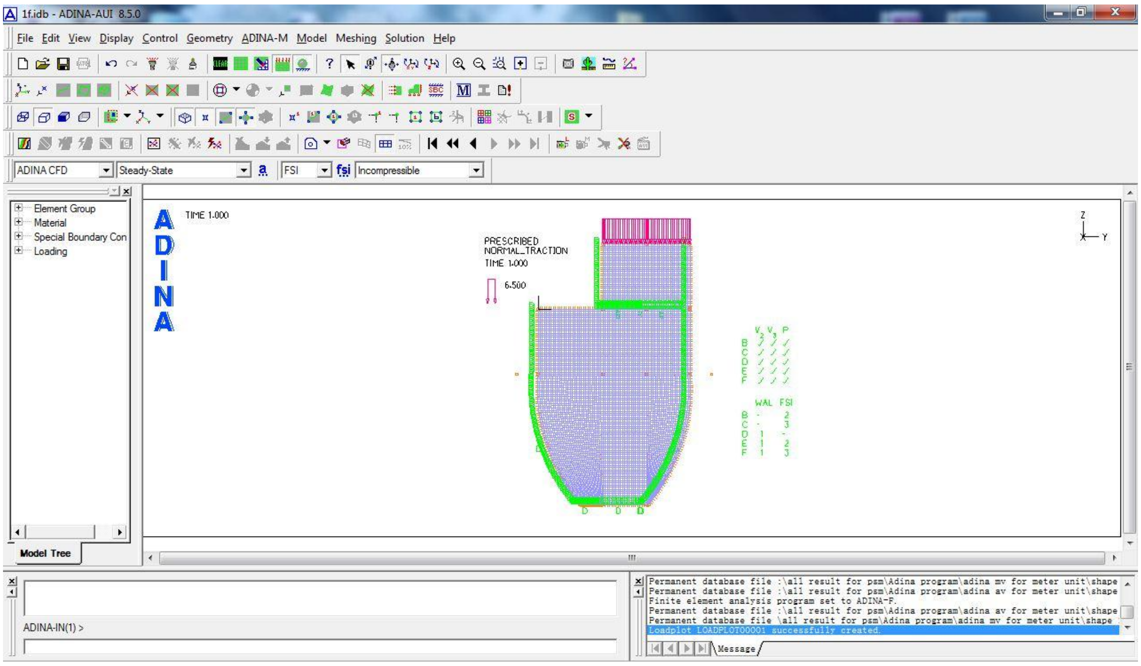

Figure A-5: Design 2D fluids (mitral valve with ventricle)

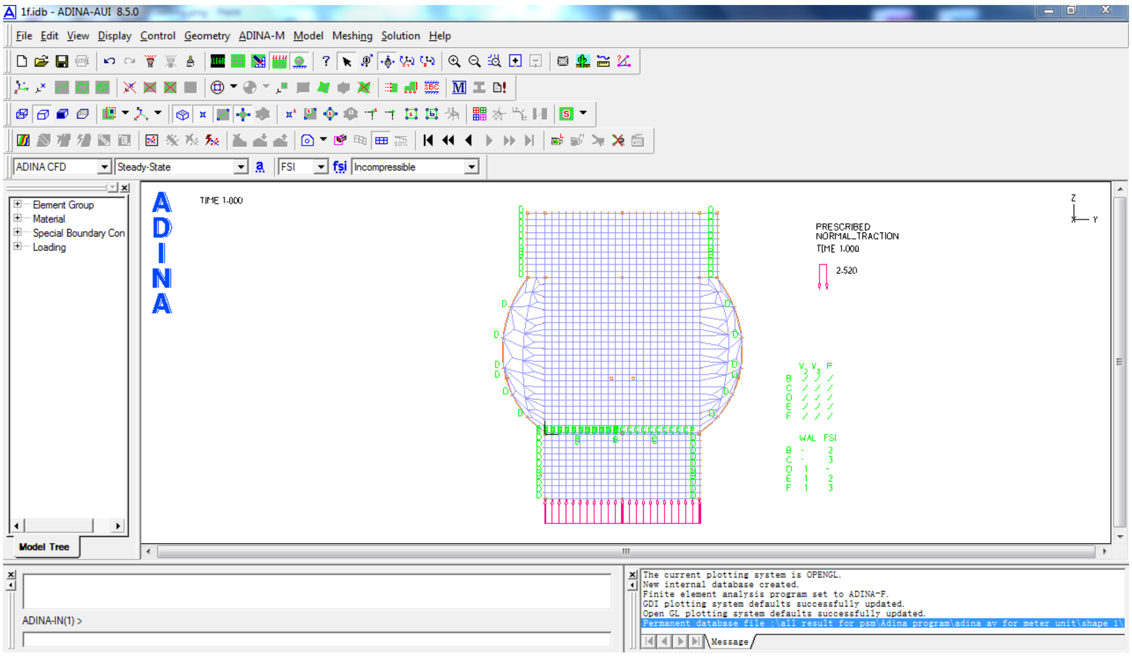

Figure A-6: Design 2D fluids (aortic valve without ventricle)

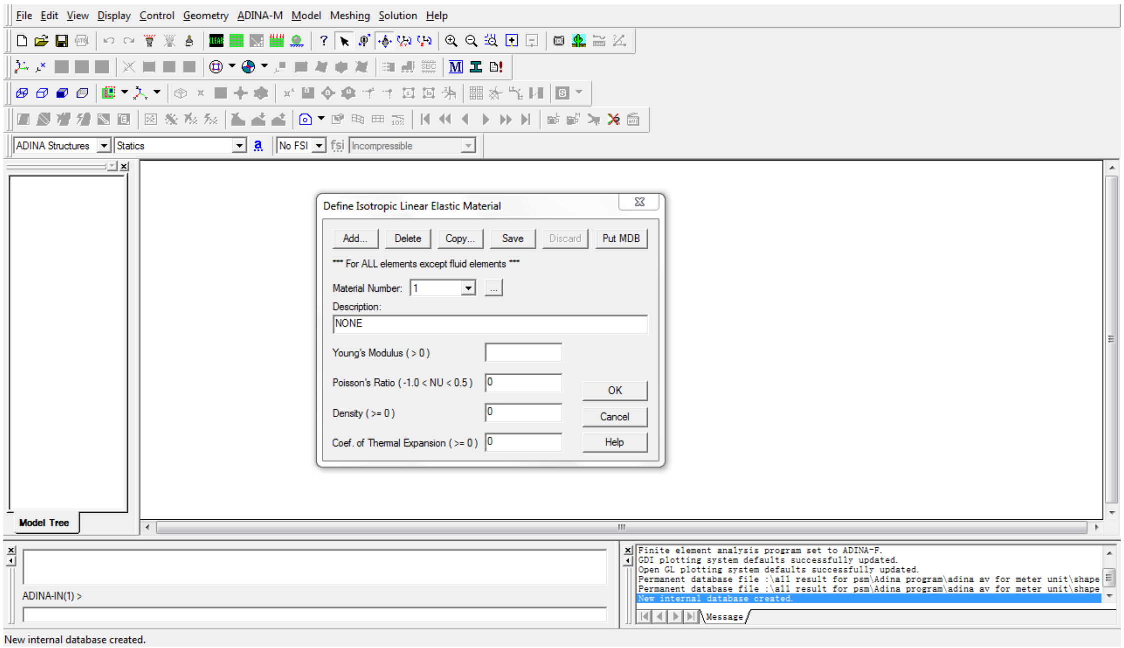

Figure A-7: Pre-Processing setting for structure part

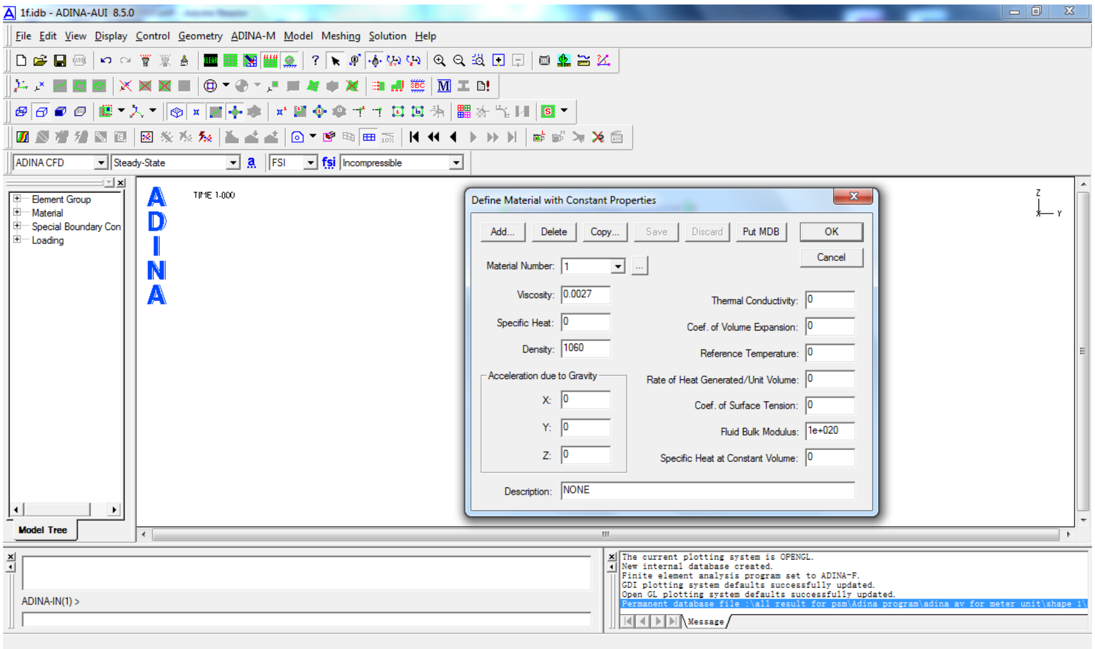

Figure A-8: Pre-Processing setting for fluid part

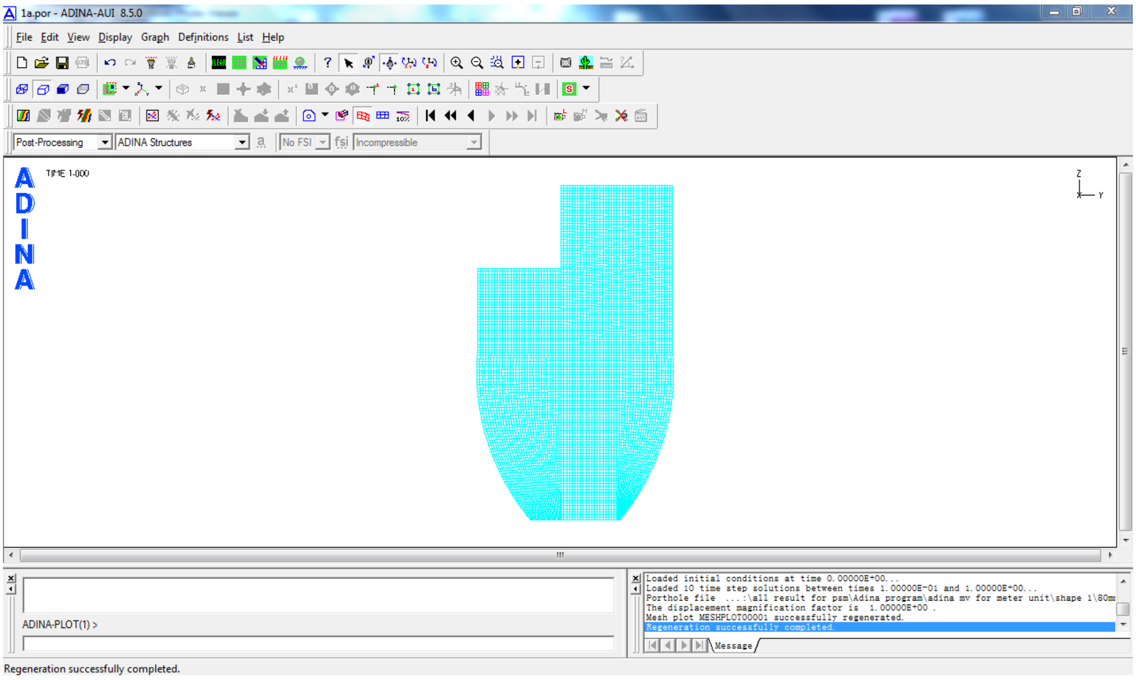

Figure A-9: FSI structure and fluid body

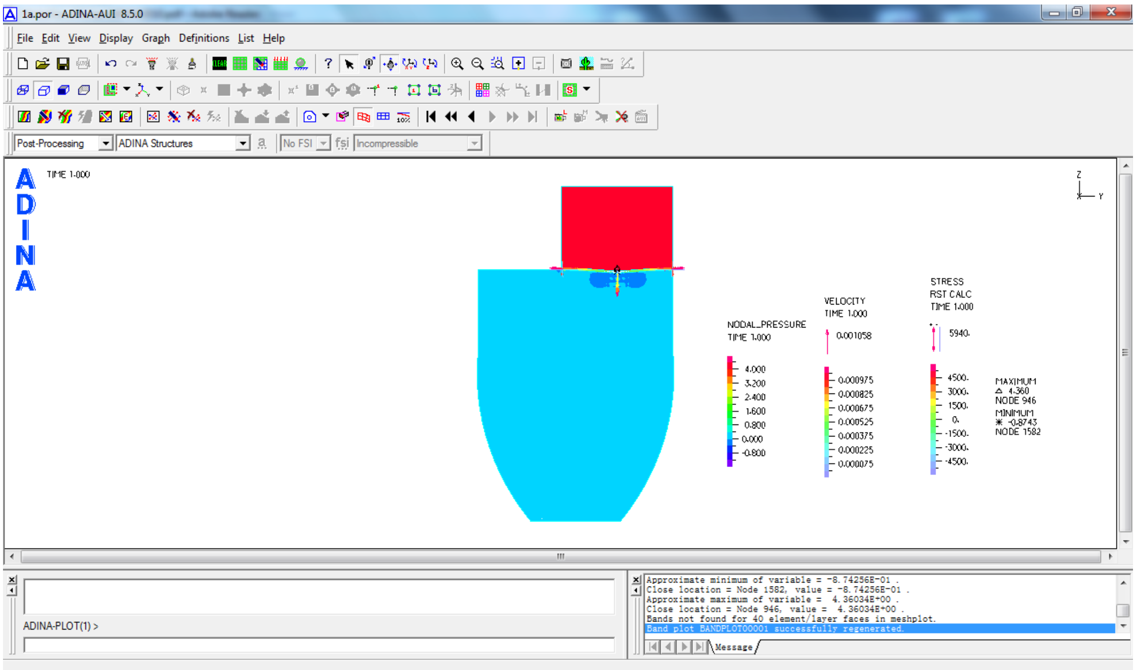

Figure A-10: FSI simulation result (mitral valve)

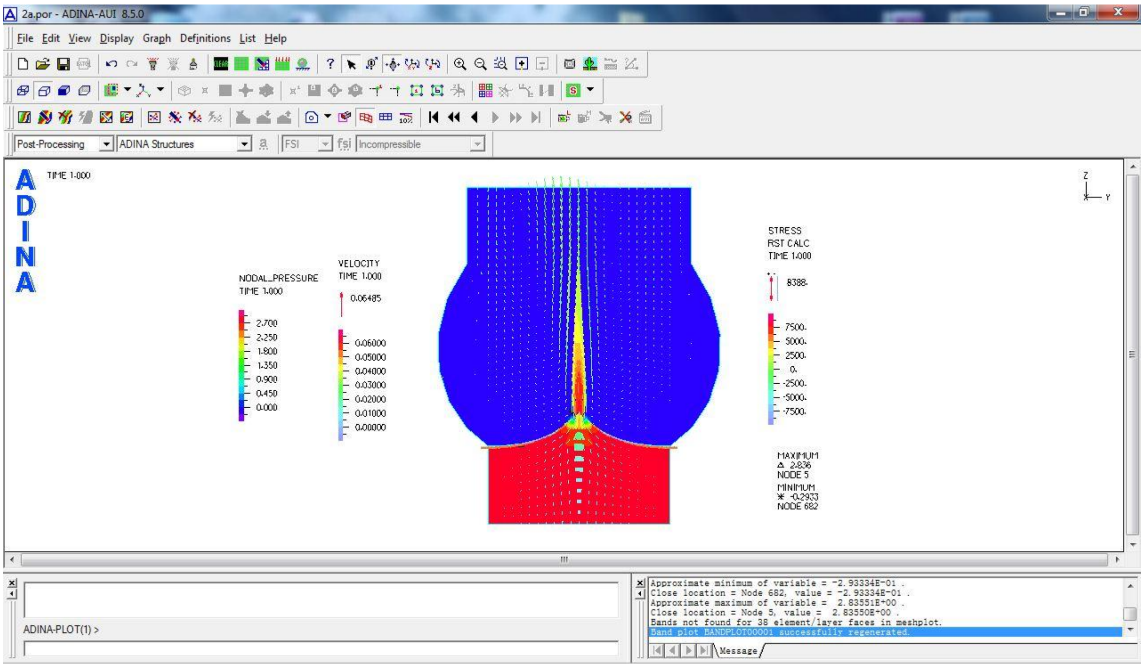

Figure A-11: FSI simulation result (aortic valve)

APPENDIX B

RESULT OF SIMULATION ADINA-FSI DISPLAY

Mitral valve at Normal diastolic stage (Blood pressure = 80 mmhg)

