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Finite Element Analysis of Human Body Thorax Subjected to the Ballistic Impact of Projectile

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ABSTRACT: The current article investigates the effect or response of three-dimension model of human body thorax to the ballistic impact of projectile using LS-DYNA finite element software. The diameter of projectile was 11.2mm and velocity of 250m/s. This high speed projectile is stopped by a steel plate with 4.5 mm thickness. This impact is considered risky to human body. The model composed of elastic and isotropic materials and assembled from two layers structure representing bone and muscle. The explicit method of analysis was utilized to predict the effect of the human thorax. The mechanisms of energy transmitting to the human thorax were represented by acceleration and displacement in this model. The human thorax model was exposed to ballistic impact and the analysis was made for the response from 3 different types of projectiles (blunt, hemispherical and conical) to identify and determine the acceleration-time, displacement-time and acceleration-displacement curves and its responses. The study has been introduced a method to analysis the human body response of blunt trauma from projectile impact without using the dead body as the specimens.

KEYWORDS: Finite element analysis, ballistic impact, projectiles and human thorax

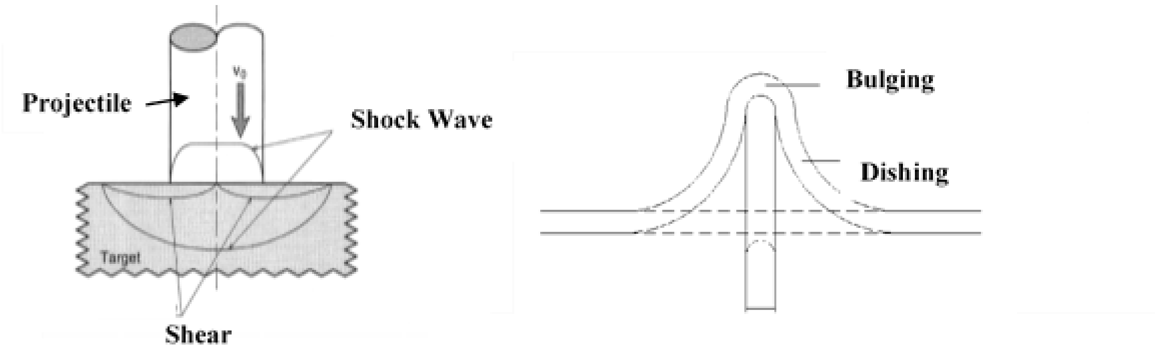
INTRODUCTION

Ballistics field is the study of the projectile motion, behavior and effects of this motion on the bodies. Understanding the response and effect of human body through impact has become a major attention, especially in the area of ballistic trauma and impacts. There are various studies that is classified to many types, such as the internal ballistics studies that examines the events inside the weapon, intermediate ballistics studies are examines the events that take place when the bullet exits the muzzle, external ballistics studies when the bullet is subjected to aerodynamic forces and terminal ballistics studies that is deals with the projectile behavior in the target and dealing with what happens when a bullet strikes a body which is includes many processes occur through the high velocity of variant projectiles [1, 2].

B. Li et al (2012) conducted many tests that concern with the impact of Aluminum alloy T6 thin plates subjected to steel projectile with different thicknesses of 0.8mm to 1.6mm with various of velocities of (100 to 400)m/s; they found very good agreement between a ballistic limits through the thickness and computed perforation areas with velocity ranges, they also found robust convergence of the numerical method in parameters of number of nodes vs. velocity error [3]. Generally, the transitions process is extraordinarily flexible since deformation processes and depends on a several parameters in addition to impact velocity. The phenomena of impact and penetration into materials has been great interest in military field, a lots of efforts have been invested on the research in analytical and experimental methods since the World War II and expanded to the present day. According to J. Buchar and J. Hřebíček [4], the penetration phenomenon can be describe to the trauma angle, material type, geometrical design of the projectile and the value of velocity, and they reported that the penetration model of target consists of four regimes: Transient regime, Steady state regime, Cavitation regime and recovery regime this model has verified by computational analysis.