Blood flow velocity- Square shape leaflets

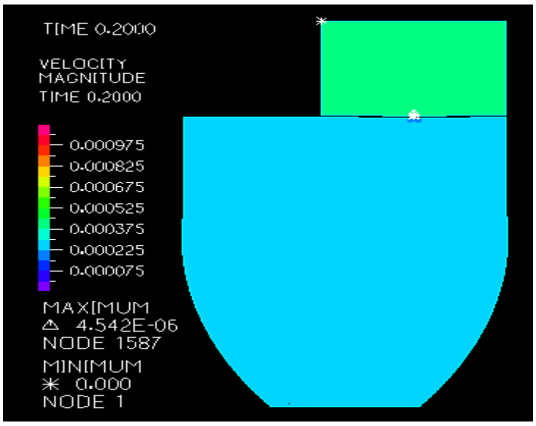

Figure B-1: 0.2 second

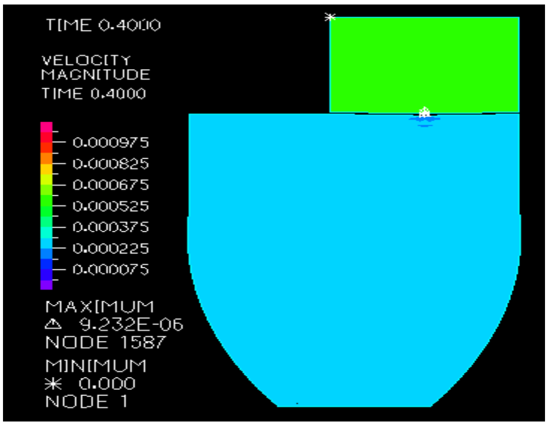

Figure B-2: 0.4 second

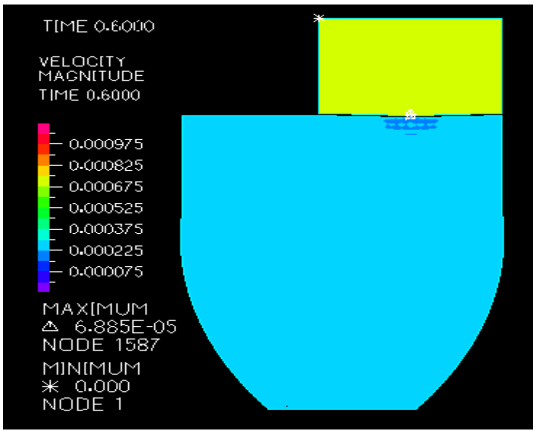

Figure B-3: 0.6 second

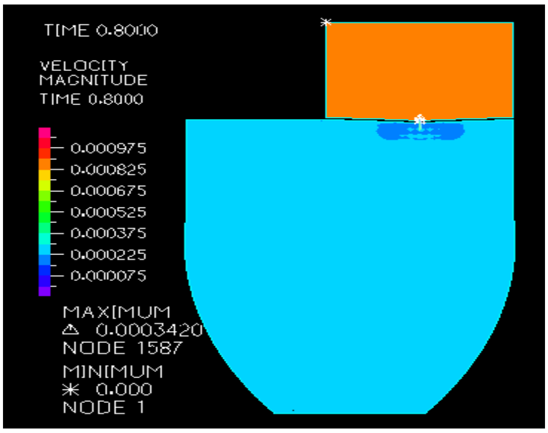

Figure B-4: 0.8 second

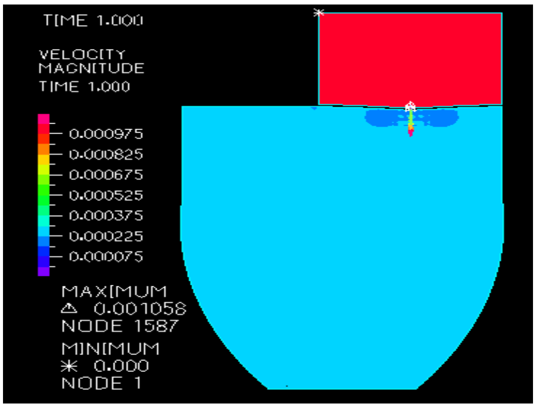

Figure B-5: 1.0 second

Blood flow velocity- Triangle shape leaflets

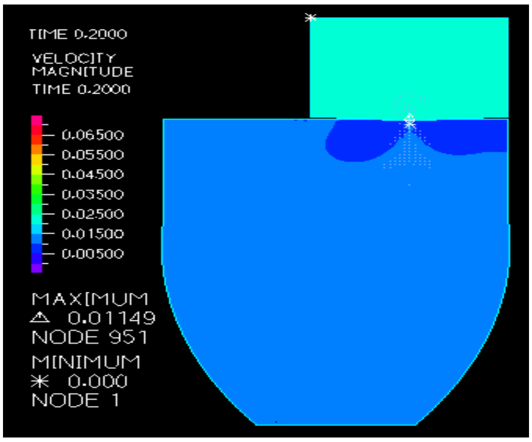

Figure B-6: 0.2 second

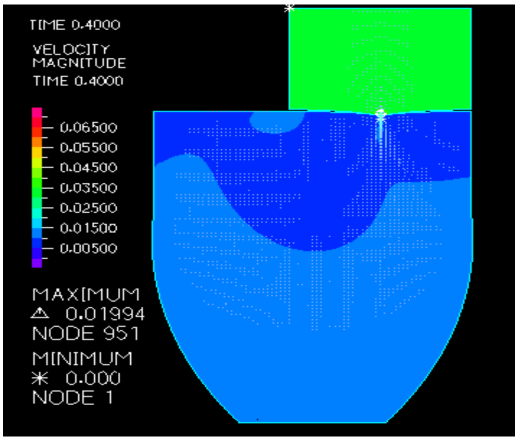

Figure B-7: 0.4 second

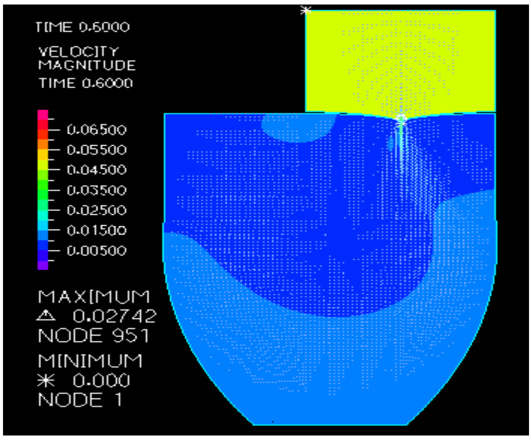

Figure B-8: 0.6 second

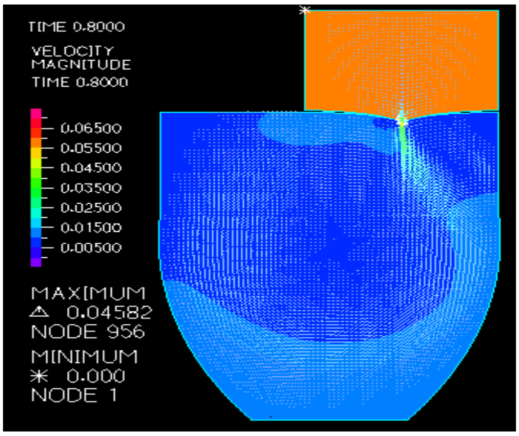

Figure B-9: 0.8 second

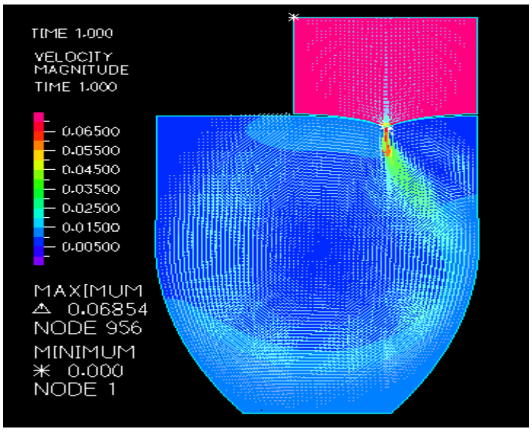

Figure B-10: 1.0 second

Blood flow velocity- Half-hemisphere shape leaflets

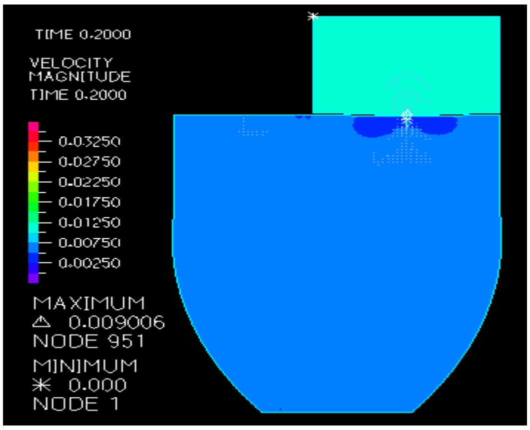

Figure B-11: 0.2 second

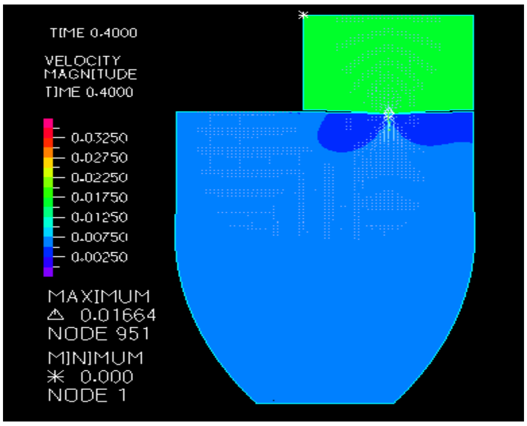

Figure B-12: 0.4 second

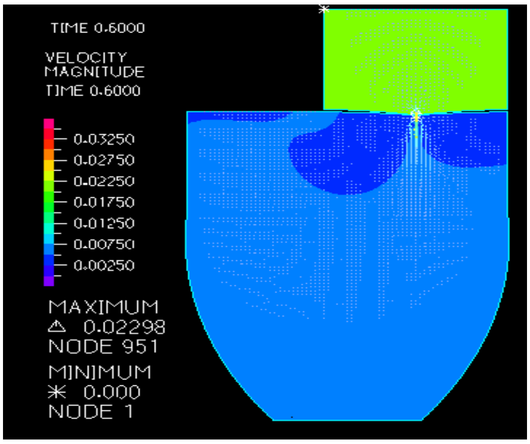

Figure B-13: 0.6 second

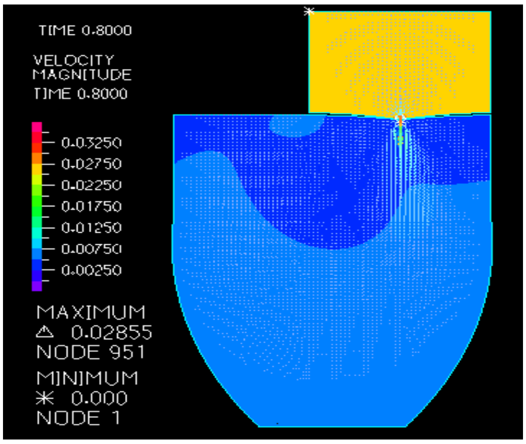

Figure B-14: 0.8 second

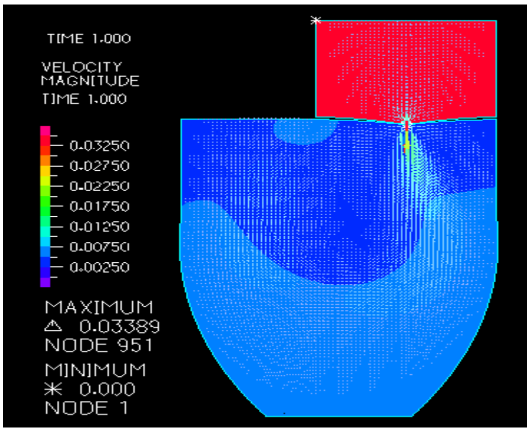

Figure B-15: 1.0 second

Blood flow velocity- Ellipse shape leaflets

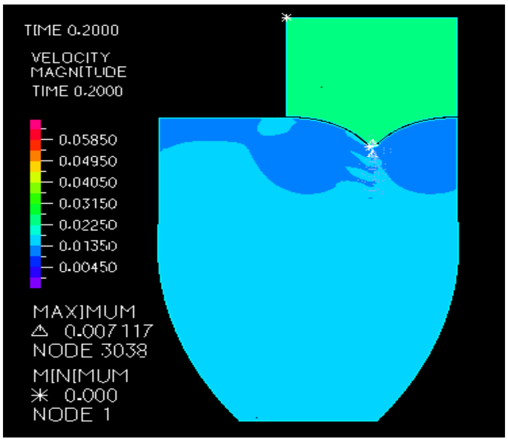

Figure B-16: 0.2 second

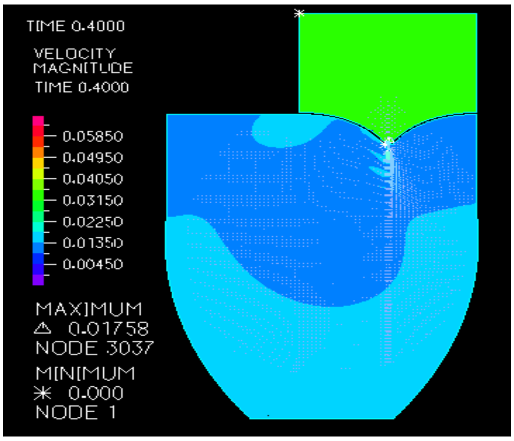

Figure B-17: 0.4 second

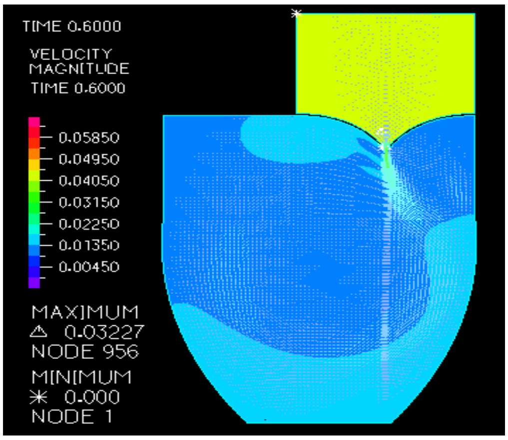

Figure B-18: 0.6 second

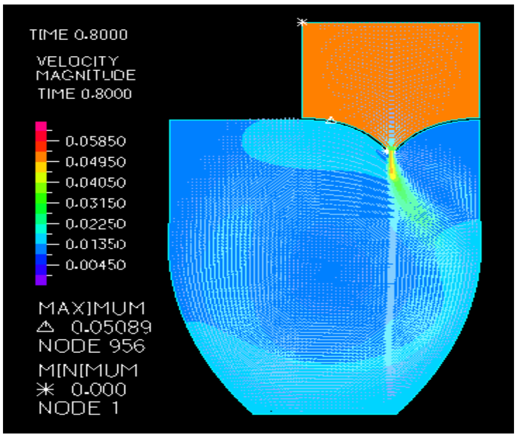

Figure B-19: 0.8 second

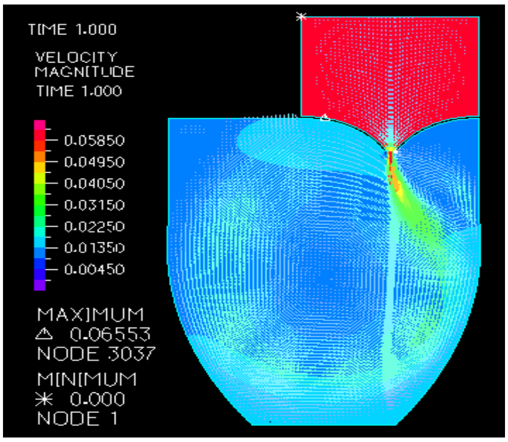

Figure B-20: 1.0 second

Blood flow velocity- V-shape leaflets

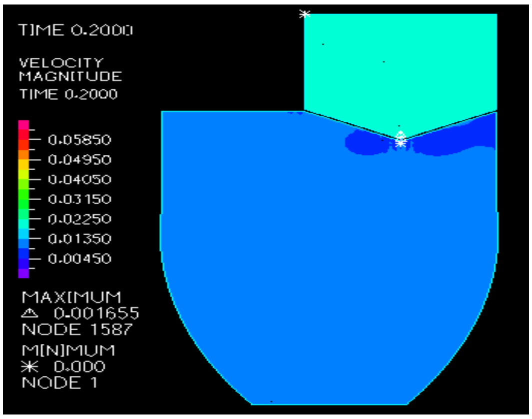

Figure B-21: 0.2 second

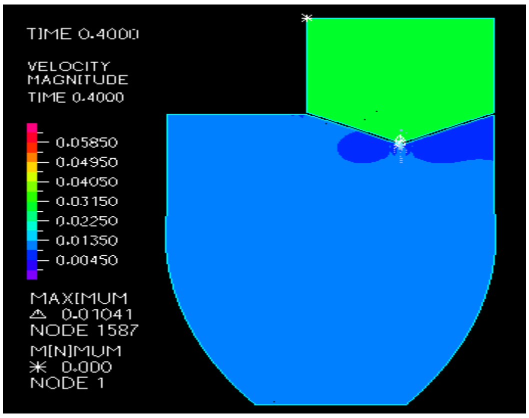

Figure B-22: 0.4 second

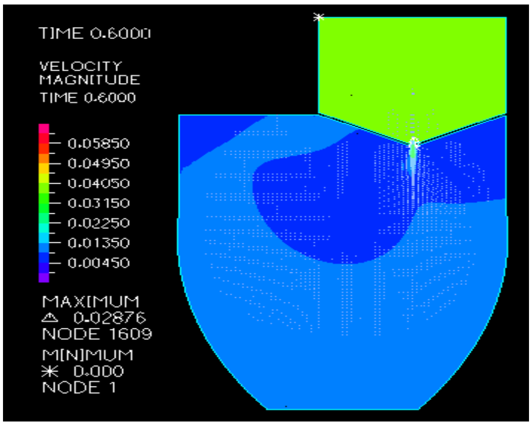

Figure B-23: 0.6 second

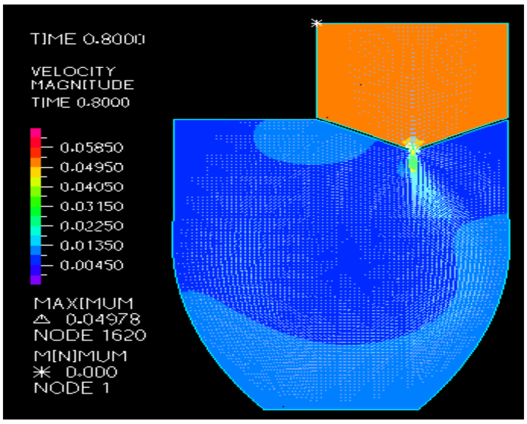

Figure B-24: 0.8 second

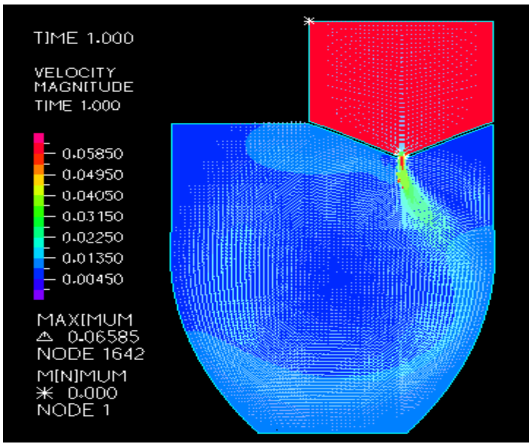

Figure B-25: 1.0 second

Mitral valve at Normal systolic stage (Blood pressure = 120 mmhg)

Blood flow velocity- Square shape leaflets

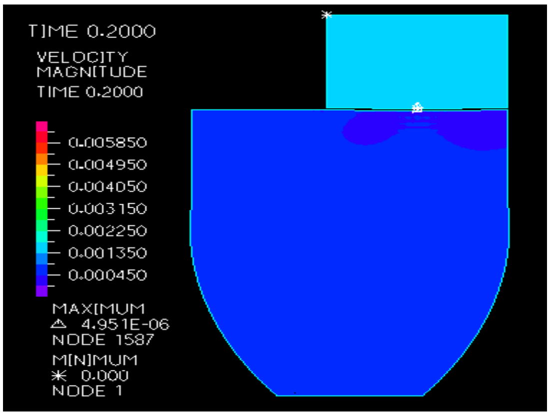

Figure B-26: 0.2 second

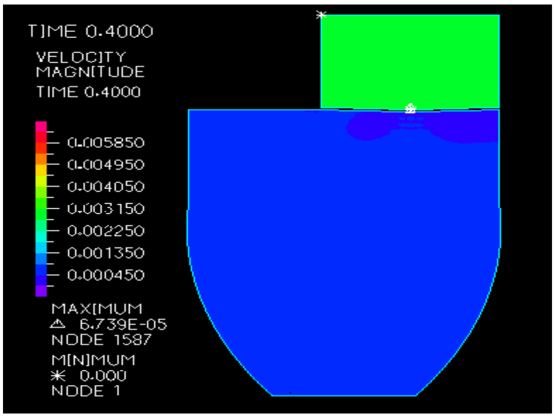

Figure B-27: 0.4 second

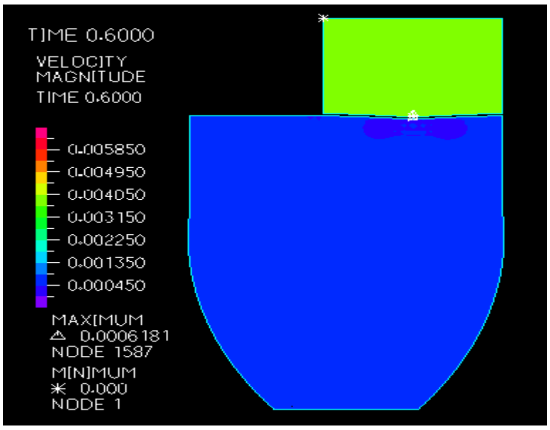

Figure B-28: 0.6 second

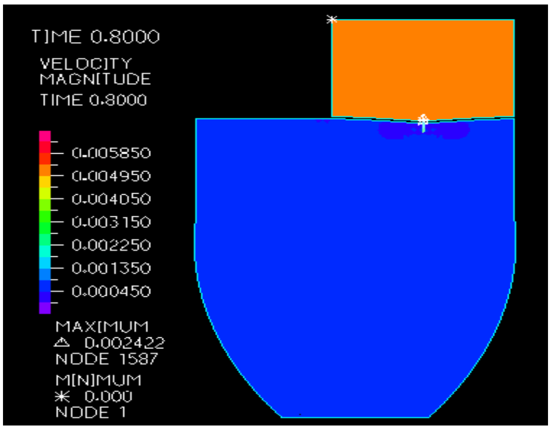

Figure B-29: 0.8 second

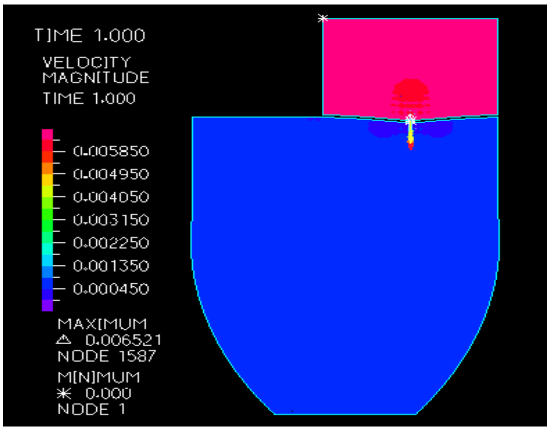

Figure B-30: 1.0 second

Blood flow velocity- Triangle shape leaflets

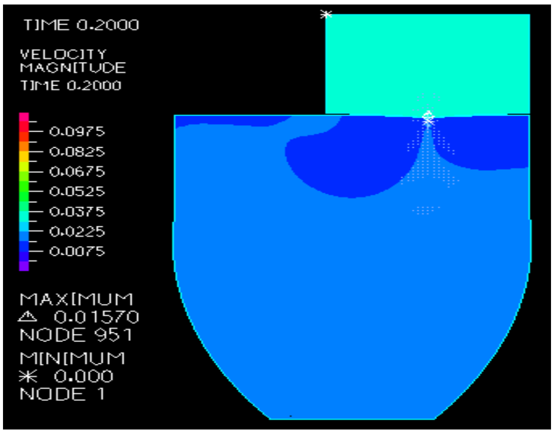

Figure B-31: 0.2 second

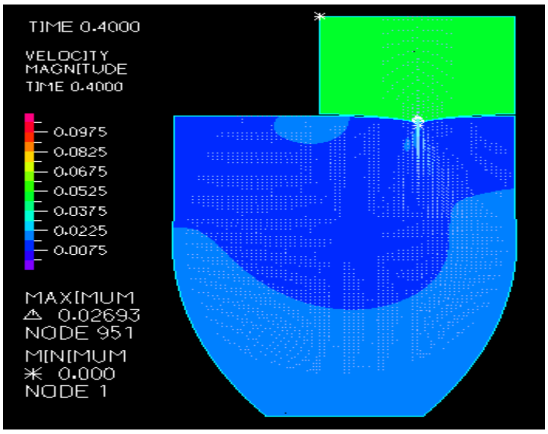

Figure B-32: 0.4 second

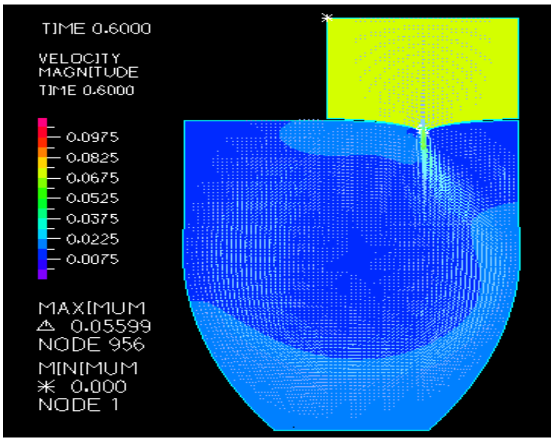

Figure B-33: 0.6 second

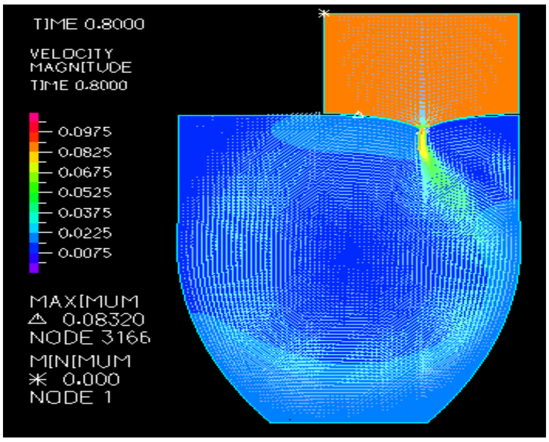

Figure B-34: 0.8 second

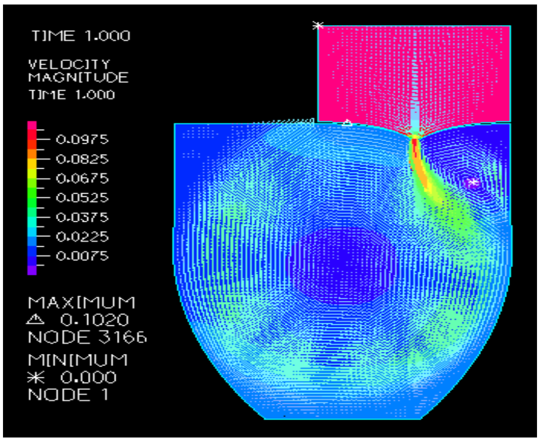

Figure B-35: 1.0 second

Blood flow velocity- Half-hemisphere shape leaflets

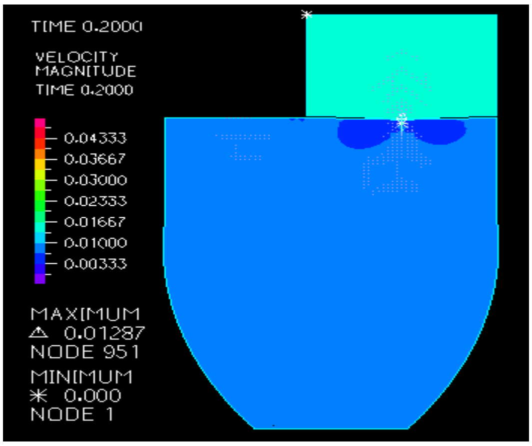

Figure B-36: 0.2 second

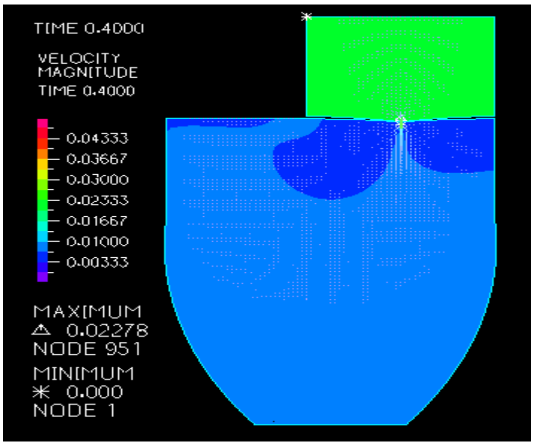

Figure B-37: 0.4 second

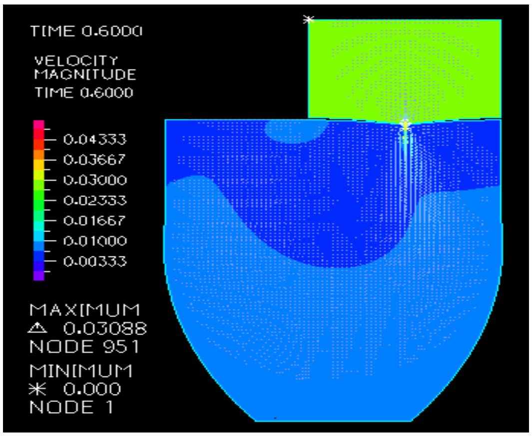

Figure B-38: 0.6 second

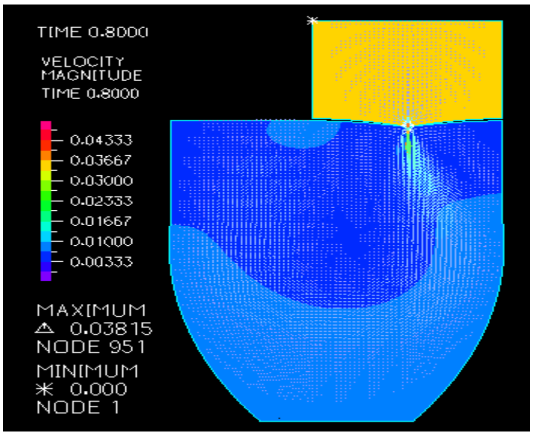

Figure B-39: 0.8 second

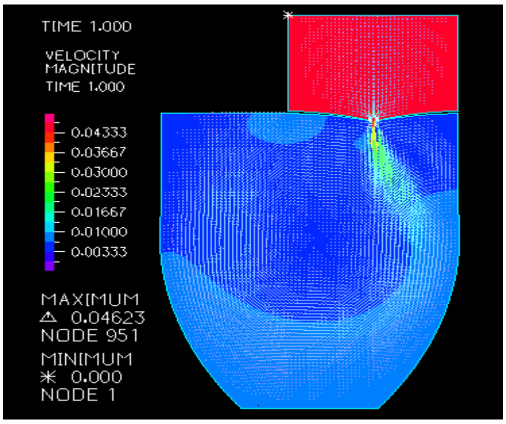

Figure B-40: 1.0 second

Blood flow velocity- Ellipse shape leaflets

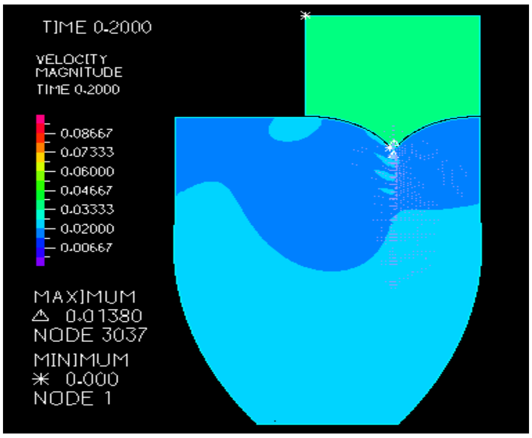

Figure B-41: 0.2 second

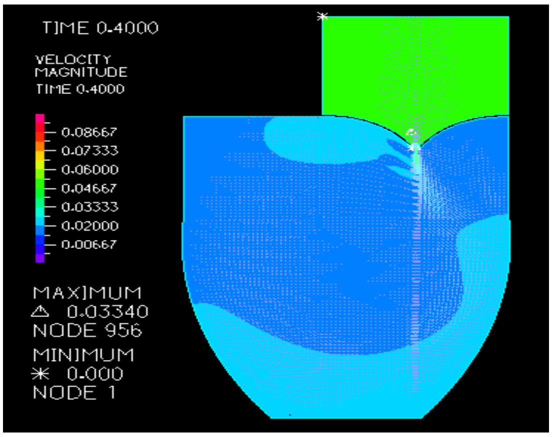

Figure B-42: 0.4 second

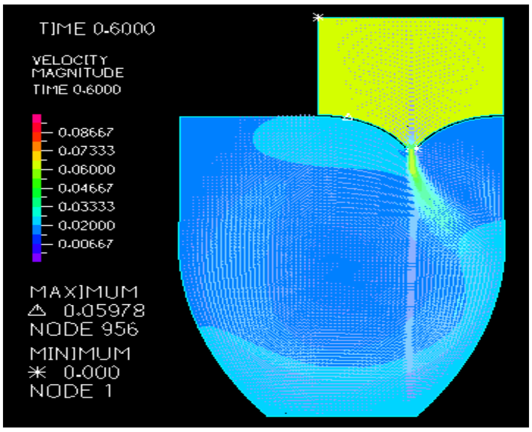

Figure B-43: 0.6 second

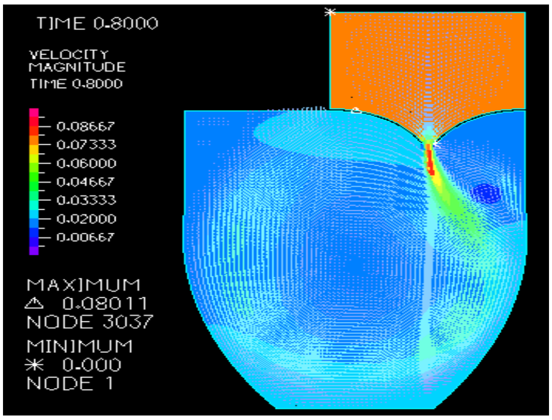

Figure B-44: 0.8 second

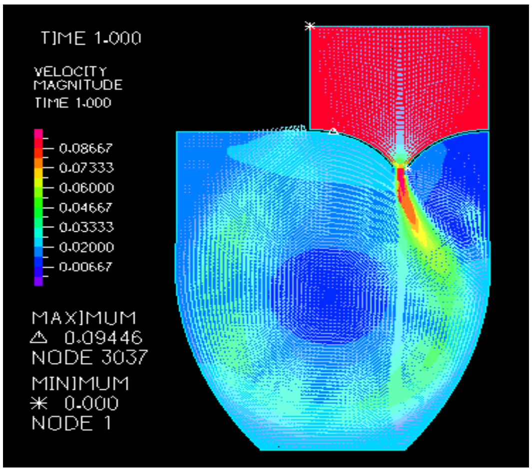

Figure B-45: 1.0 second

Blood flow velocity- V-shape leaflets

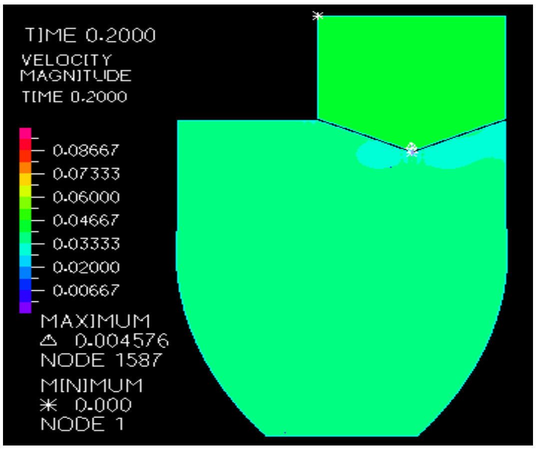

Figure B-46: 0.2 second

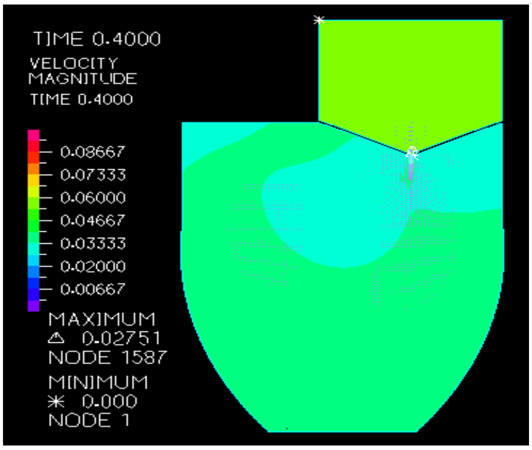

Figure B-47: 0.4 second

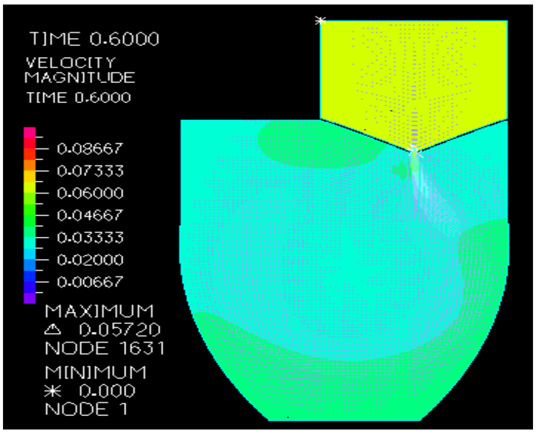

Figure B-48: 0.6 second

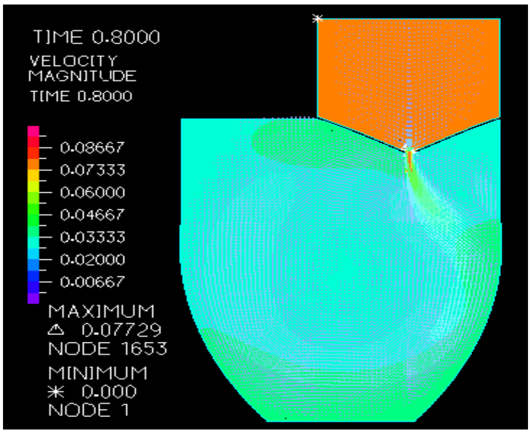

Figure B-49: 0.8 second

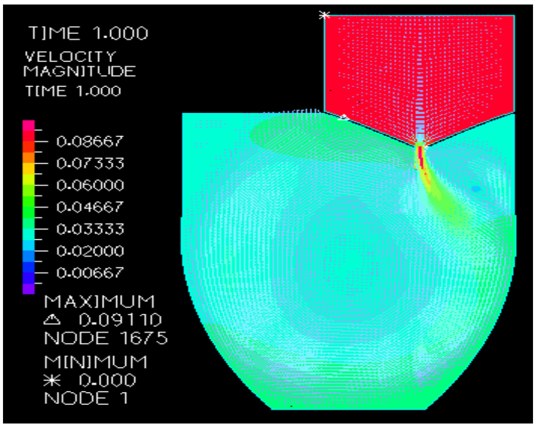

Figure B-50: 1.0 second

Mitral valve at Normal diastolic stage (Blood pressure = 80 mmhg)

Leaflets displacement changes - Square shape leaflets

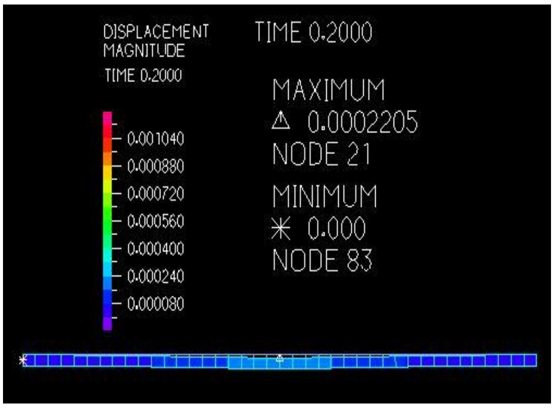

Figure B-51: 0.2 second

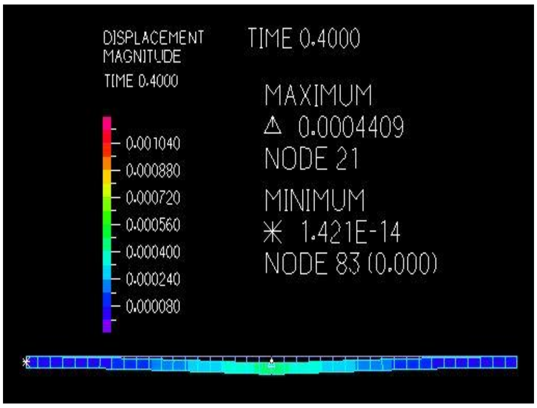

Figure B-52: 0.4 second

Figure B-53: 0.6 second

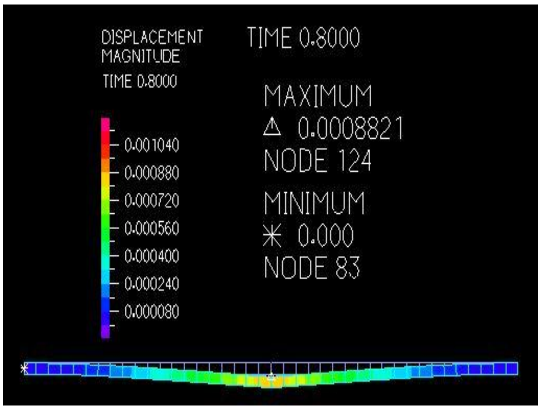

Figure B-54: 0.8 second

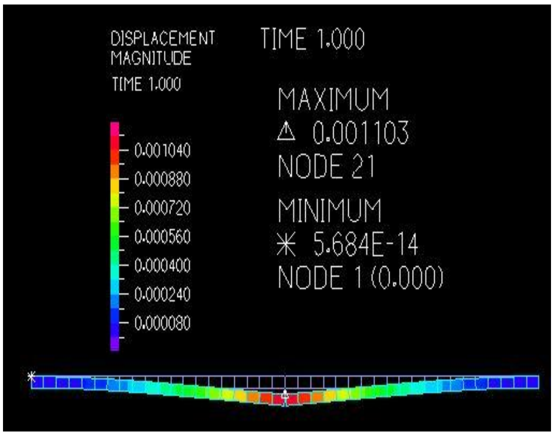

Figure B-55: 1.0 second

Leaflets displacement changes - Triangle shape leaflets

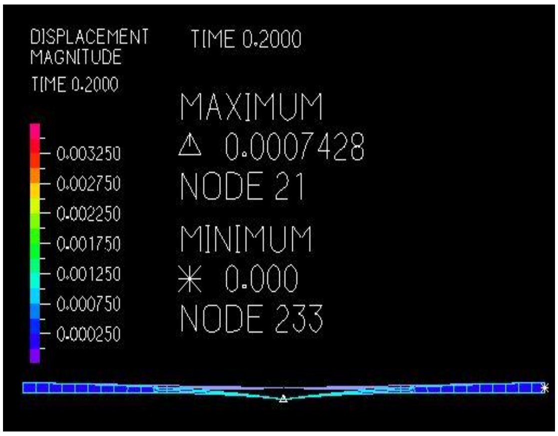

Figure B-56: 0.2 second

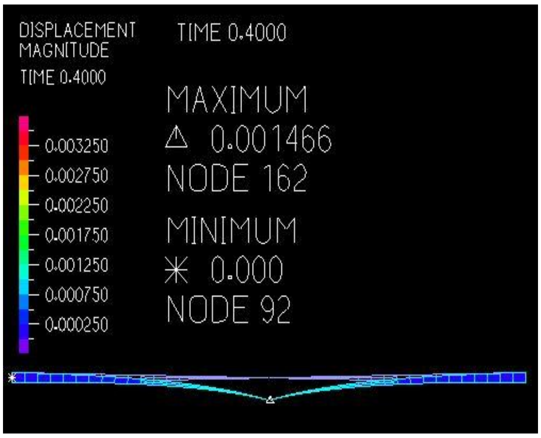

Figure B-57: 0.4 second

Figure B-58: 0.6 second

Figure B-59: 0.8 second

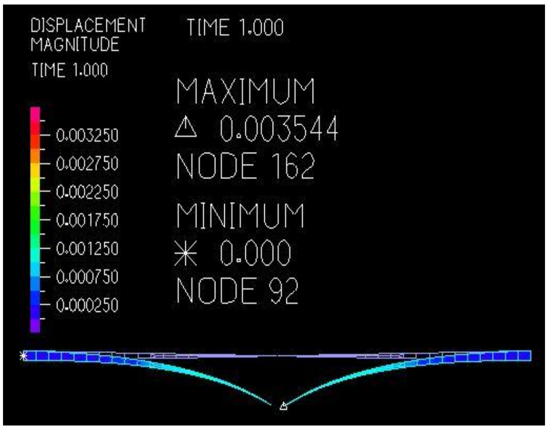

Figure B-60: 1.0 second

Leaflets displacement changes - Half-hemisphere shape leaflets

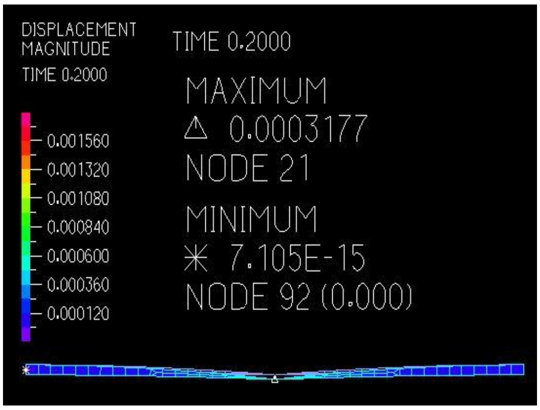

Figure B-61: 0.2 second

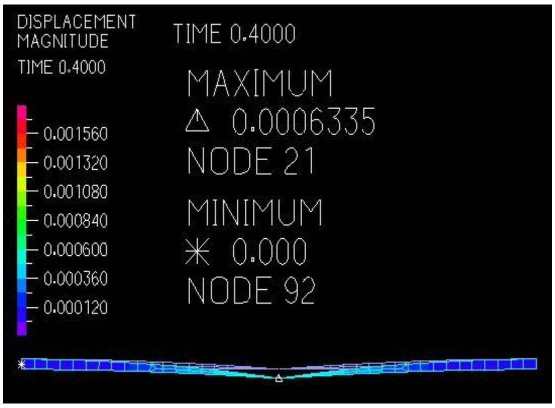

Figure B-62: 0.4 second

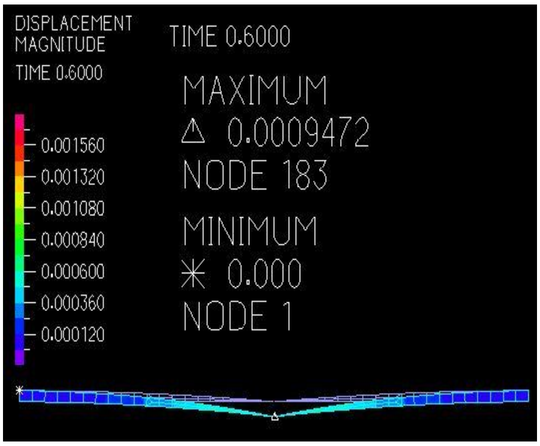

Figure B-63: 0.6 second

Figure B-64: 0.8 second

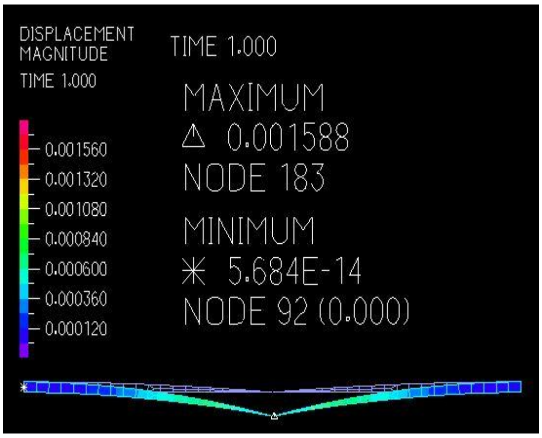

Figure B-65: 1.0 second

Leaflets displacement changes - Ellipse shape leaflets

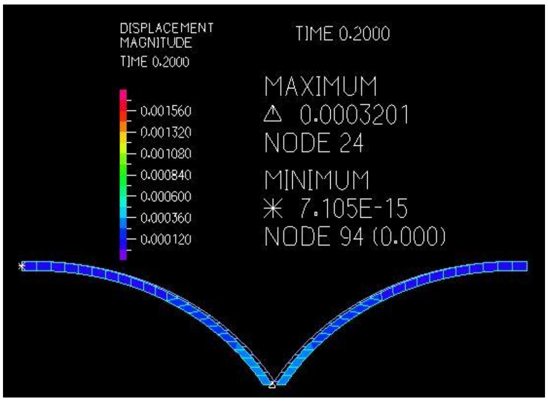

Figure B-66: 0.2 second

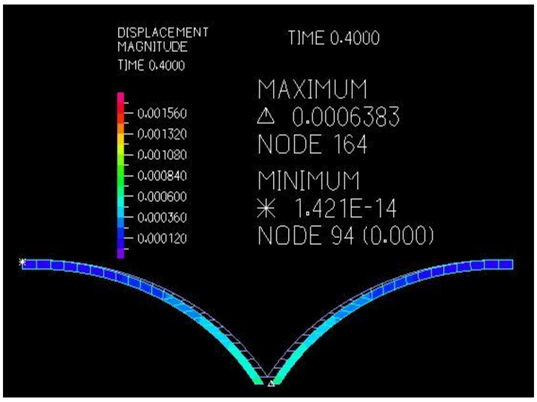

Figure B-67: 0.4 second

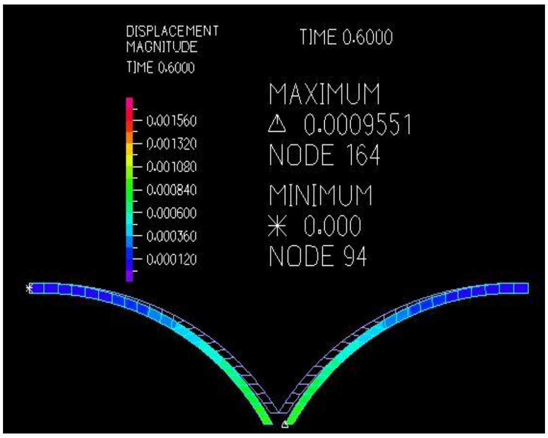

Figure B-68: 0.6 second

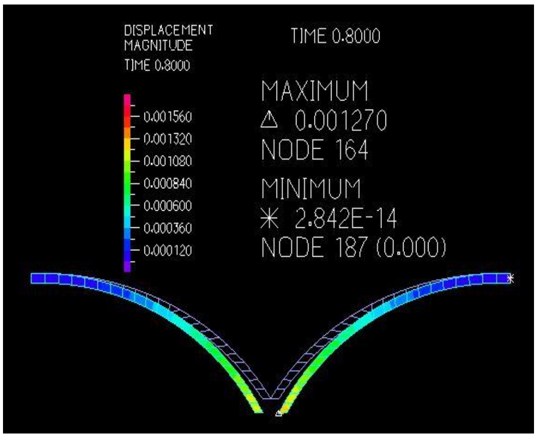

Figure B-69: 0.8 second

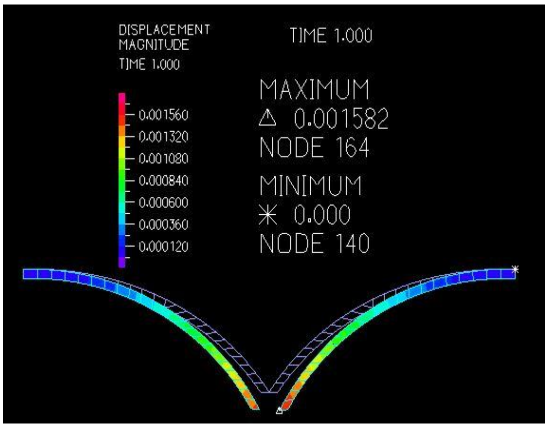

Figure B-70: 1.0 second

Leaflets displacement changes - V-shape leaflets

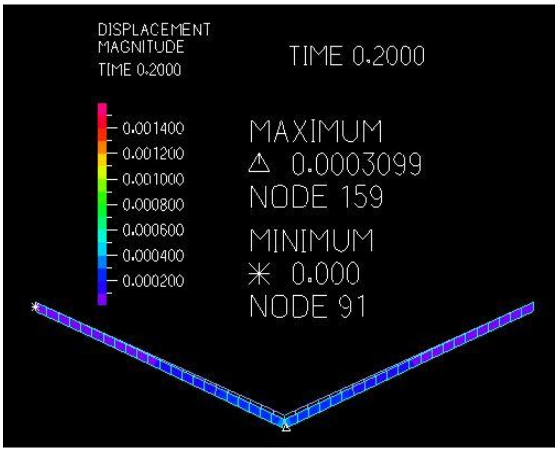

Figure B-71: 0.2 second

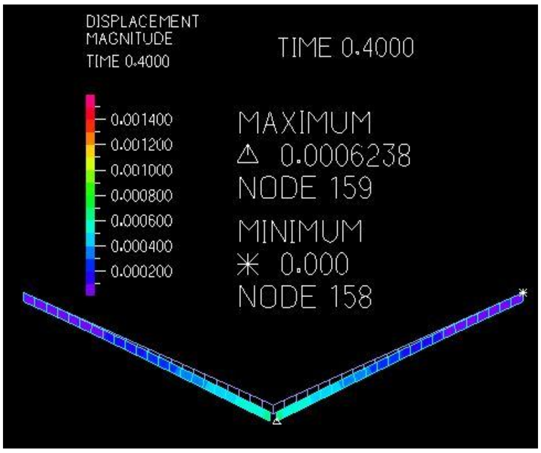

Figure B-72: 0.4 second

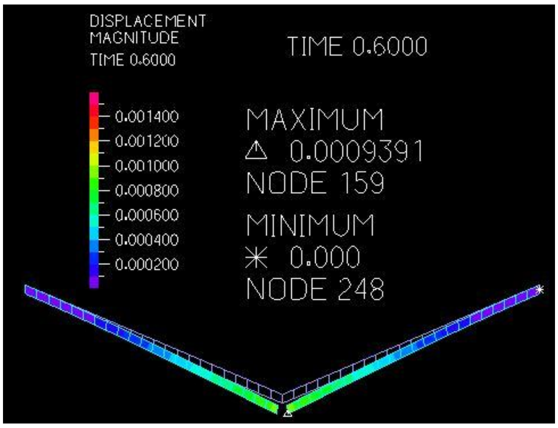

Figure B-73: 0.6 second

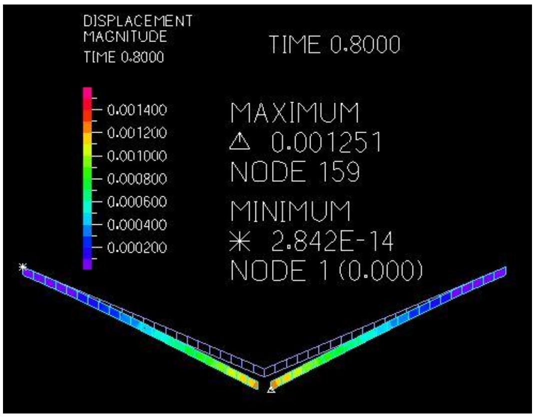

Figure B-74: 0.8 second

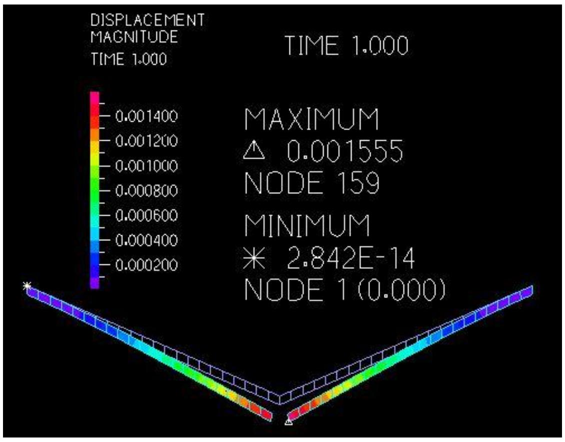

Figure B-75: 1.0 second

Mitral valve at Normal systolic stage (Blood pressure = 120 mmhg)