Figure 1-a shows wave pattern of projectile and target through the penetration phenomena. Figure1-b represent a schematic diagram of failure modes which is consist of two types of failure modes as a transverse displacement

of thin element due to permanent deformation: Bulging mode, where the element mechanism of the penetrator nose in the contact area and dishing mode, which is followed by bending process, which may be extended to distances from the impact area. The meaning of deformation mechanism or failure mode refers to the maximum displacement of the panel surface from armor that is caused by impact or a hit that does not penetrate the armor at initial contact area [5]. There are many researchers mentioned to penetration phenomena in range of initial velocities because these velocities have so significant effects on this phenomena with other considerations, these velocity ranges can be divided into four categories: 1) Sub-ordnance range; the velocity range from 25-500m/s, it is achievable in pneumatic guns or any other laboratory tests, 2) Nominal ordnance range; the velocity range from 500 to 1300m /s, such as conventional guns which the propellant can burn behind the projectile, 3) Ultra ordnance range: the velocity range from 1300 to 3000m/s, which is representing by warhead fragments and for special purpose guns and 4) Hypervelocity range; this range involving shaped charges, meteors and light-gas guns [6].



a) wave during the transient regime, [4]   b) Configuration of Bulging and Dishing [5]

Figure 1: Schematic diagrams represent the behavior of projectile and Target

Aristide Awoukeng et al (2014), explained investigation of penetration phenomena of human tissue numerically using finite element investigations and simulation analysis of steel projectile with a different velocity, they compared their study with experimental work and analytical data of literature, the study gave encouraging results for additional investigations of penetrating projectile into human body. In penetration procedures, most of numerical analysis and simulation undergo to complicated analysis. Generally, Simulation process is expensive analysis because of this process requires several hours of time by the computer programs [7]. In the last twenty years the composite materials which has special properties and high strength to weight ratio, it has been in the development of engineering applications especially in laminated composite materials [8, 9]. Composite materials such as Kevlar fiber used in armor vest and ballistic impact, the energy is absorbed and dispersed from the fibers to other fibers (layers) in the weave and ultimately to the body. This shock to the body is known as blunt trauma and must be kept at a level, in which injury from it does not occur, and the human body can withstand a certain amount of blunt trauma and this tolerance is measured in millimeters during body armor testing. In body armor standards require that a projectile should be stopped under ballistic impact, and the penetration depth into a clay witness backing the armor should not exceed 1.7 inches. If the penetration depth exceeds this value, a wearer can incur serious blunt trauma. Several parameters, such as the ratio of target thickness to projectile diameter, the projectile nose shape and the materials involved, are known to affect the penetration mechanisms [10,11].

The armors are protecting of the human thorax against the damage or hostile actions, the bullet should be reduced or stopped the effects of the penetrating of the projectile, and a part of energy is transferred through the layers of the armor to protect the body. The effects of the body thorax were studied, analyzed and evaluated behavior of displacement versus time, the force versus time and acceleration-time curves with suitable impact. Combination of these effects provided a force-displacement curve of the thorax; these studies used many kinds of projectile shapes [12]. The current study used three types of projectile as shown in Figure 2. The problem statement of ballistic impact process is how to evaluate the protection systems of human body that consist of many layers, and understanding of the behavior material under the ballistic impact. However; experimental tests are very expensive issue and if such testing to be carried out required a special licenses, so to save the time and cost, finite element analysis was used in this study. The main objective of the current paper is to develop finite element model for metal plate projectiles and study human body effects for blunt, hemisphere and conical projectiles on human thorax with different shapes were used for this study. This model composed of elastic and isotropic materials and assembled from two layers structure representing bone and muscle. The explicit method of analysis was utilized to predict the effect of the human thorax.

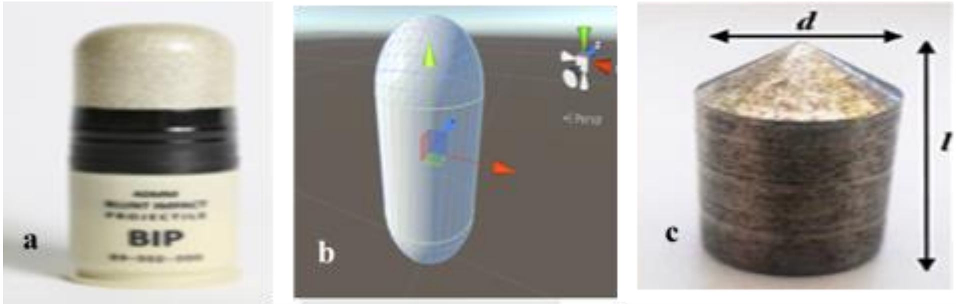


Figure 2: Projectile nose shapes, (a) Blunt head, (b) Hemispherical and (c) Conical