Leaflets displacement changes - Square shape leaflets

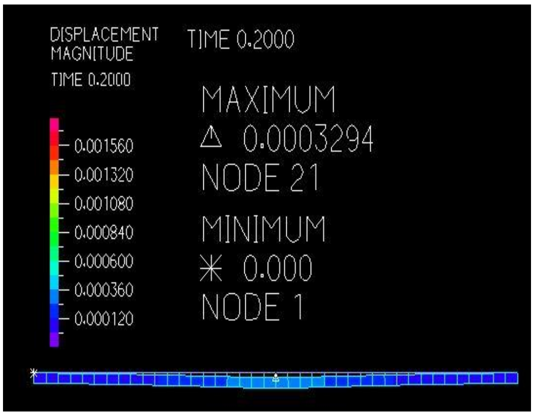

Figure B-76: 0.2 second

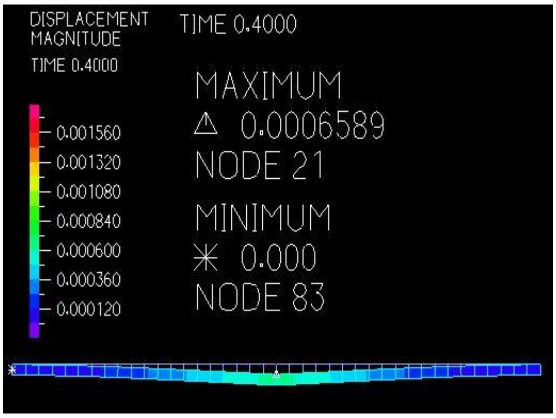

Figure B-77: 0.4 second

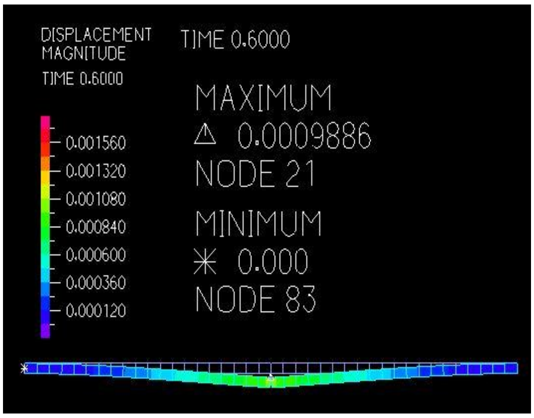

Figure B-78: 0.6 second

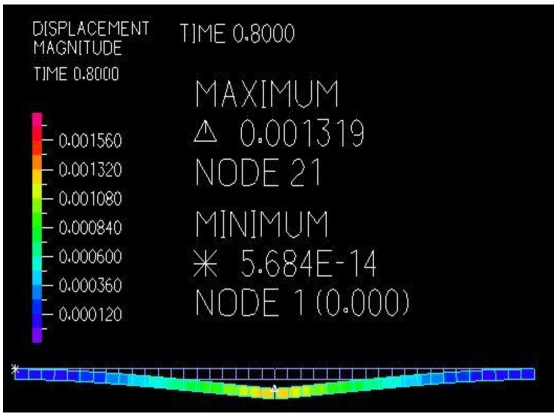

Figure B-79: 0.8 second

Figure B-80: 1.0 second

Leaflets displacement changes - Triangle shape leaflets

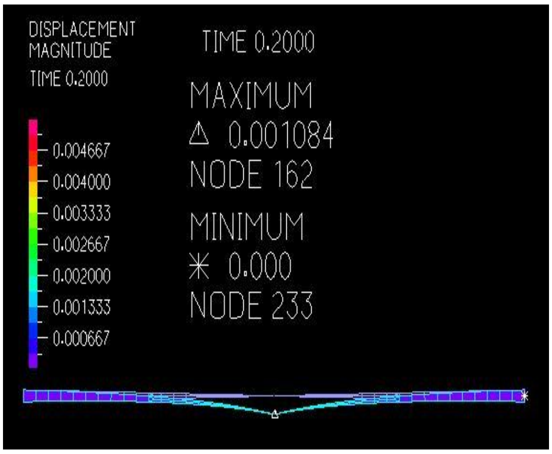

Figure B-81: 0.2 second

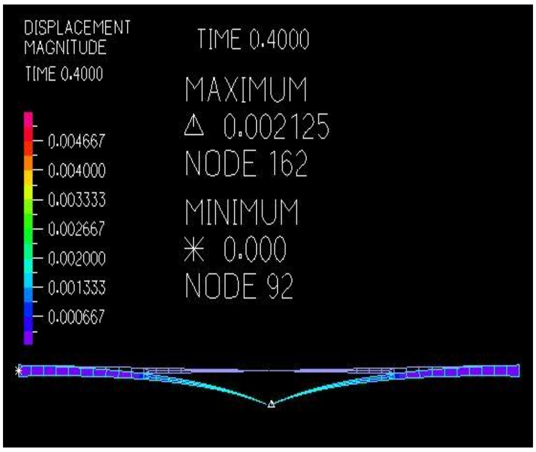

Figure B-82: 0.4 second

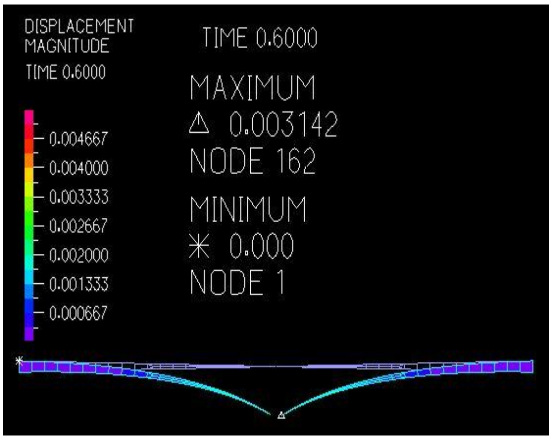

Figure B-83: 0.6 second

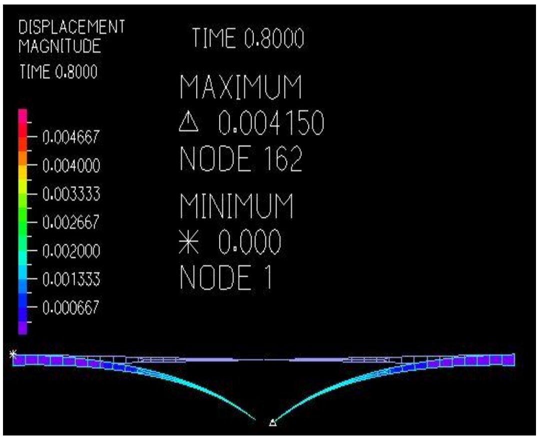

Figure B-84: 0.8 second

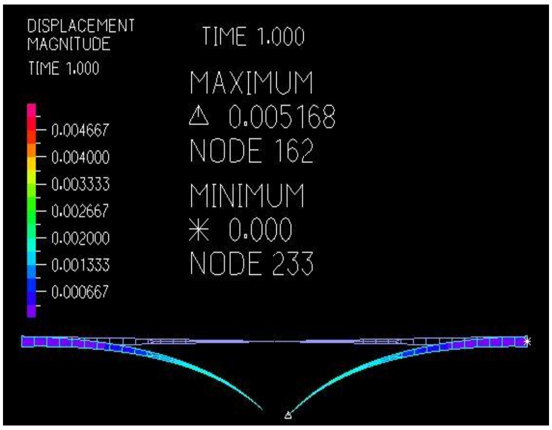

Figure B-85: 1.0 second

Leaflets displacement changes - Half-hemisphere shape leaflets

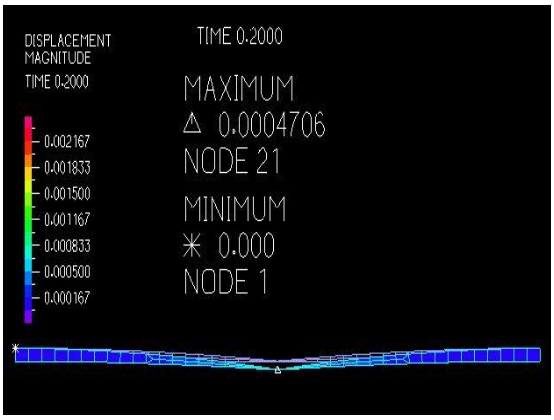

Figure B-86: 0.2 second

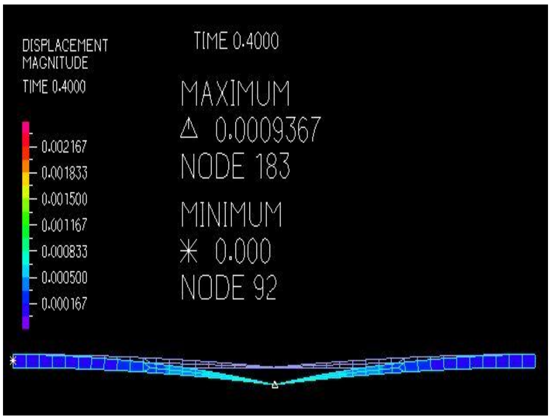

Figure B-87: 0.4 second

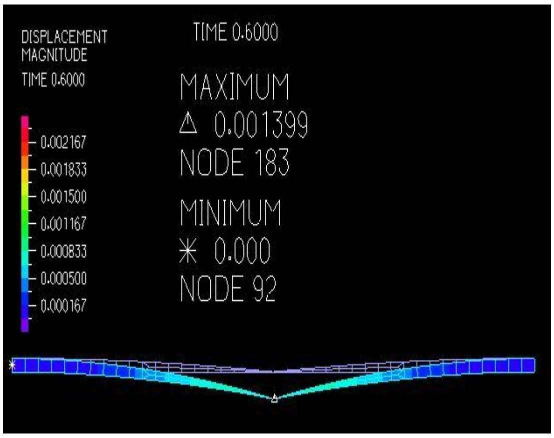

Figure B-88: 0.6 second

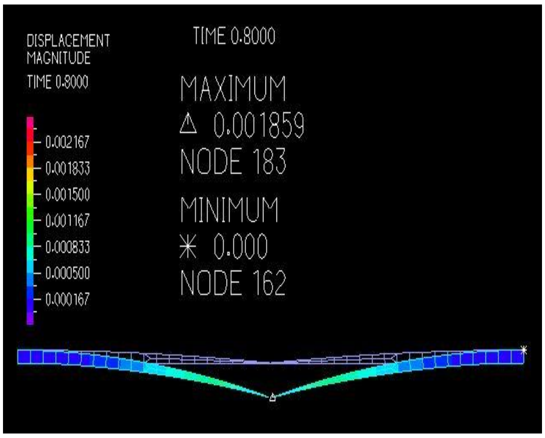

Figure B-89: 0.8 second

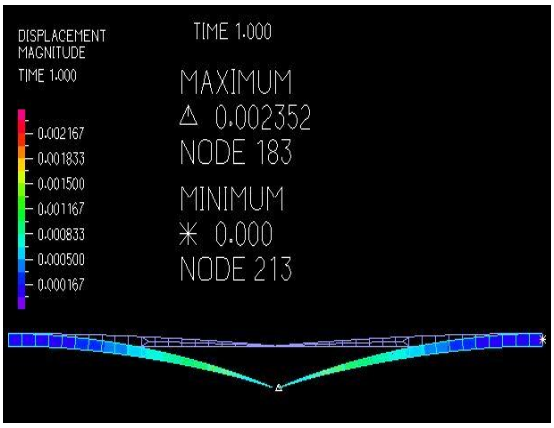

Figure B-90: 1.0 second

Leaflets displacement changes - Ellipse shape leaflets

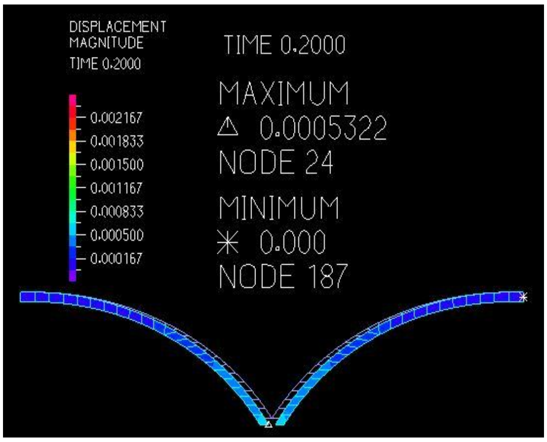

Figure B-91: 0.2 second

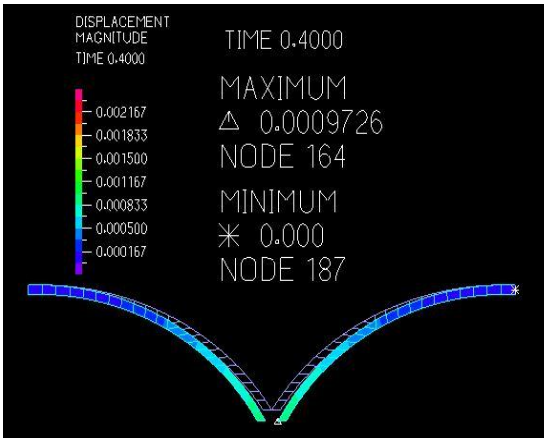

Figure B-92: 0.4 second

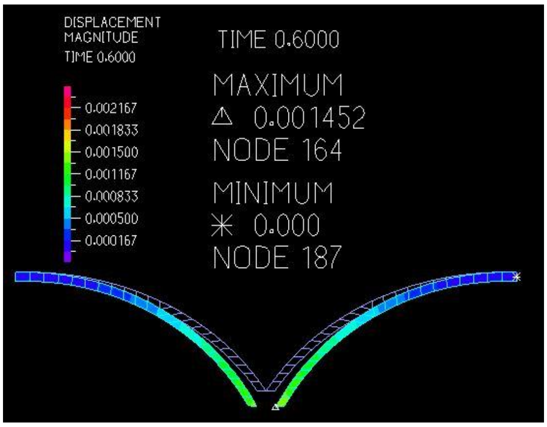

Figure B-93: 0.6 second

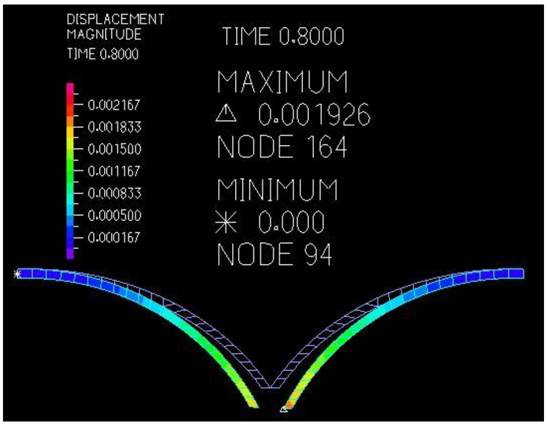

Figure B-94: 0.8 second

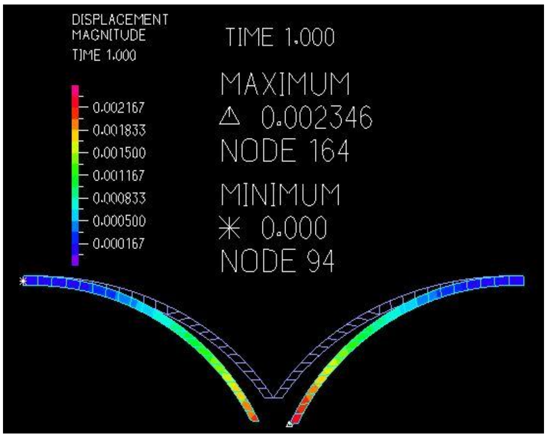

Figure B-95: 1.0 second

Leaflets displacement changes - V-shape leaflets

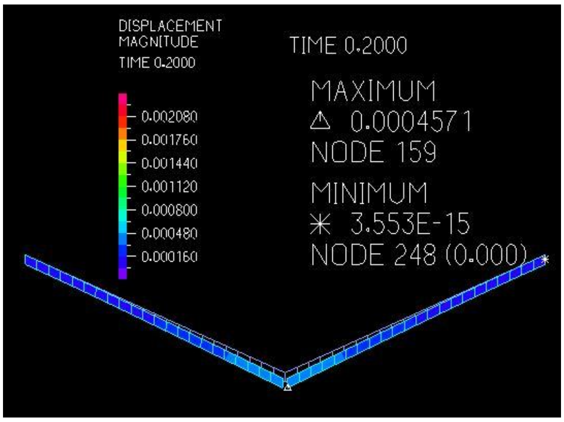

Figure B-96: 0.2 second

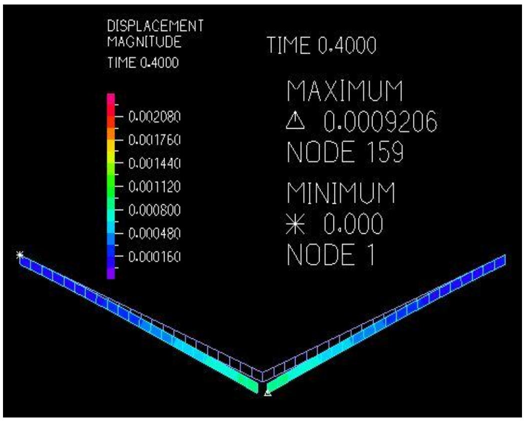

Figure B-97: 0.4 second

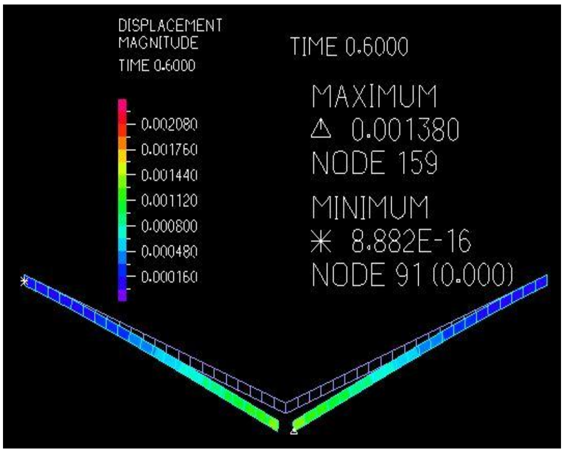

Figure B-98: 0.6 second

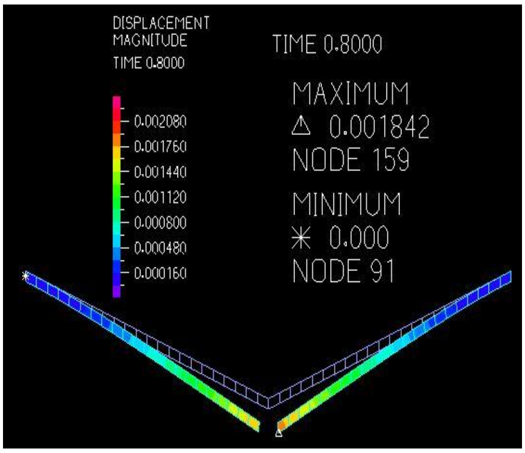

Figure B-99: 0.8 second

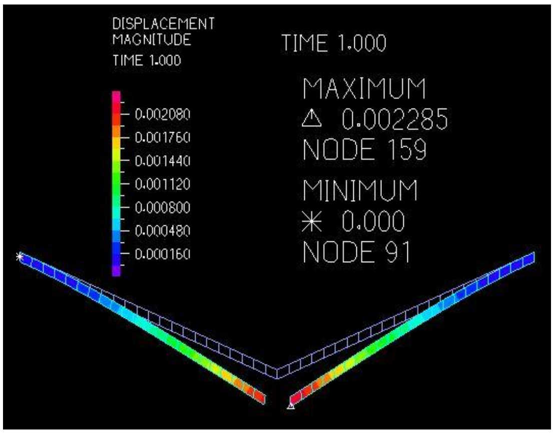

Figure B-100: 1.0 second

RESULT OF SIMULATION ADINA-FSI DISPLAY

Aortic valve at Normal diastolic stage (Blood pressure = 80 mmhg)

Blood flow velocity- Square shape leaflets

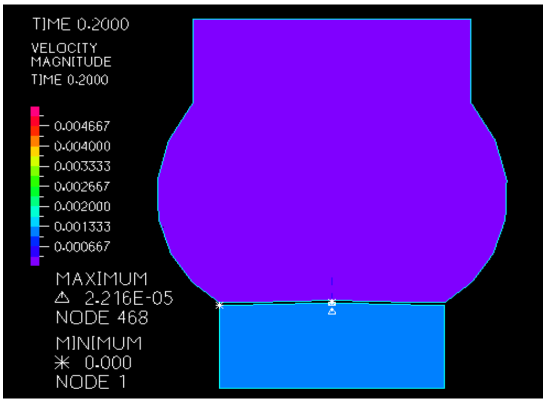

Figure B-101: 0.2 second

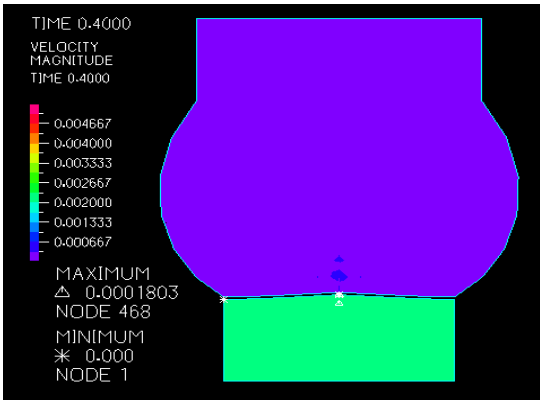

Figure B-102: 0.4 second

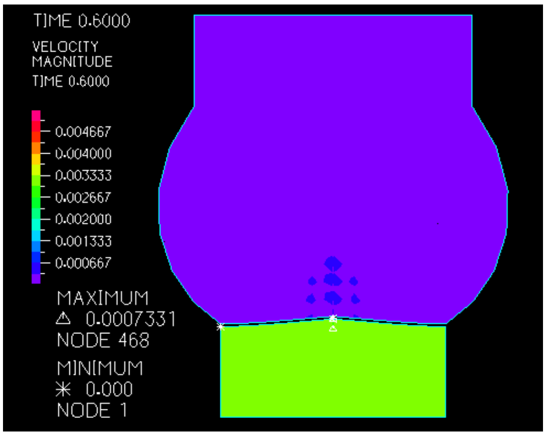

Figure B-103: 0.6 second

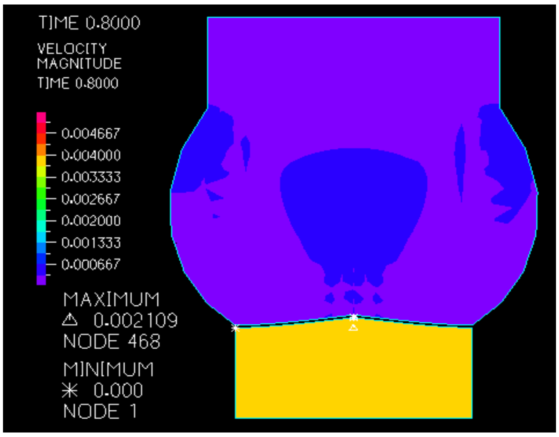

Figure B-104: 0.8 second

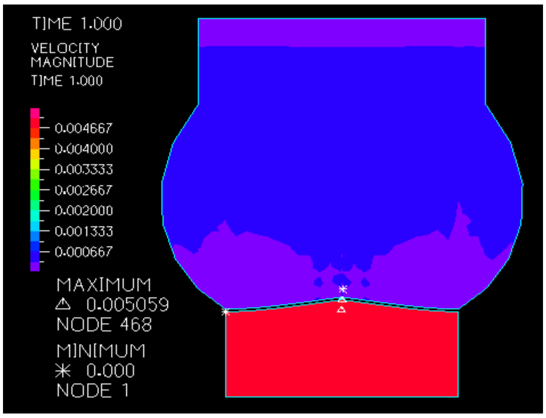

Figure B-105: 1.0 second

Blood flow velocity- Triangle shape leaflets

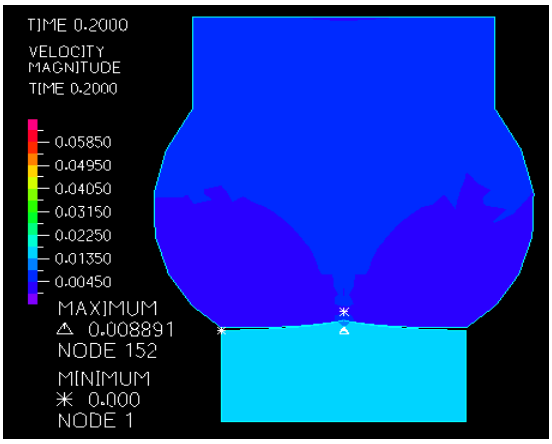

Figure B-106: 0.2 second

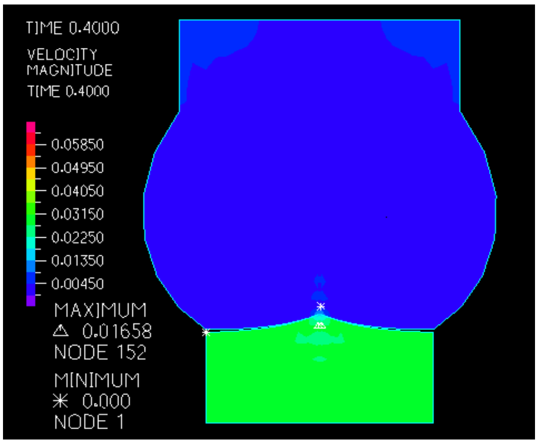

Figure B-107: 0.4 second

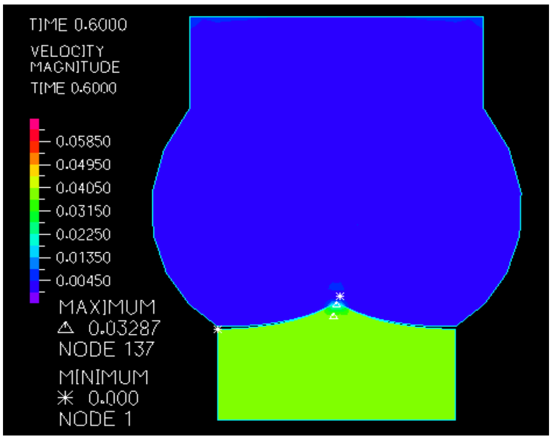

Figure B-108: 0.6 second

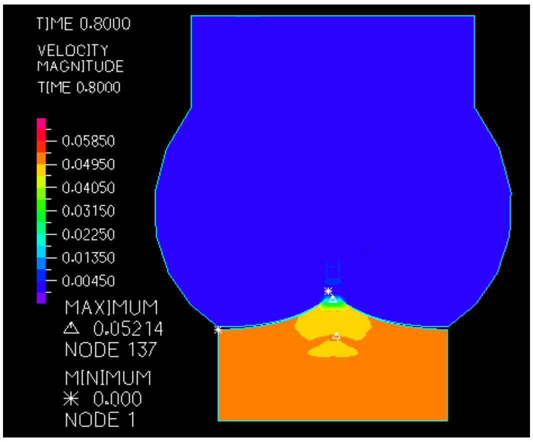

Figure B-109: 0.8 second

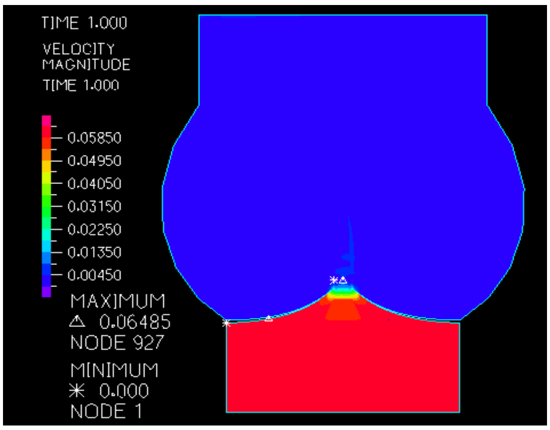

Figure B-110: 1.0 second

Blood flow velocity- Half-hemisphere shape leaflets

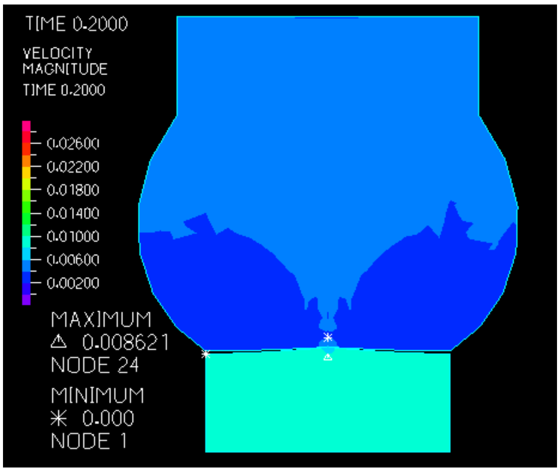

Figure B-111: 0.2 second

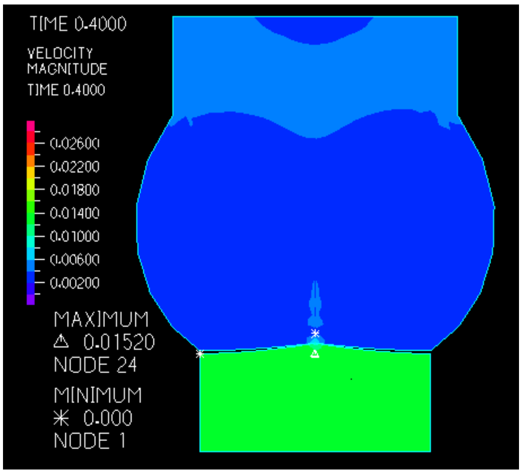

Figure B-112: 0.4 second

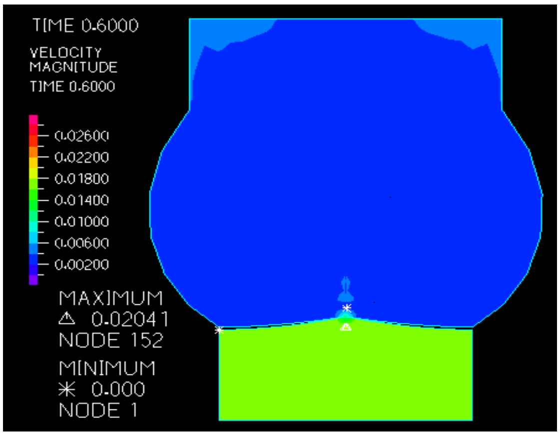

Figure B-113: 0.6 second

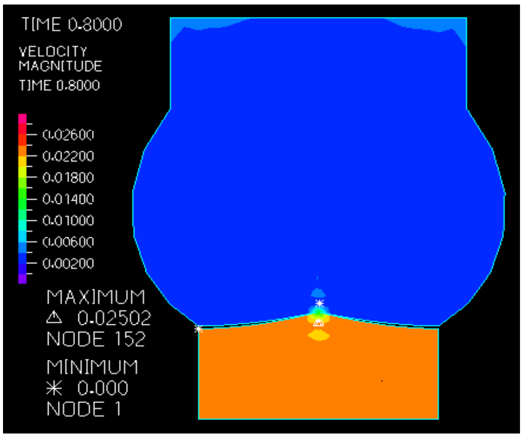

Figure B-114: 0.8 second

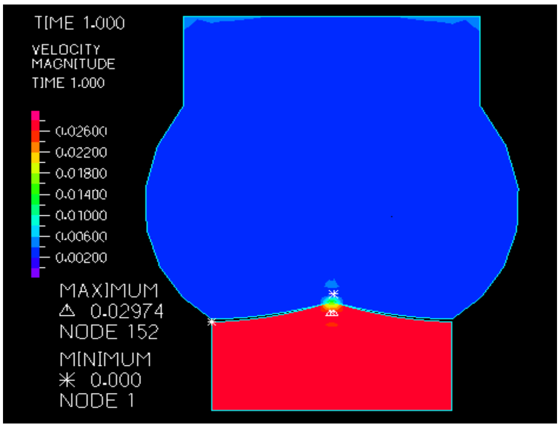

Figure B-115: 1.0 second

Blood flow velocity- Ellipse shape leaflets

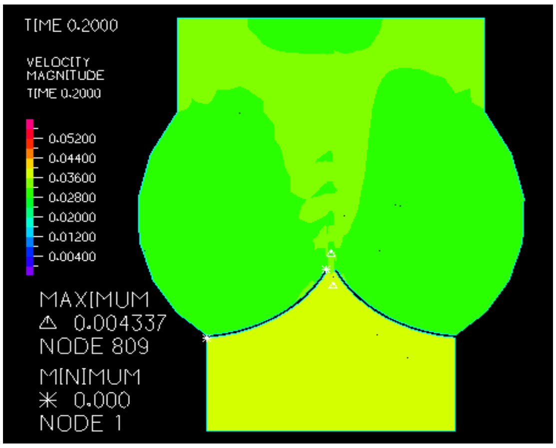

Figure B-116: 0.2 second

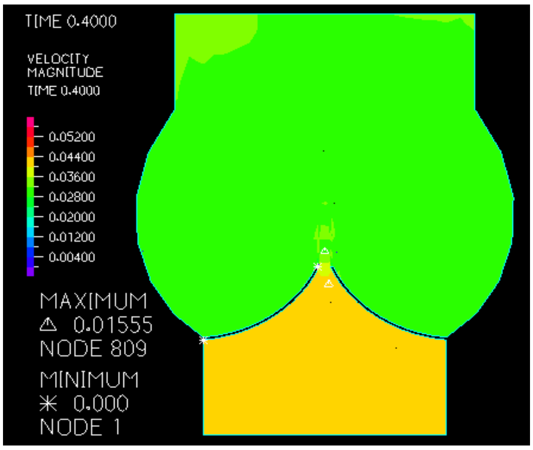

Figure B-117: 0.4 second

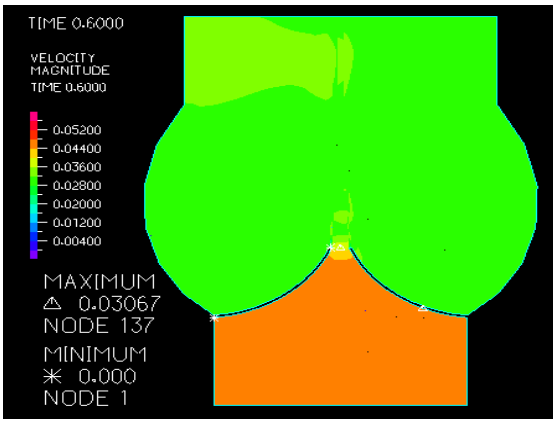

Figure B-118: 0.6 second

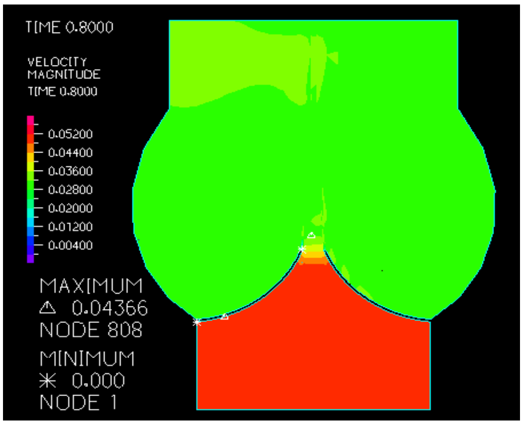

Figure B-119: 0.8 second

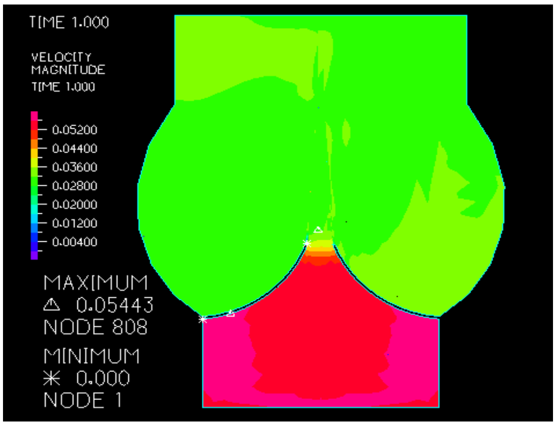

Figure B-120: 1.0 second

Blood flow velocity- V-shape leaflets

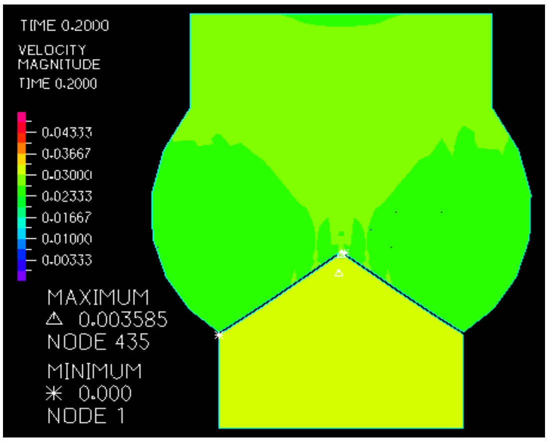

Figure B-121: 0.2 second

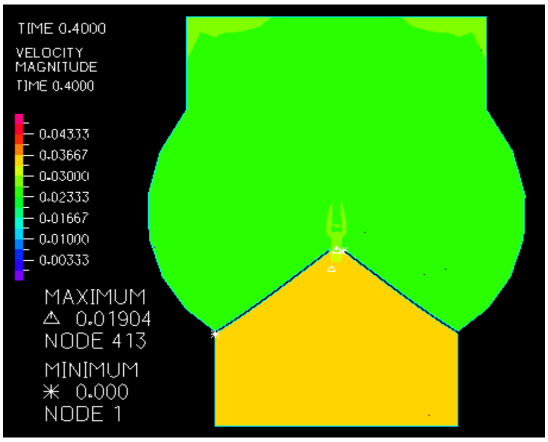

Figure B-122: 0.4 second

Figure B-123: 0.6 second

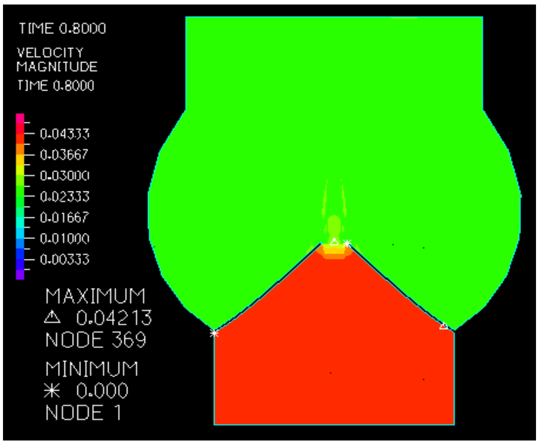

Figure B-124: 0.8 second

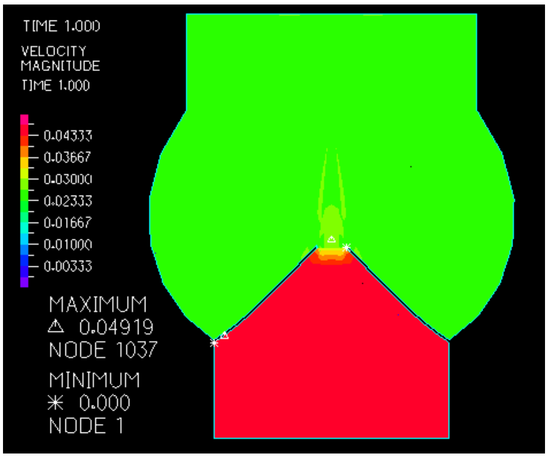

Figure B-125: 1.0 second

Aortic valve at Normal systolic stage (Blood pressure = 120 mmhg)

Blood flow velocity- Square shape leaflets

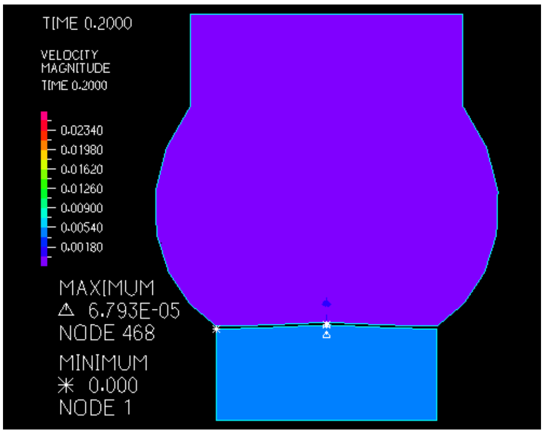

Figure B-126: 0.2 second

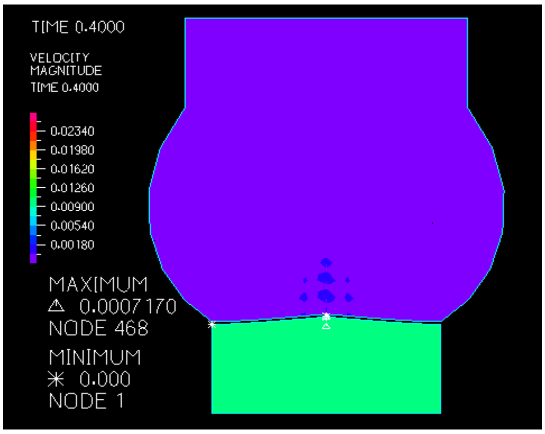

Figure B-127: 0.4 second

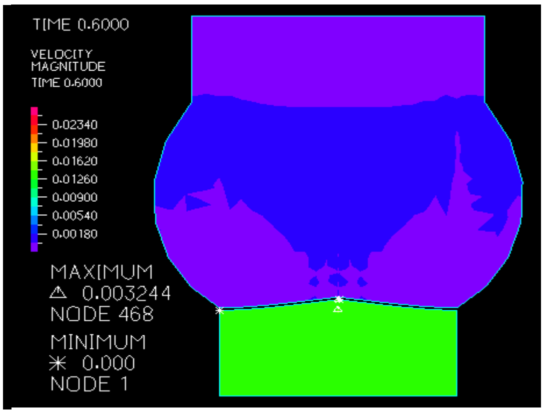

Figure B-128: 0.6 second

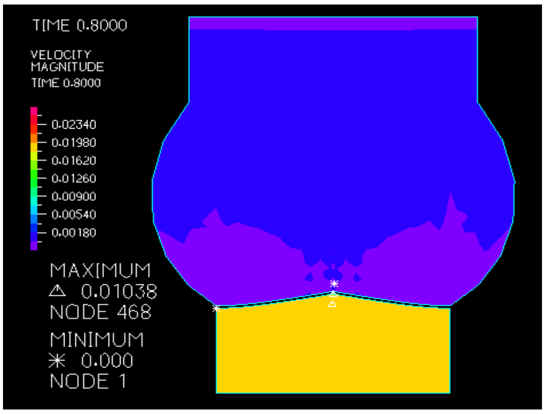

Figure B-129: 0.8 second

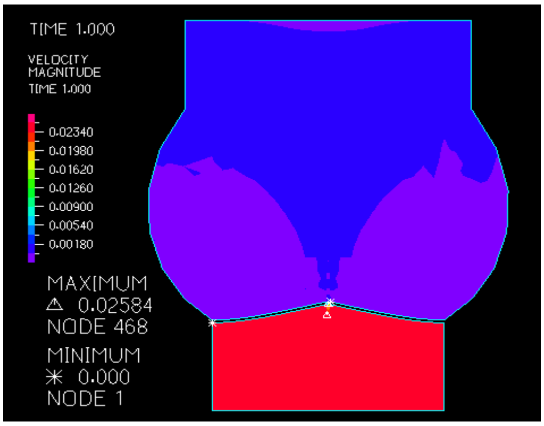

Figure B-130: 1.0 second

Blood flow velocity- Triangle shape leaflets

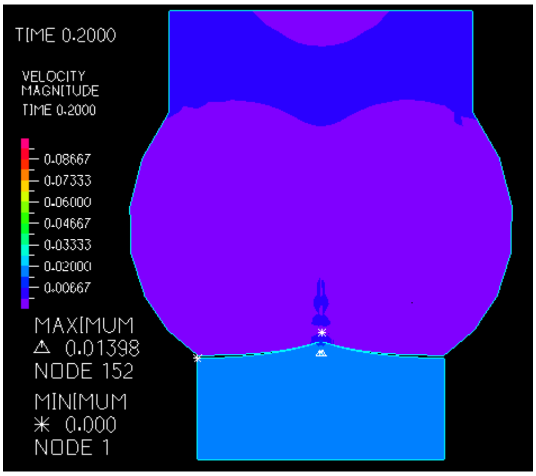

Figure B-131: 0.2 second

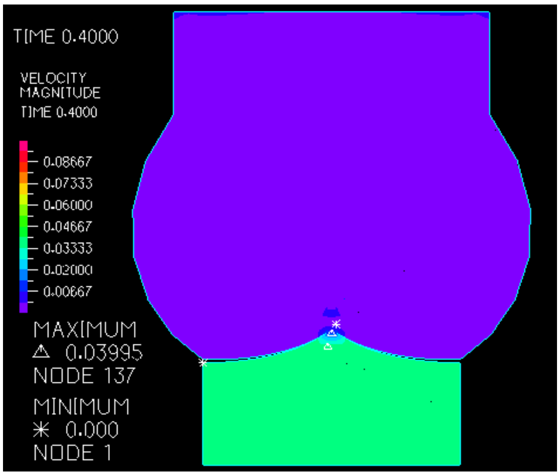

Figure B-132: 0.4 second

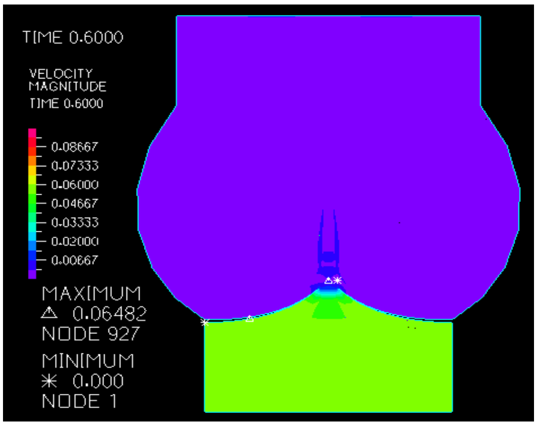

Figure B-133: 0.6 second

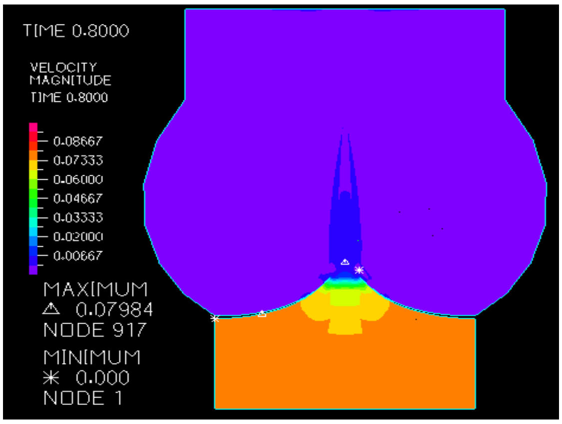

Figure B-134: 0.8 second

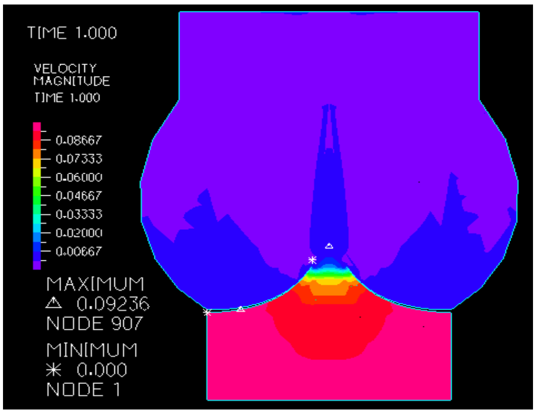

Figure B-135: 1.0 second

Blood flow velocity- Half-hemisphere shape leaflets

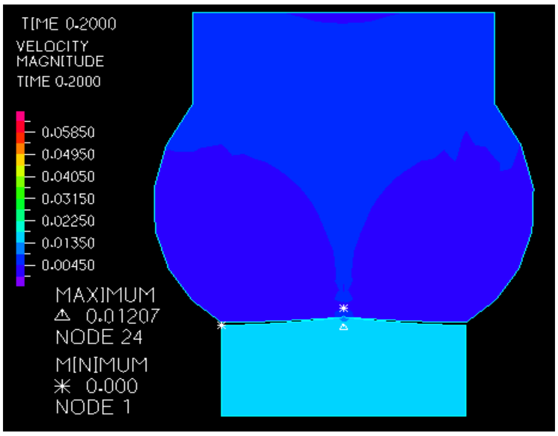

Figure B-136: 0.2 second

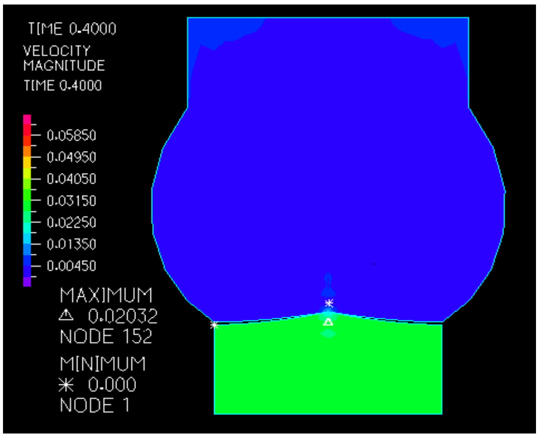

Figure B-137: 0.4 second

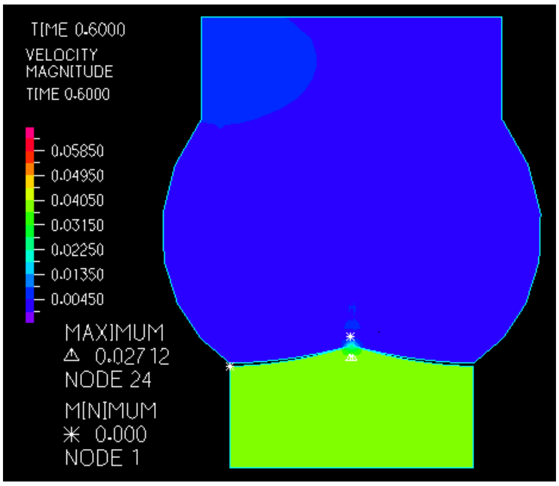

Figure B-138: 0.6 second

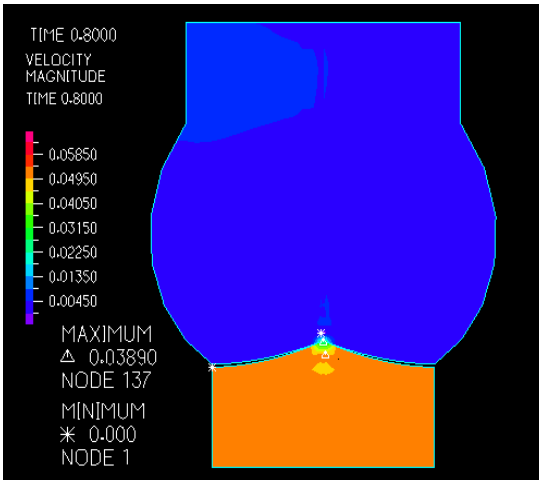

Figure B-139: 0.8 second

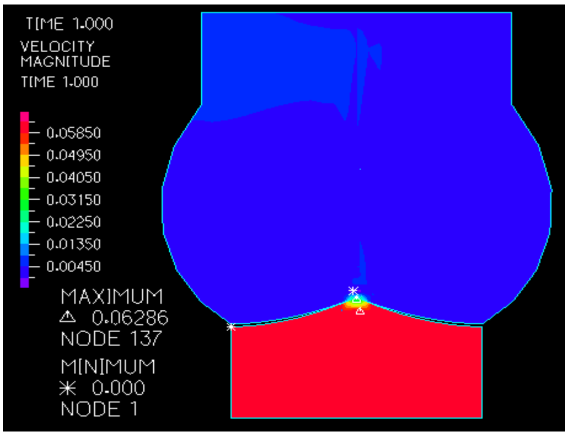

Figure B-140: 1.0 second

Blood flow velocity- Ellipse shape leaflets

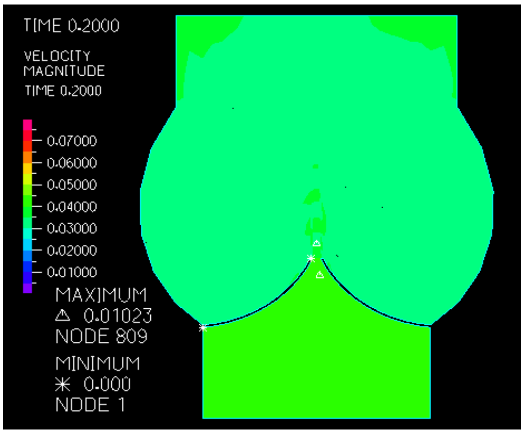

Figure B-141: 0.2 second

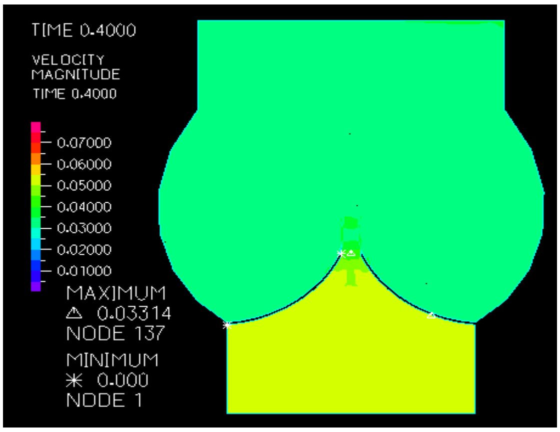

Figure B-142: 0.4 second

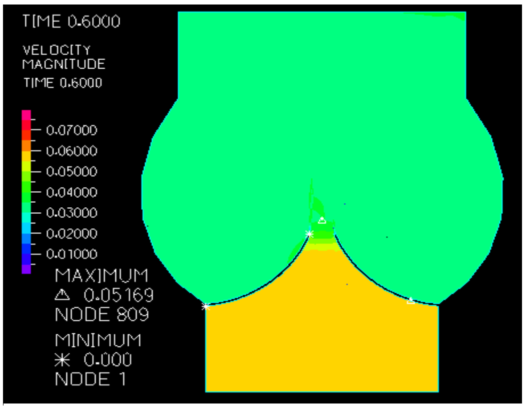

Figure B-143: 0.6 second

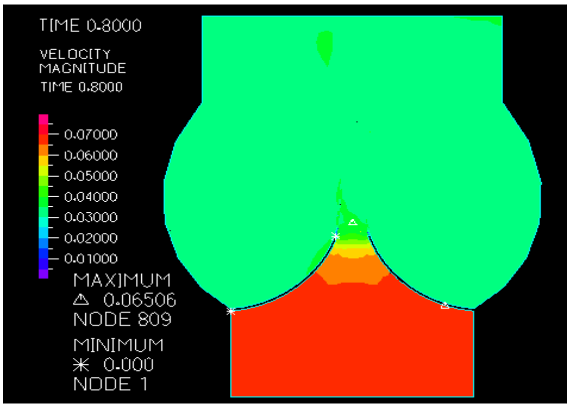

Figure B-144: 0.8 second

Figure B-145: 1.0 second

Blood flow velocity- V-shape leaflets

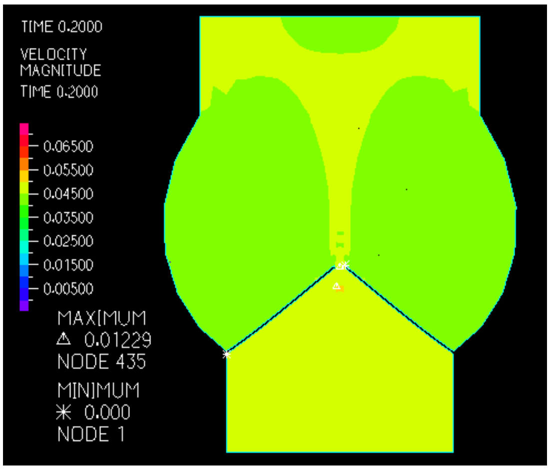

Figure B-146: 0.2 second

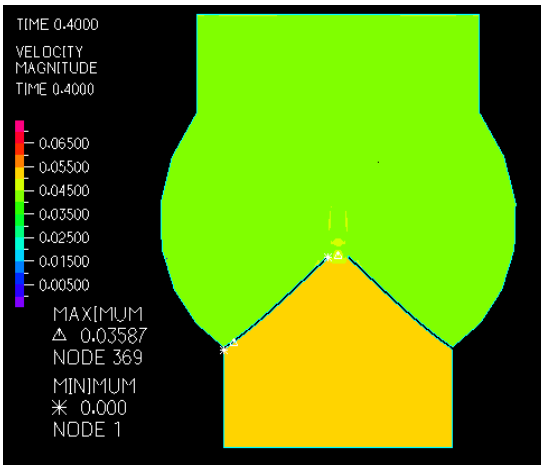

Figure B-147: 0.4 second

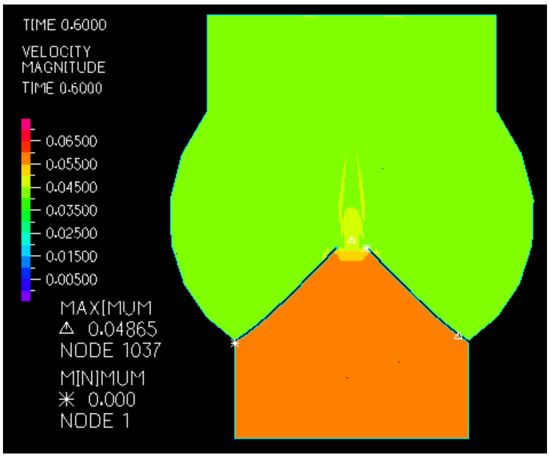

Figure B-148: 0.6 second

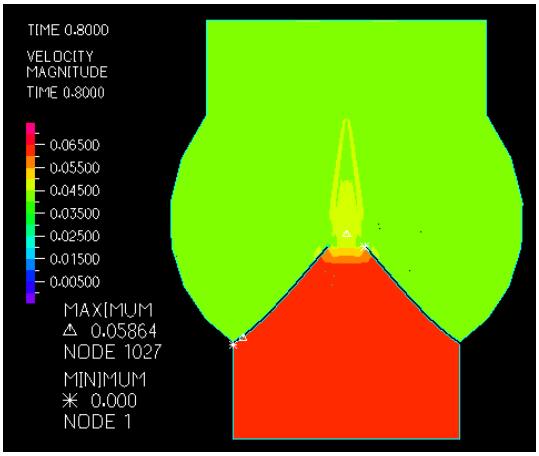

Figure B-149: 0.8 second

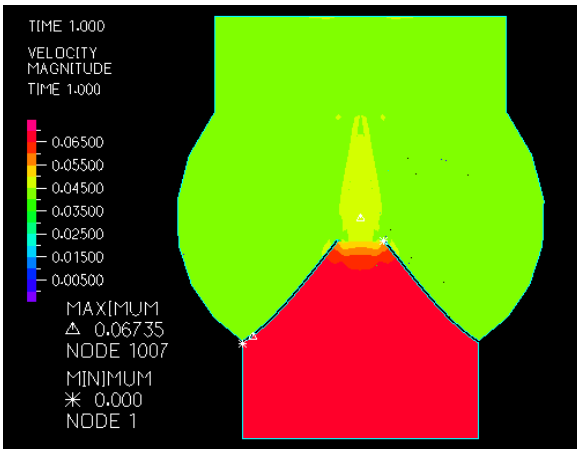

Figure B-150: 1.0 second

Aortic valve at Normal diastolic stage (Blood pressure = 80 mmhg)