FINITE ELEMENT MODELING

Through the finite element analysis, step-by-step modeling must be carrying out to identify and verify the finite element model referring to conducting parametric studies. The analysis study consists of three important stages, which are Pre-Processing or initial process, then processing data and post-processing stage. Some of the parameters should be considered in the models such as velocity value and the projectile nose shapes are changed through the study. The effect of human chest was obtained and phenomenon was simulated for the new projectile shapes which were blunt head, hemisphere and conical projectile. After conducting the analysis and referring to the results, discussion and recommendation were included in this work. For current analysis ANSYS/LS-DYDA Finite element software was used to design and analysis the three models. These models consists of a thorax model and plate made of steel type 4340 affected by three types of projectiles (blunt head, hemisphere and conical) projectile. To reduce the time; quarter models were simulated as shown in Figure 3. There are two layers represented the human thorax (muscle and bone) to simplification the real thorax body. The current model is limited to under the impact zone only, that is mean the expansion of the energy in the full thorax is not deemed.

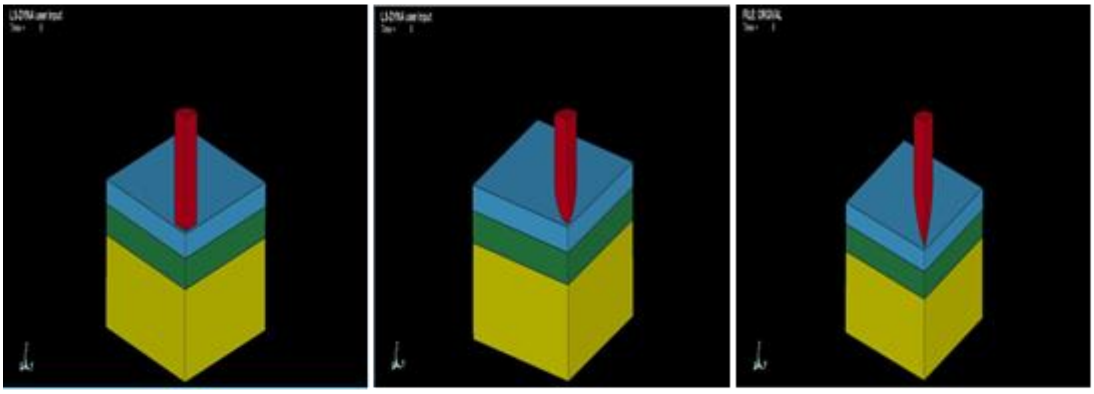


Figure 3: Model of the human thorax for: (a) blunt head, (b) hemisphere and (conical projectile)

It is apparent that the initial distance between the projectile and the plate is to be very small, it was 0.5mm to reduce the analysis time and computational cost and by reducing the traveling of projectile and number of stages through the analysis before impacting the plate to saving the time during analysis. Table 1 represents the coordinates for different layers of the plate and the human thorax

Table 1. Coordinates for different layers of Human thorax

Parameter	Symbol	Steel
Density (g/cc)	ρ	7.85
Shear Modulus (GPa)	G	80
Poisson Ratio	***v***	0.29
Modulus of Elasticity(GPa)	E	200

ELEMENT TYPE, MESHING AND BOUNDARY CONDITIONS

Three-dimension solid elements (SOLID164) were used for the modeling of solid structures; eight nodes have the following degrees of freedom at each node: translations, velocities, and accelerations in the nodal directions. The deformation of the projectile is assumed to be very small, thus the projectile was considered to be rigid body and doesn't deform. Table 2 shows the steel constants.

Table 2. Material constants for projectile

Parameter	Symbol	Steel
Density (Kg/m^3)	ρ	7850
Poisson Ratio	υ	0.29
Modulus of Elasticity (MPa)	E	210000
Static Yield Limit (MPa)	σ_y	792

All rotations should be restricted or constrained in the analysis of the model. The plastic kinematics material was used to represent the steel plate. Isotropic and kinematics hardening was used for this model with the option of including rate effects. In this model, strain rate was accounted for using a special model which scales the yield stress. These material constants of steel are listed in Table 3.

Table 3. Material constants for steel

	Coordinates					
Layer	X1	X2	Y1	Y2	Z1	Z2
Plate	0	-50E-3	0	-50E-3	0	-5E-3
Human thorax (Muscle)	0	-50E-3	0	-50E-3	-5E-3	-10E-3
human thorax (Bone)	0	-50E-3	0	-50E-3	-10E-3	-15E-3

For the thorax body model, the material constitutive laws for both muscle and bone are isotropic homogeneous and linearly elastic materials. Mechanical characteristic of the layers are tabulated in Table 4. A free mesh using tetrahedral element is applied to the projectile mesh generation as rigid material. The meshing of the projectile as shown in Figure 4