Leaflets displacement changes - Square shape leaflets

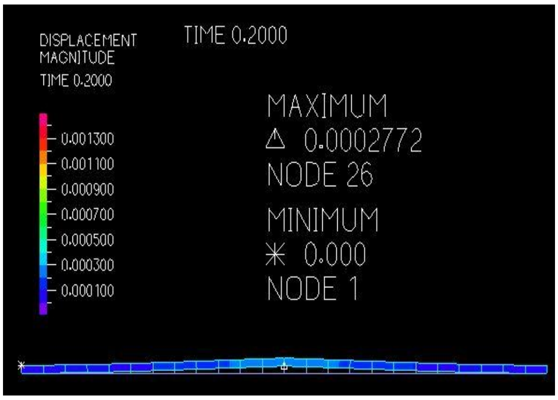

Figure B-151: 0.2 second

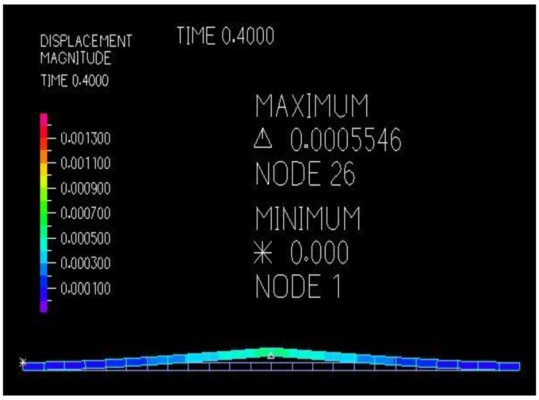

Figure B-152: 0.4 second

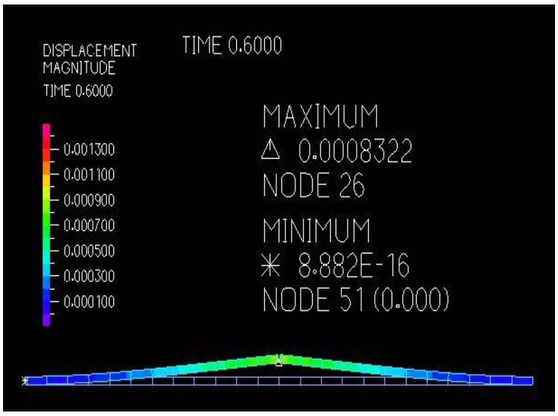

Figure B-153: 0.6 second

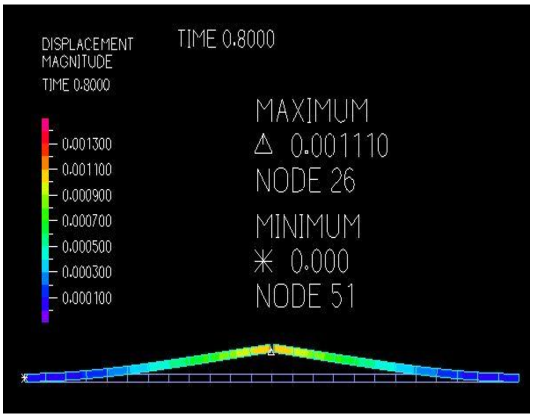

Figure B-154: 0.8 second

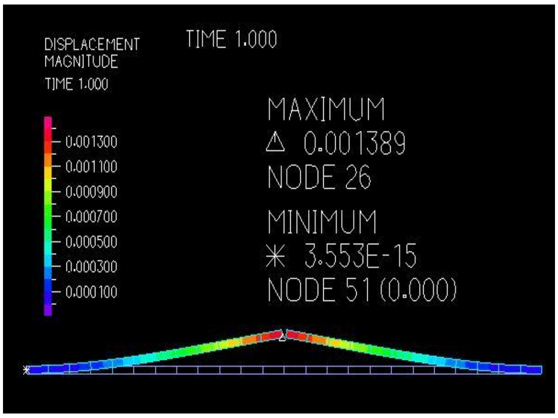

Figure B-155: 1.0 second

Leaflets displacement changes - Triangle shape leaflets

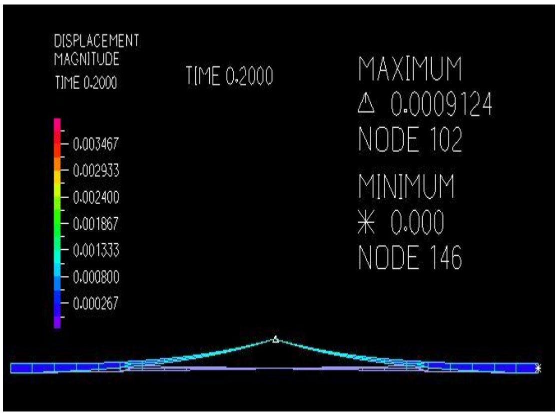

Figure B-156: 0.2 second

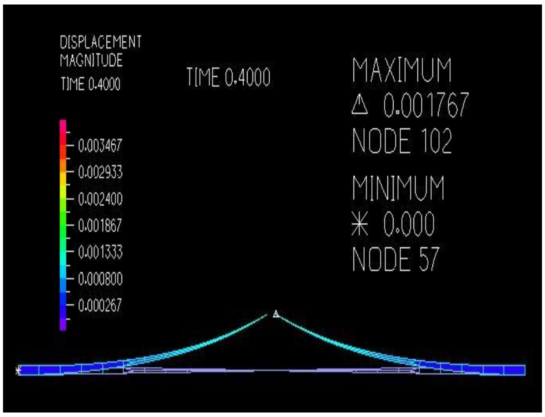

Figure B-157: 0.4 second

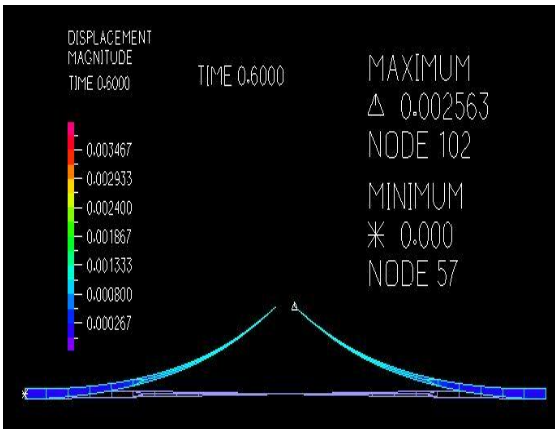

Figure B-158: 0.6 second

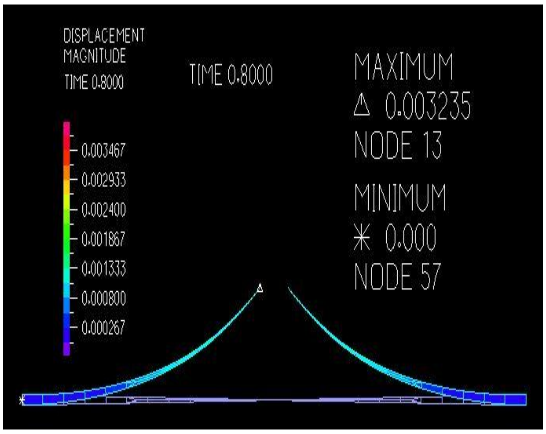

Figure B-159: 0.8 second

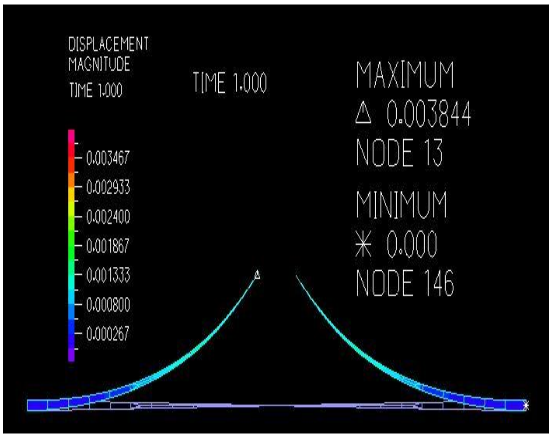

Figure B-160: 1.0 second

Leaflets displacement changes - Half-hemisphere shape leaflets

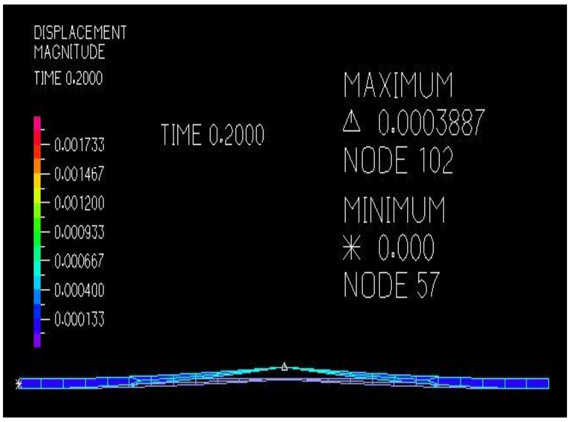

Figure B-161: 0.2 second

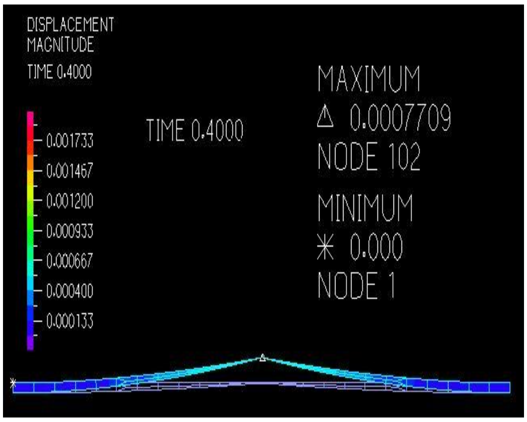

Figure B-162: 0.4 second

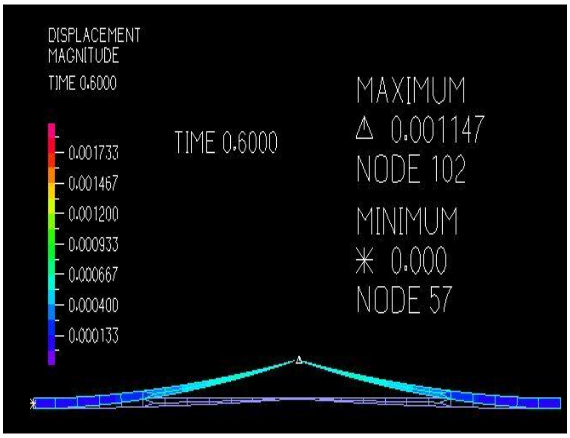

Figure B-163: 0.6 second

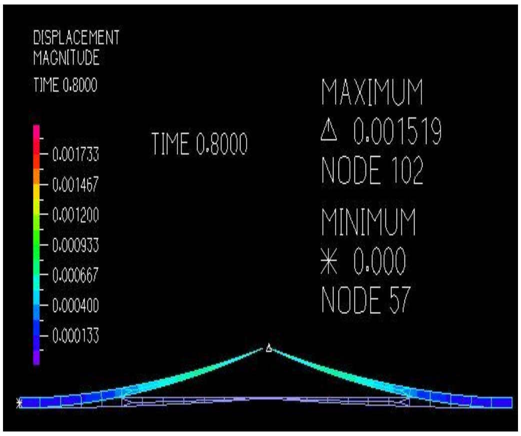

Figure B-164: 0.8 second

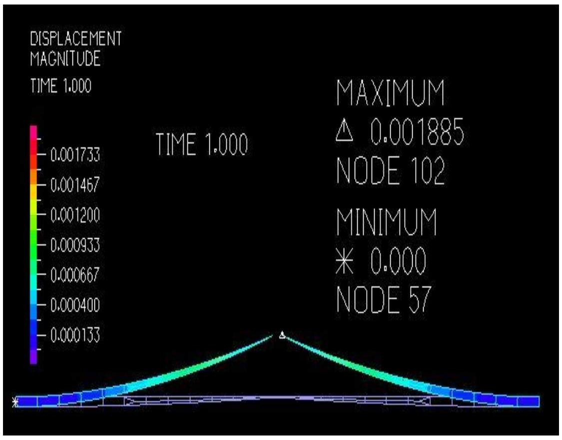

Figure B-165: 1.0 second

Leaflets displacement changes - Ellipse shape leaflets

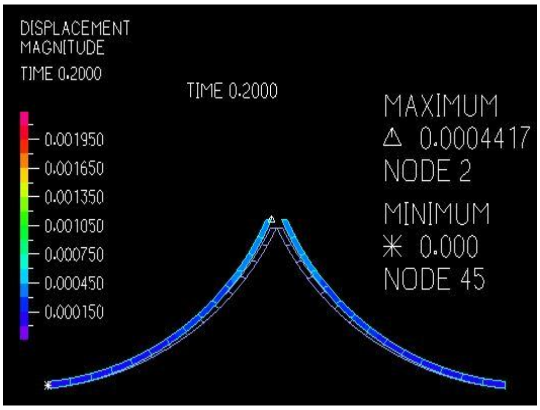

Figure B-166: 0.2 second

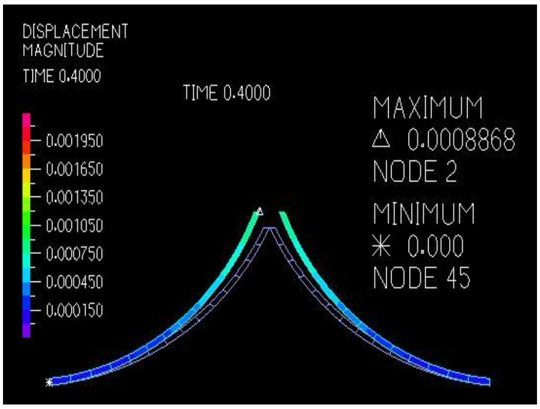

Figure B-167: 0.4 second

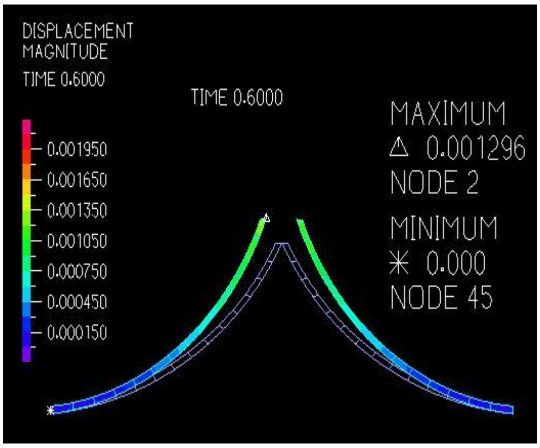

Figure B-168: 0.6 second

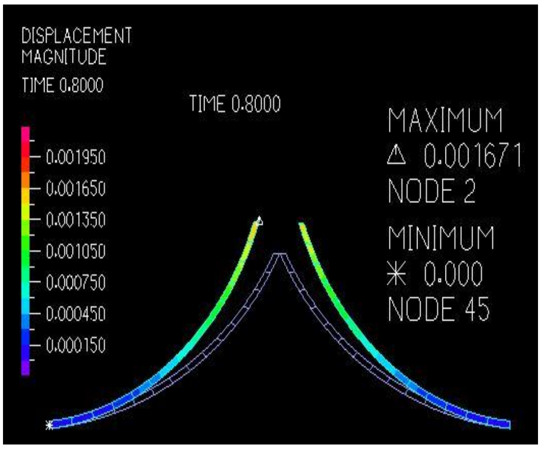

Figure B-169: 0.8 second

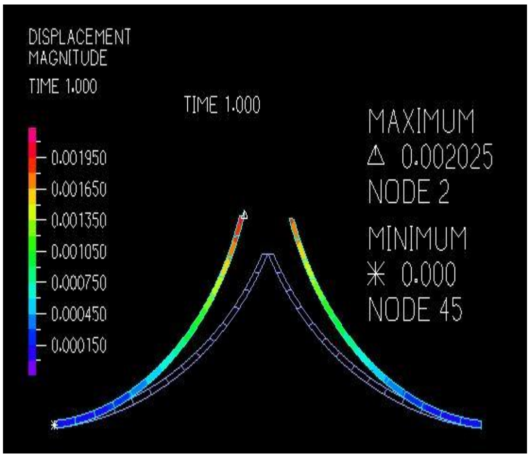

Figure B-170: 1.0 second

Leaflets displacement changes - V-shape leaflets

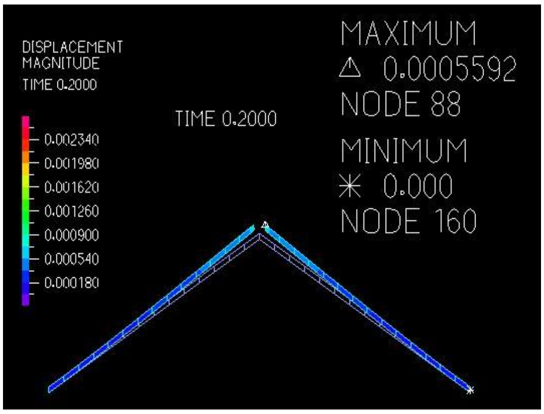

Figure B-171: 0.2 second

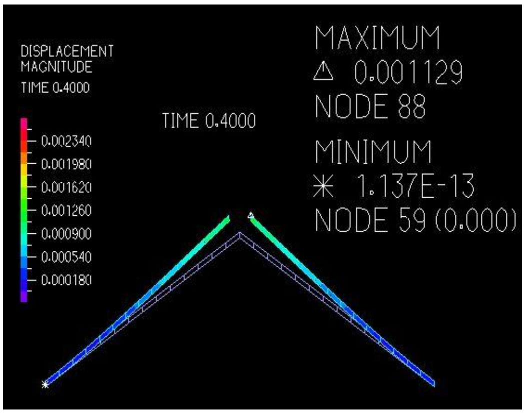

Figure B-172: 0.4 second

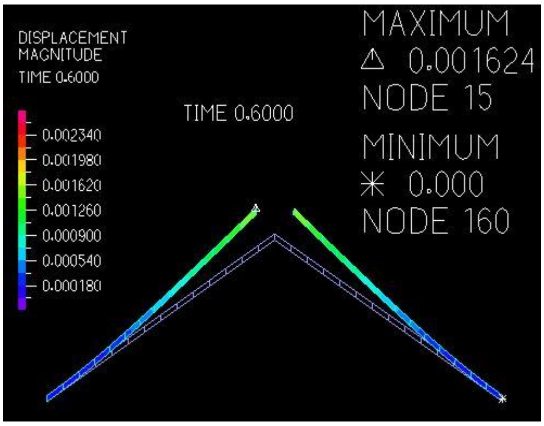

Figure B-173: 0.6 second

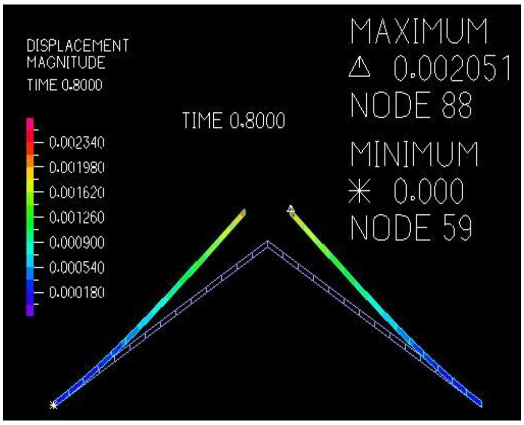

Figure B-174: 0.8 second

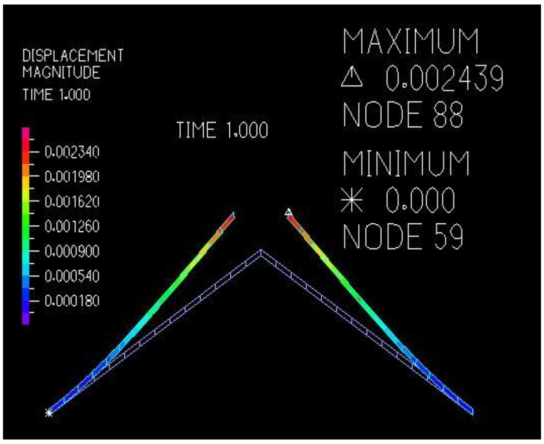

Figure B-175: 1.0 second

Aortic valve at Normal systolic stage (Blood pressure = 120 mmhg)

Leaflets displacement changes - Square shape leaflets

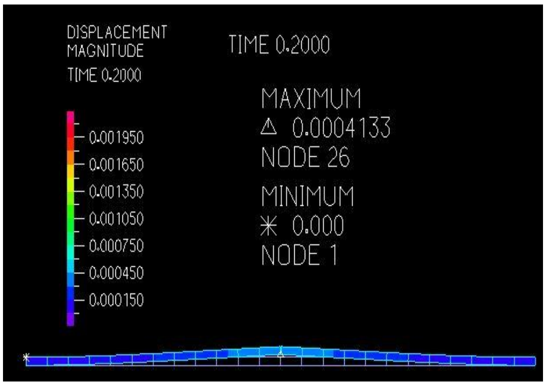

Figure B-176: 0.2 second

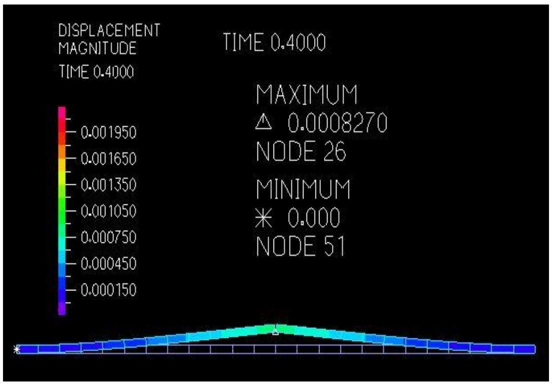

Figure B-177: 0.4 second

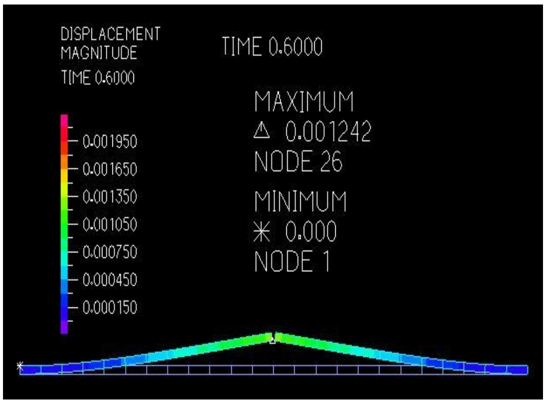

Figure B-178: 0.6 second

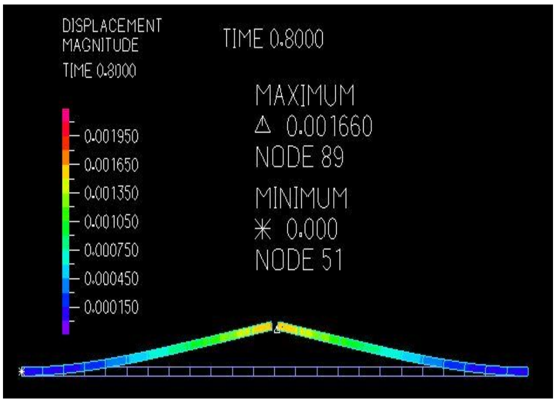

Figure B-179: 0.8 second

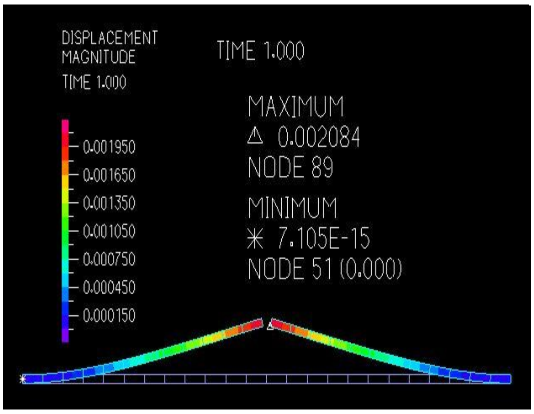

Figure B-180: 1.0 second

Leaflets displacement changes - Triangle shape leaflets

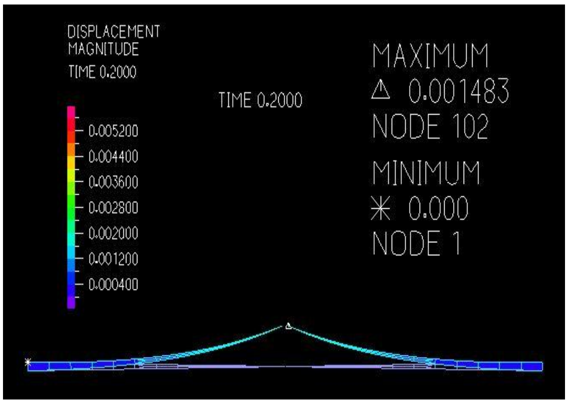

Figure B-181: 0.2 second

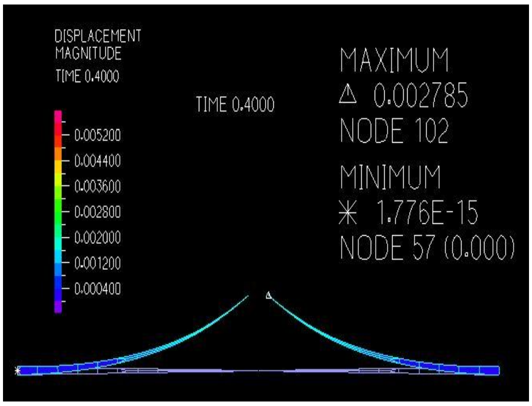

Figure B-182: 0.4 second

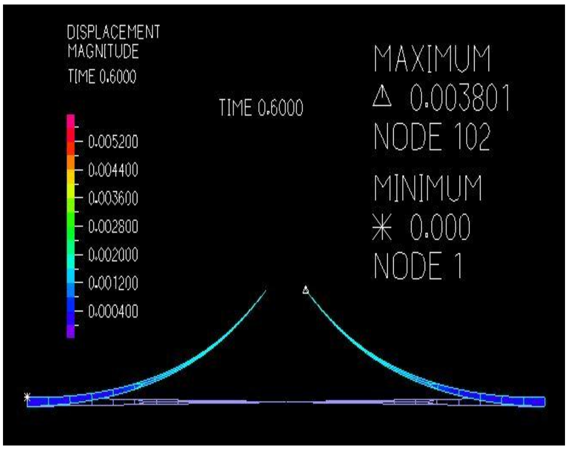

Figure B-183: 0.6 second

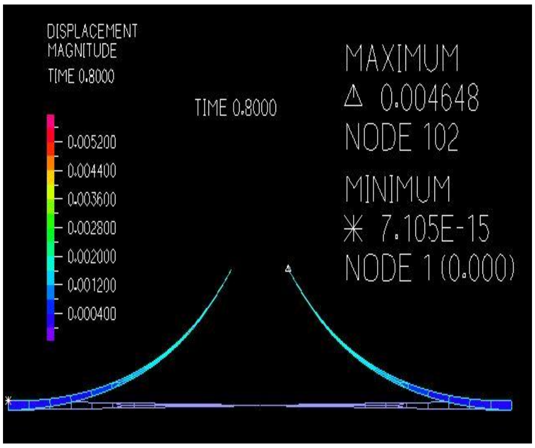

Figure B-184: 0.8 second

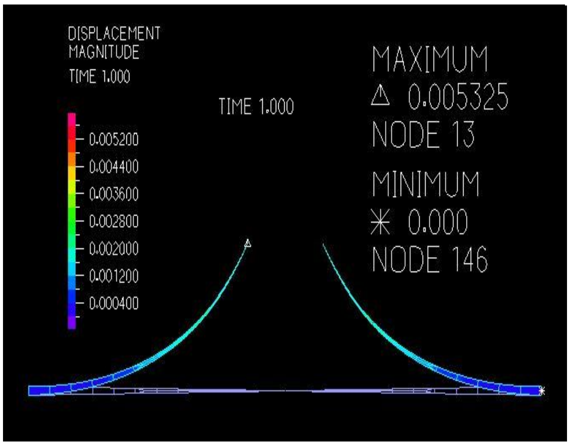

Figure B-185: 1.0 second

Leaflets displacement changes - Half-hemisphere shape leaflets

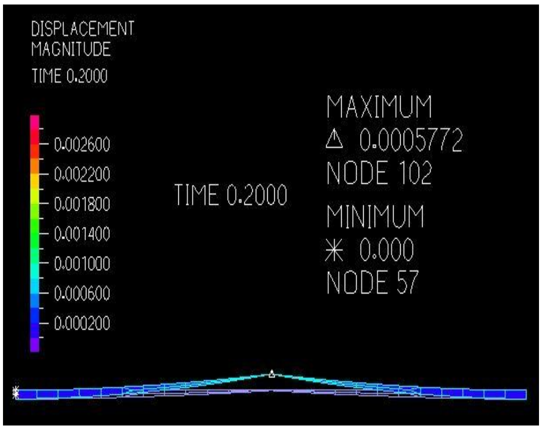

Figure B-186: 0.2 second

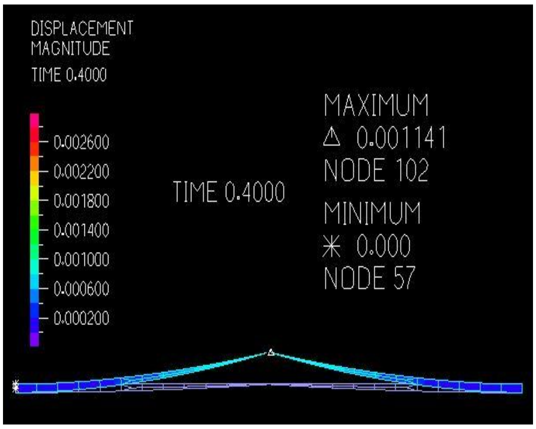

Figure B-187: 0.4 second

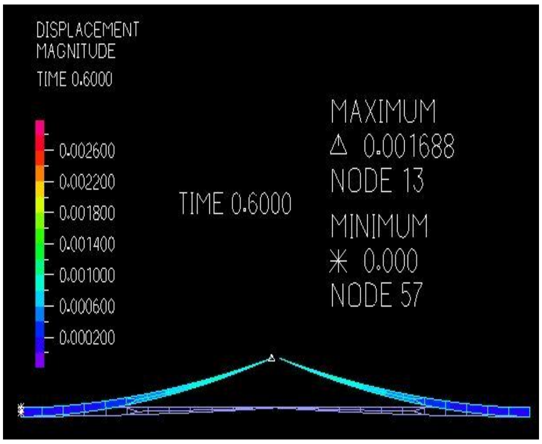

Figure B-188: 0.6 second

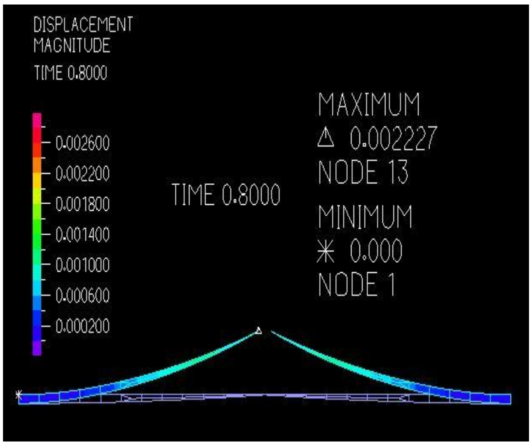

Figure B-189: 0.8 second

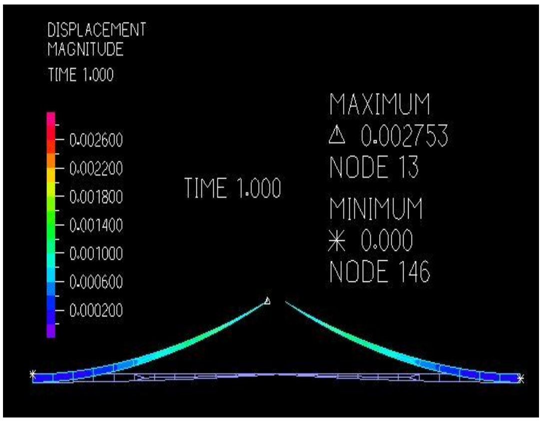

Figure B-190: 1.0 second

Leaflets displacement changes - Ellipse shape leaflets

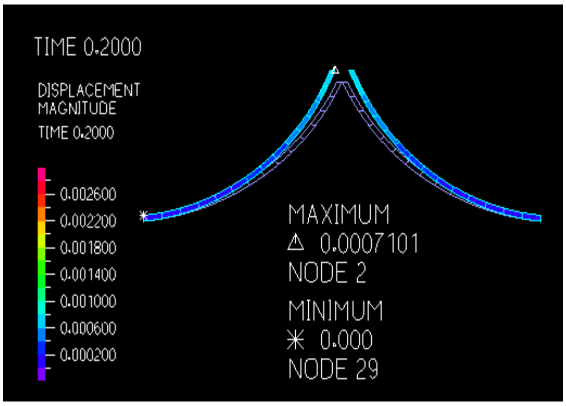

Figure B-191: 0.2 second

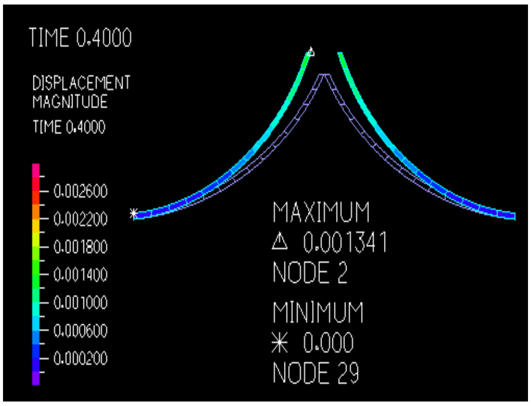

Figure B-192: 0.4 second

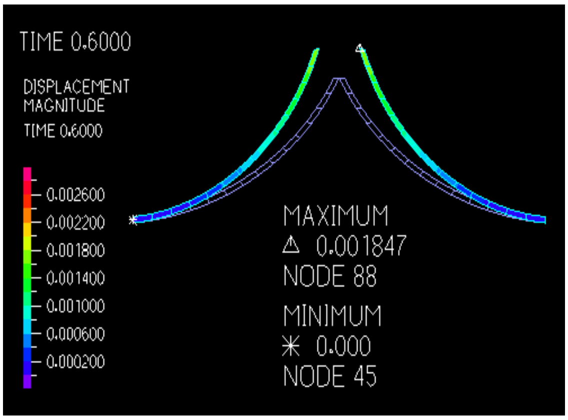

Figure B-193: 0.6 second

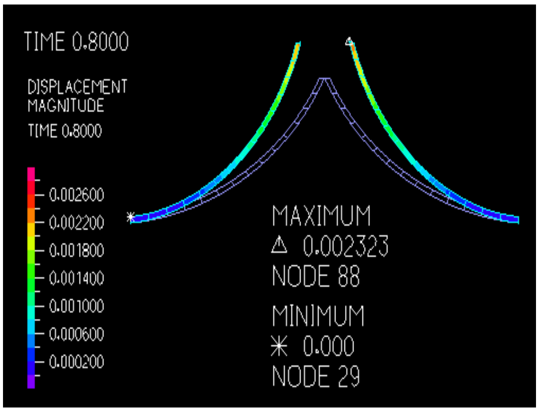

Figure B-194: 0.8 second

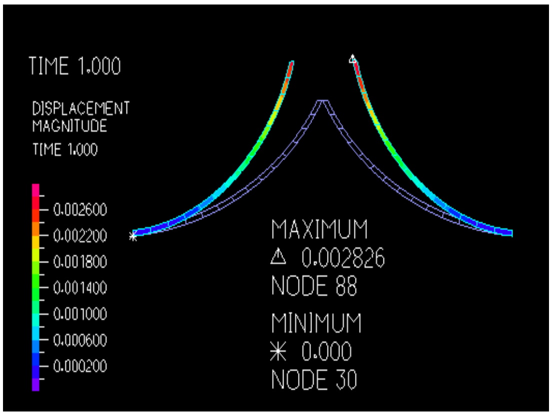

Figure B-195: 1.0 second

Leaflets displacement changes - V-shape leaflets

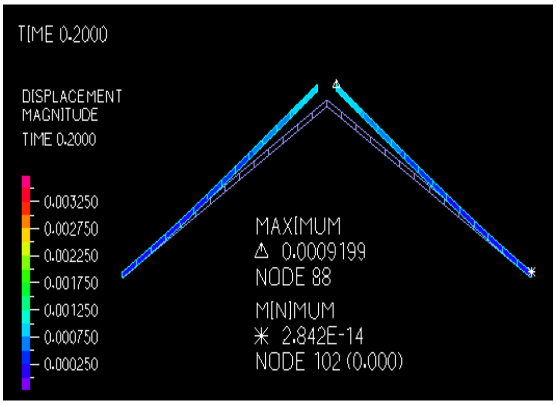

Figure B-196: 0.2 second

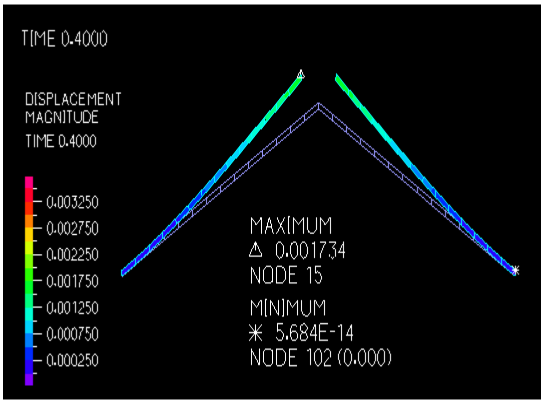

Figure B-197: 0.4 second

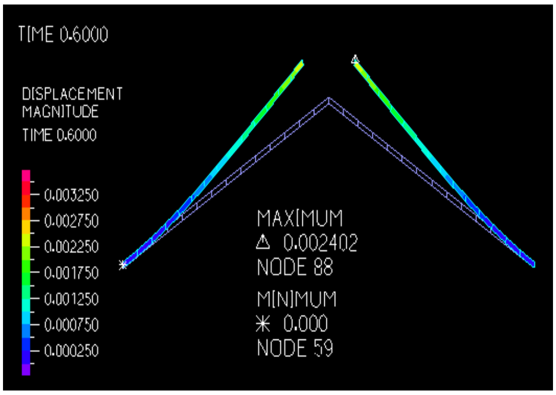

Figure B-198: 0.6 second

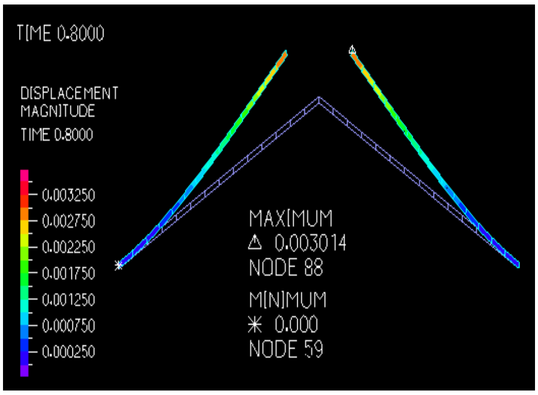

Figure B-199: 0.8 second

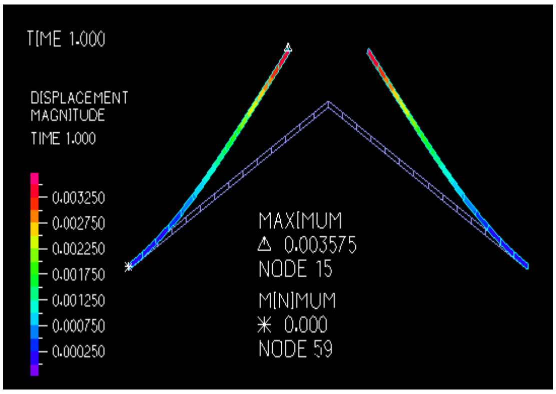

Figure B-200: 1.0 second

APPENDIX C

GANTT CHART FOR FINAL YEAR PROJECT 1

PROJECT PROGRESS	Semester 1															
	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Midterm Break	Week 8	Week 9	Week 10	Week 11	Week 12	Week 13	Week 14	Week 15
1.Introduction and briefing about the project																
2. Determine objective and scope																
3. Find the related information																
4. Do research and collect the suitable information																
5. Design and modelling the 2D mitral valve and aortic valve																
6. Trial run on the modelling																
7. Prediction on initial finding and result analyse																
8. Report writing and presentation																

Planning **Actual**

APPENDIX D

GANTT CHART FOR FINAL YEAR PROJECT 2

PROJECT PROGRESS	Semester 1															
	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Midterm Break	Week 8	Week 9	Week 10	Week 11	Week 12	Week 13	Week 14	Week 15
1.FSI simulation on the validation of parameters																
2.Data collected																
3.Data analysed																
4.Results discussion and conclusion																
5.Report writing																
6.Presentation																

Planning **Actual**

APPENDIX E

SOLIDWORKS DRAWING FOR MITRAL VALVE

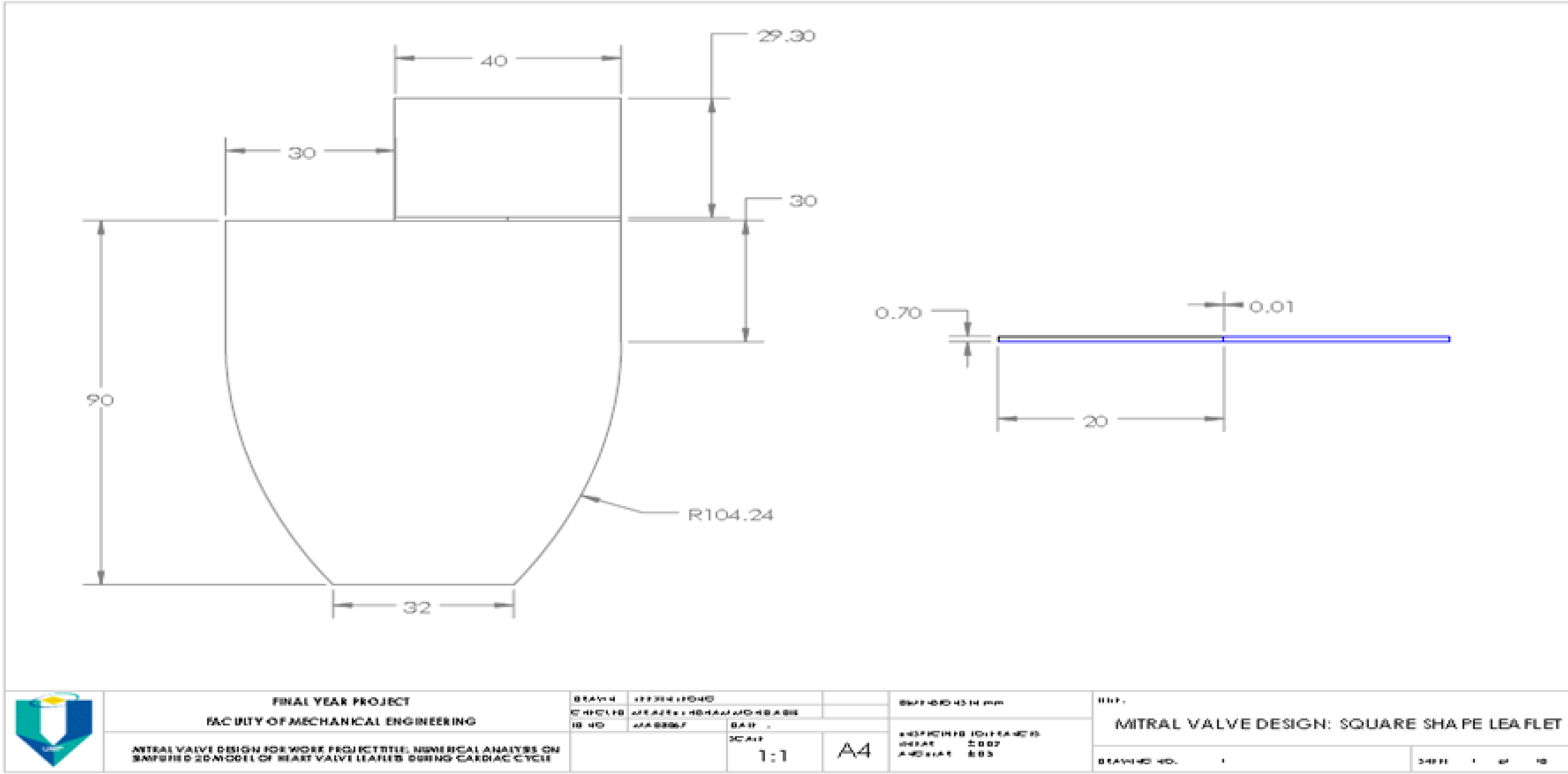

Figure E-1: Square Shape

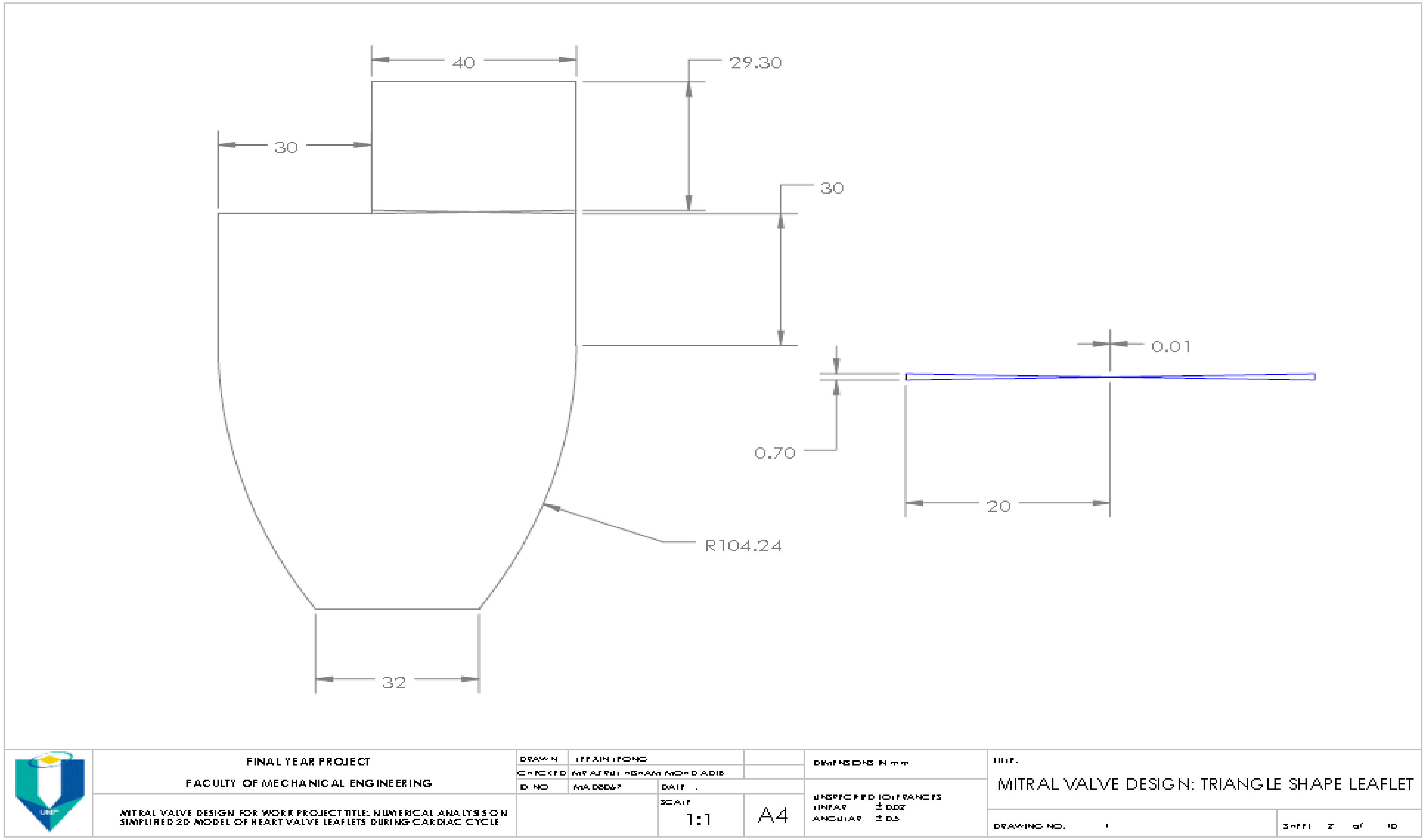

Figure E-2: Triangle Shape

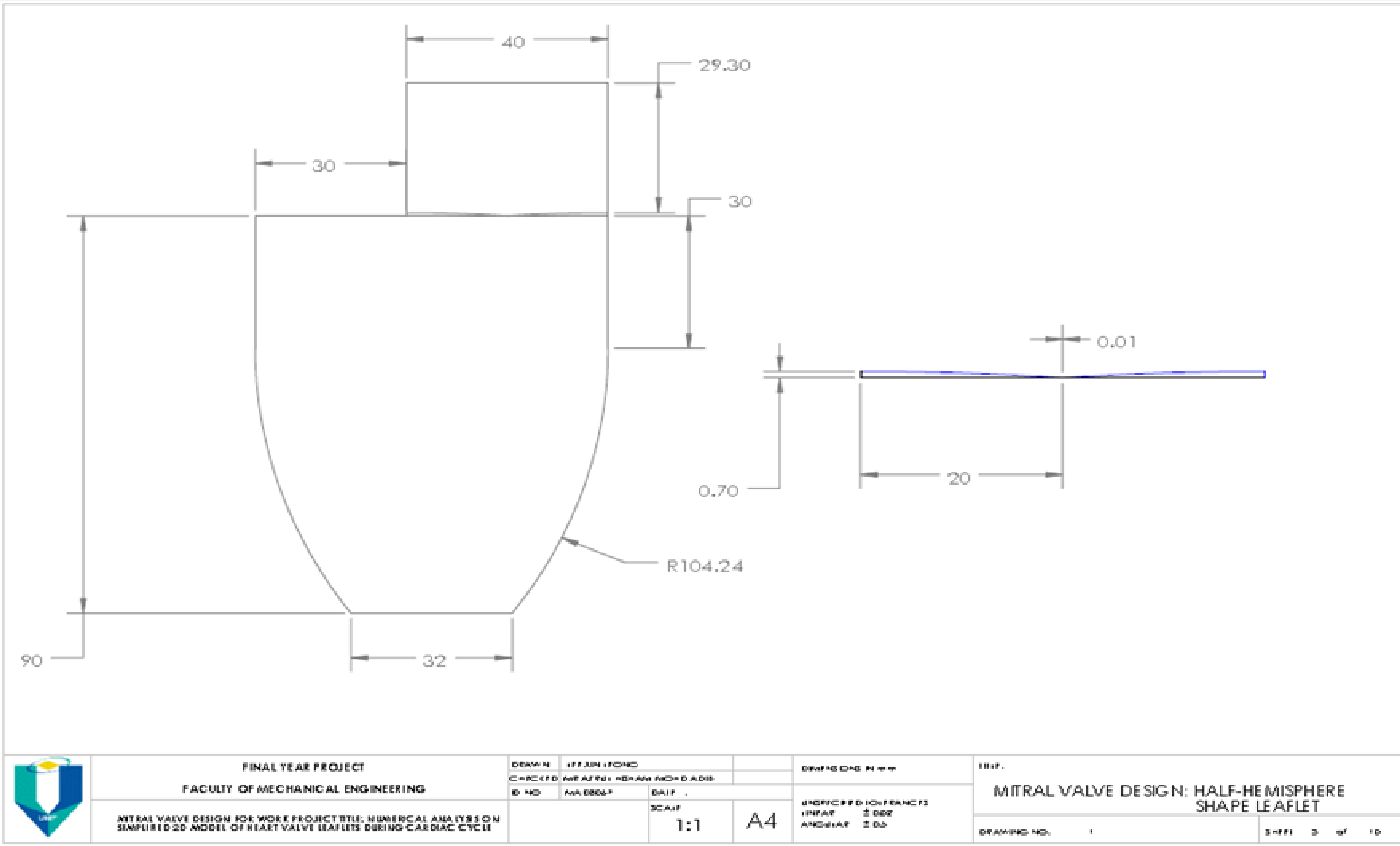

Figure E-3: Half-hemisphere Shape

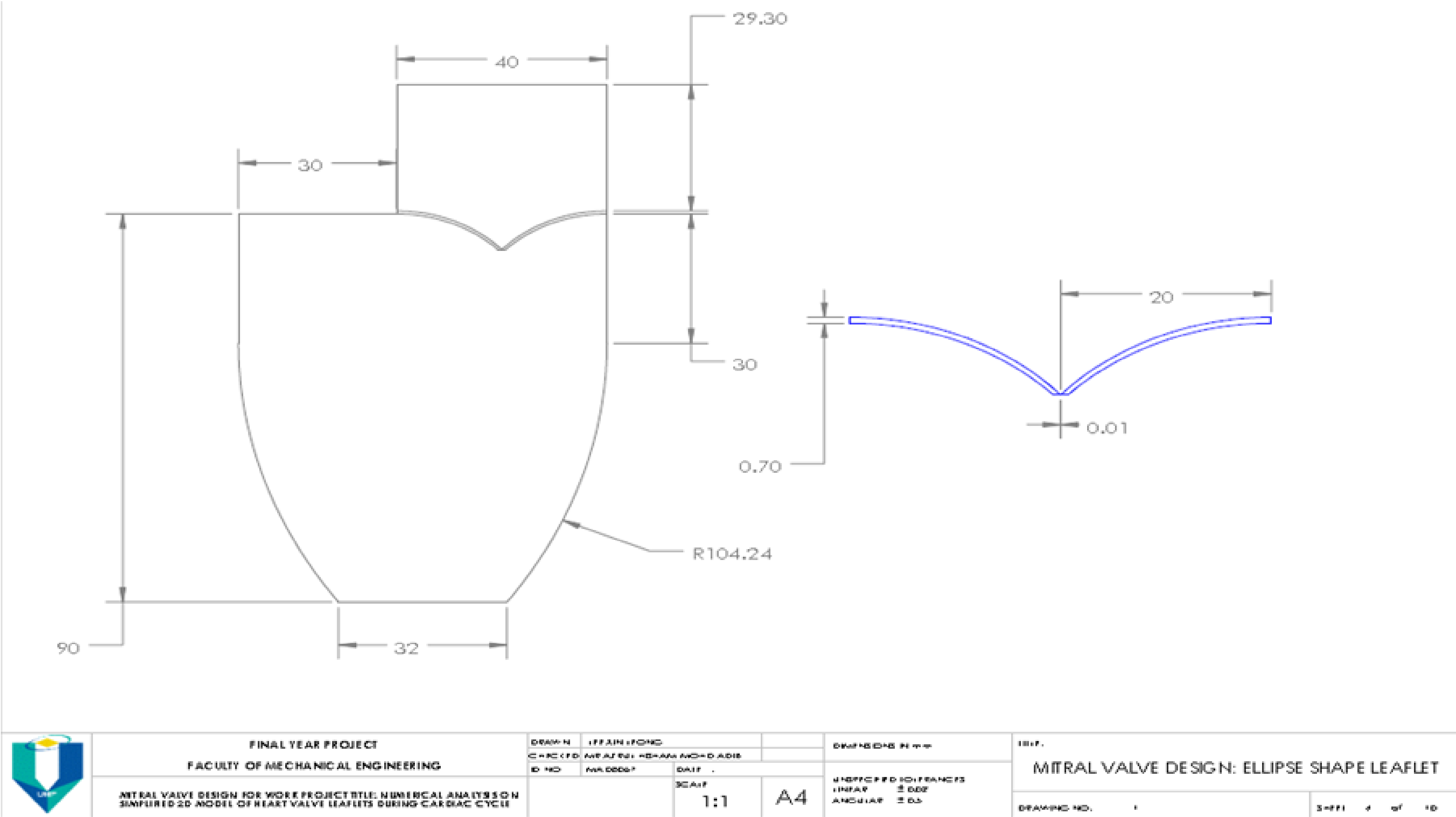

Figure E-4: Ellipse Shape

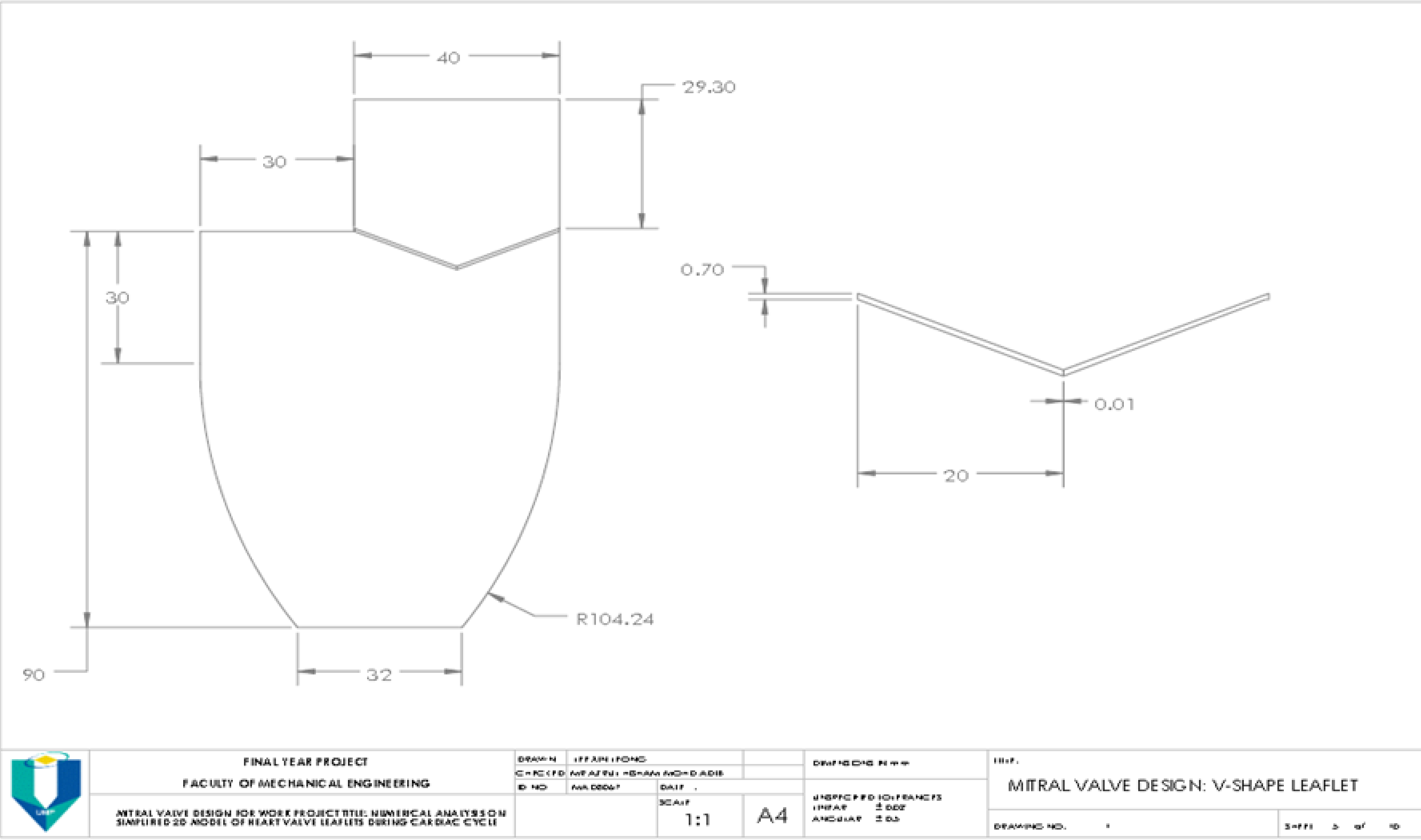

Figure E-5: V-Shape

APPENDIX F

SOLIDWORKS DRAWING FOR AORTIC VALVE

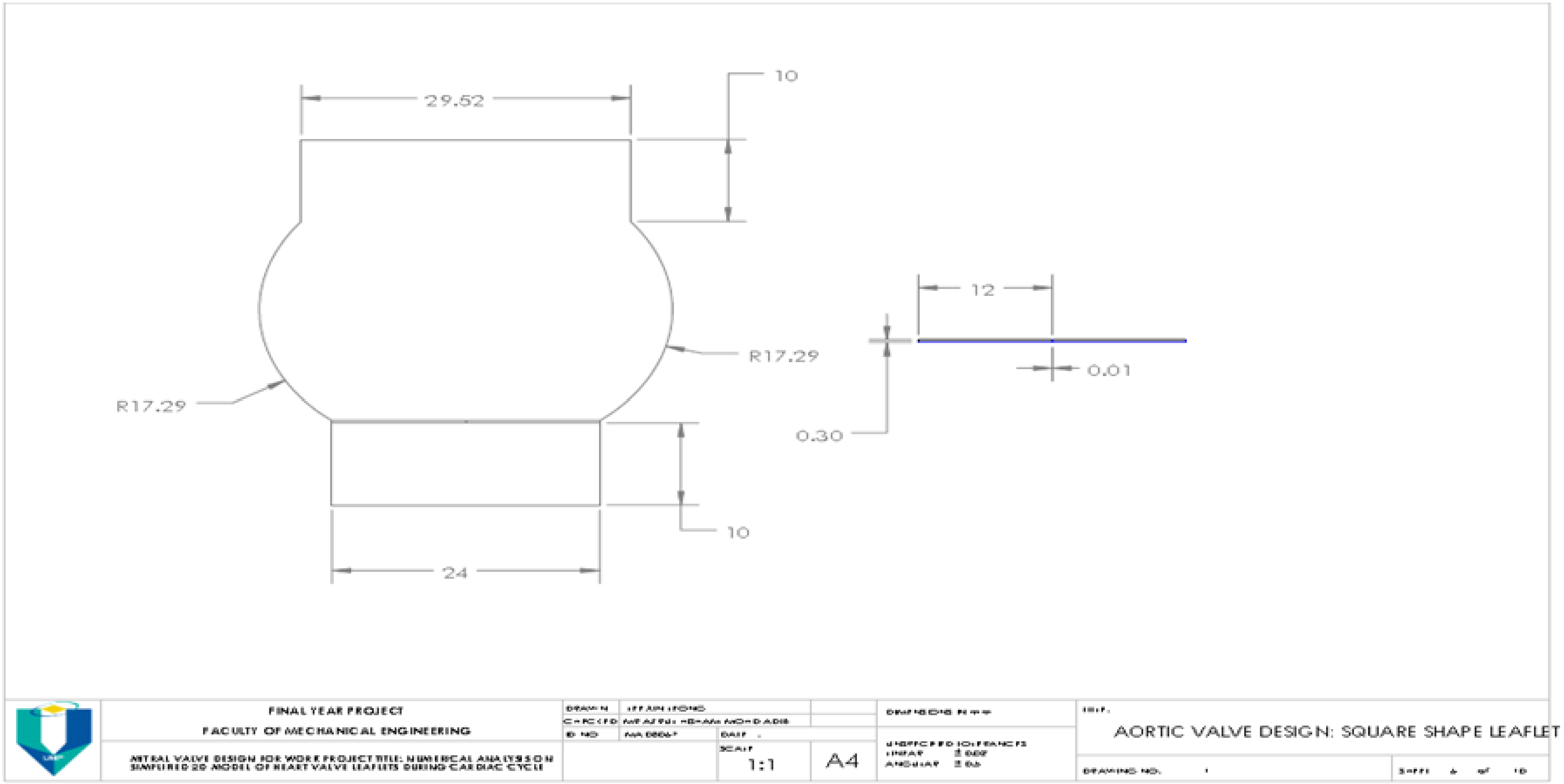

Figure F-1: Square Shape

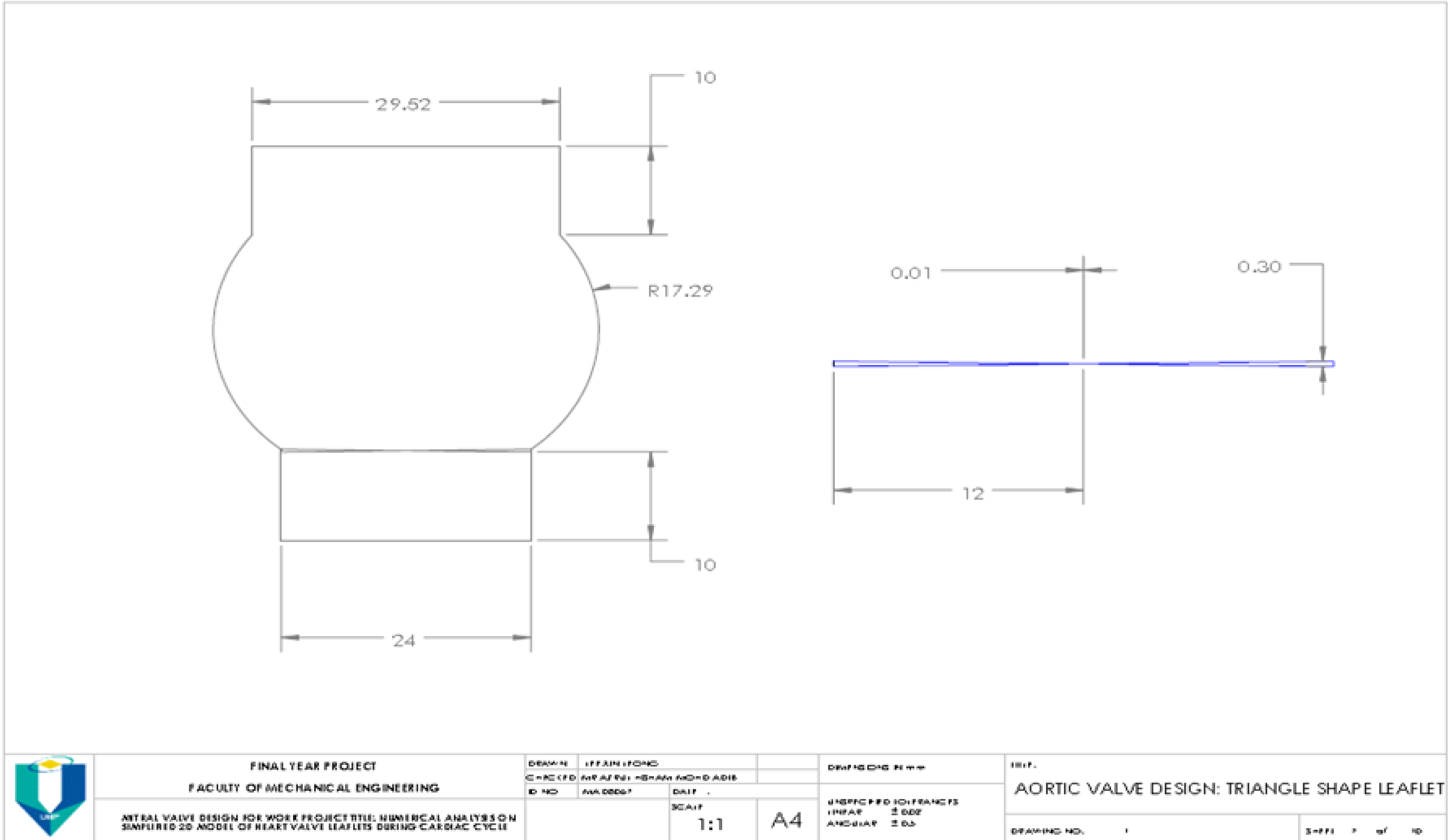

Figure F-2: Triangle Shape

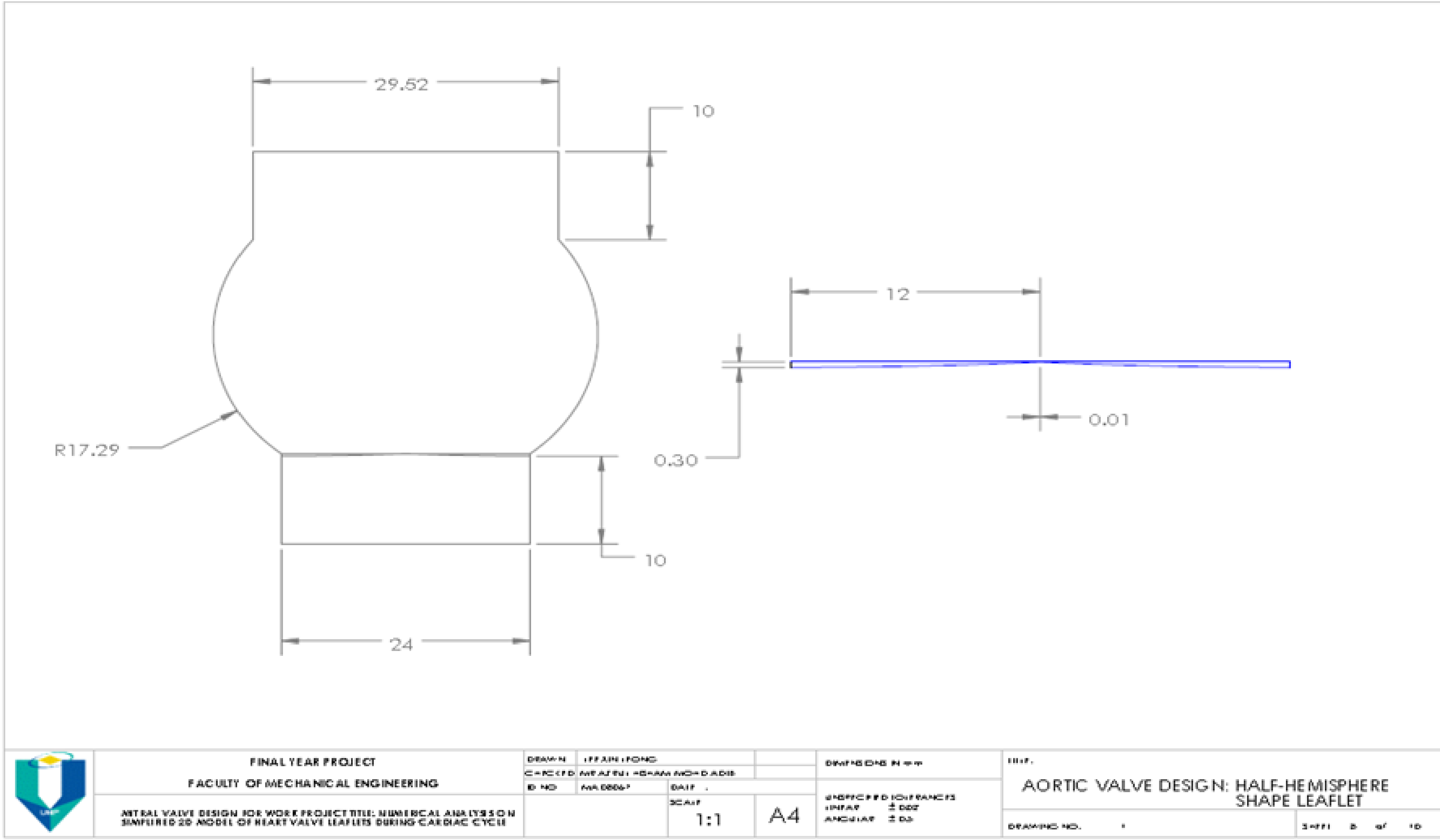

Figure F-3: Half-hemisphere Shape

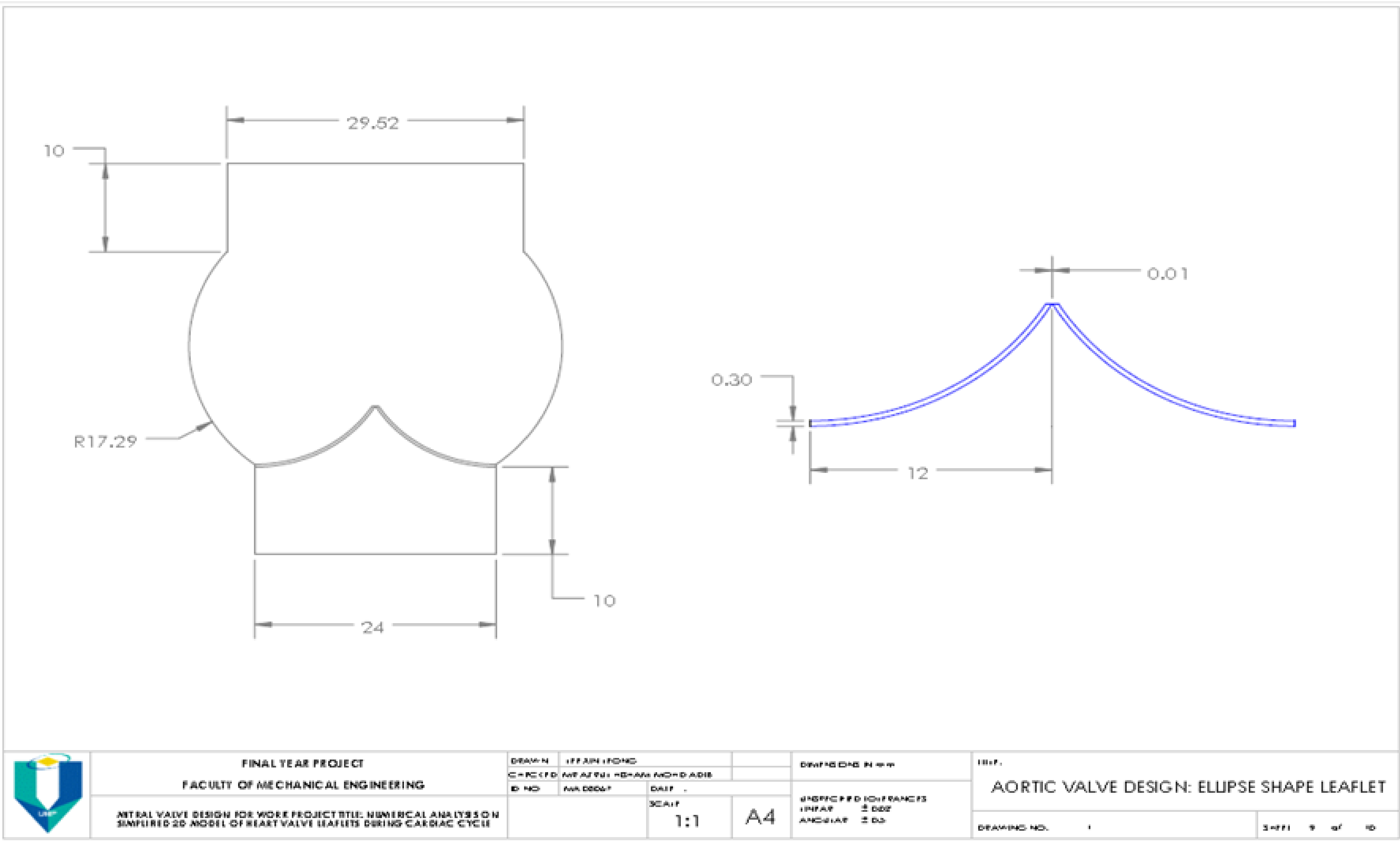

Figure F-4: Ellipse Shape

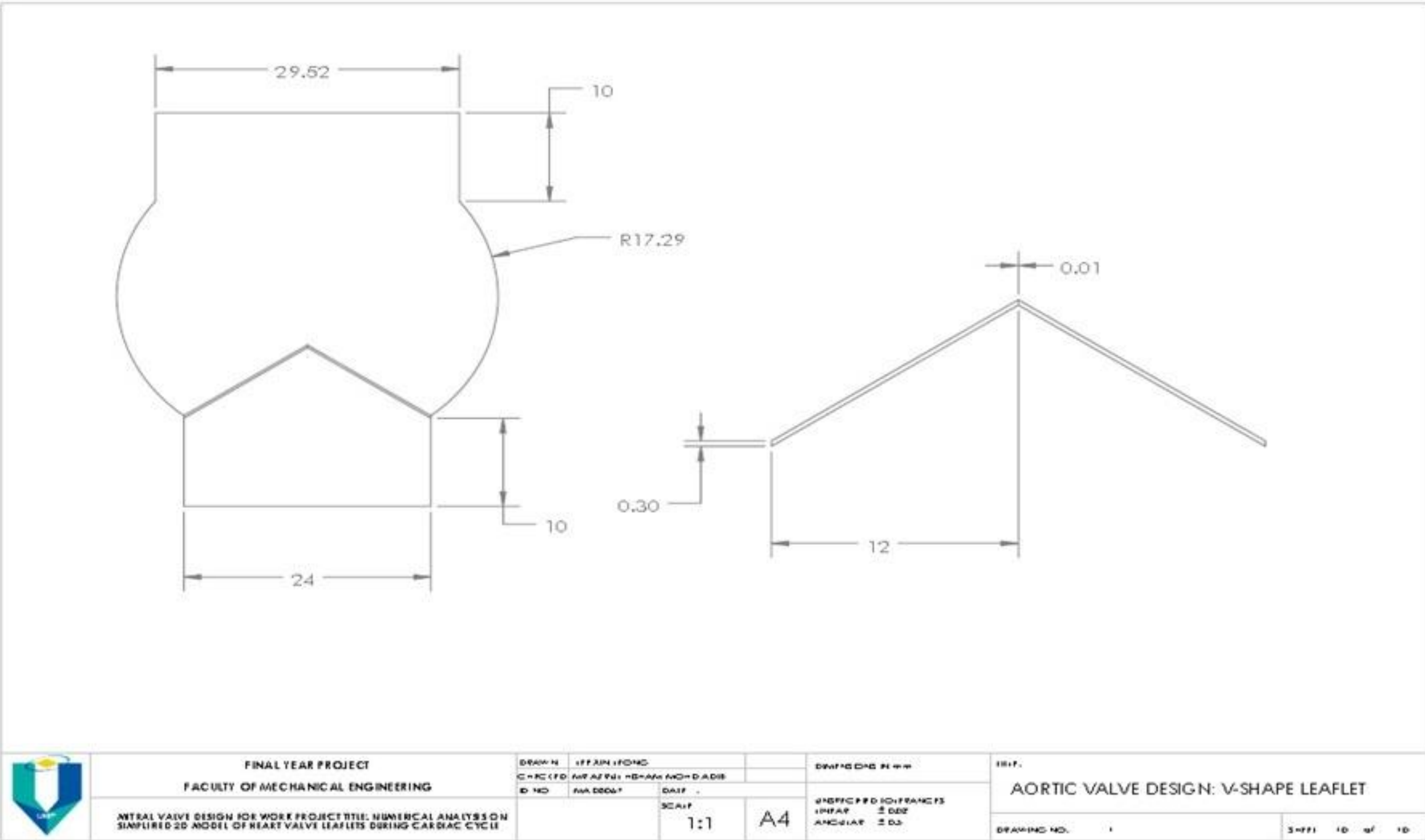

Figure F-5: V-Shape