Table 4. Mechanical and geometrical characteristic of the layers

Parameter	Symbol	Layer 1 (muscle)	Layer 2 (bone)
Modulus of Elasticity (GPa)	E	0.675	11
Poisson Ratio	υ	0.45	0.3
Density (kg/m^3)	ρ	1000	2000
Thickness (cm)	t	0.5	1.5

The plate and thorax models represented as quarter (1/4) of the whole geometry; boundary conditions are put on the symmetrical planes, eight nodes with hexahedral elements were used. To mesh the steel plate, plastic kinematics material used to mesh generation of the thorax model, the size element for both layers muscle and bone are same as the element size of plate. It is important to assign the correct boundary condition as constraining any node which led to existence of reaction force. The simulation of boundary conditions is the most of accurate modeling of the structure for a finite element analysis. The model was assumed to be unconstrained condition. Only quarter of the whole geometry was modeled, there must be constraints applied on the area cut section of the model to assign that the model built in ANSYS is symmetric. Constraint must be applied for translation in Y direction and rotation in X and Z axis. Similarly, for those area cut sections fall along the Y axis, constraint must be applied for translation in X direction and rotation in Y and Z axis. Figure 5 represent the meshing and boundary conditions of projectile, plate and thorax.

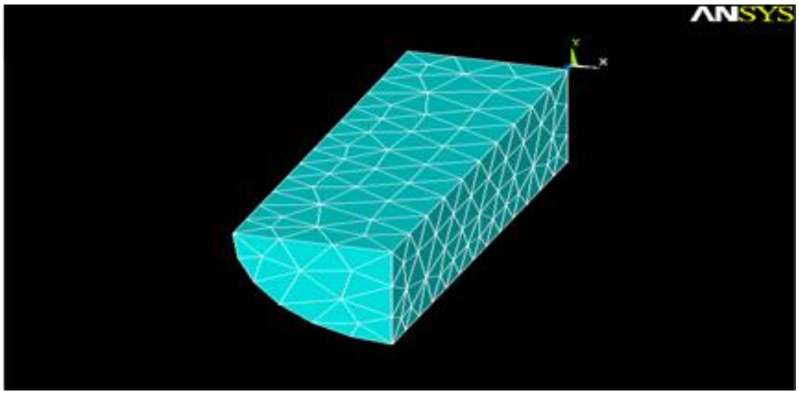


Figure 4. Typical Free Meshing of Projectile

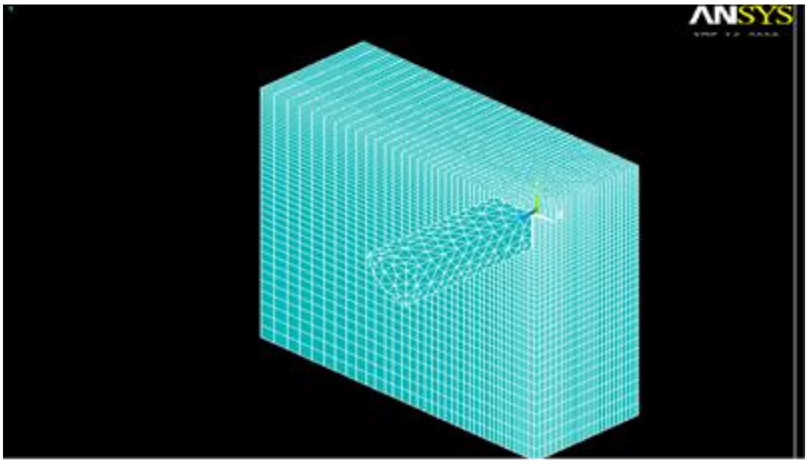


Figure 5. Meshing and boundary conditions of the model

CONTACT AND LOADING CONDITIONS

Accurate modeling of contact interfaces between bodies is critical issue to the prediction capability of the finite element simulations. LS-DYNA software offers a library with number of contact types, some of these types are specific applications, and others are suitable for more applications use. Automatic surface to surface (ASTS) contact was used in the analysis. This type of surface contact will automatically appear for the nearest nodes when blunt trauma and it also search for any other nodes come into contact with defining the master and the slave. In order to simulate the projectile which is moving to the target plate at a high speed, the projectile must be assigned with an initial velocity. This velocity here is the speed of projectile or impact velocity before any impact occurs and reaches the plate. Initial velocity value as negative value in the representation of Z-direction and initially put as 250m/s. During the analysis, there is always a duration of time to be set in, this time manage the termination of process duration running the analysis. For the velocity of 250m/s, the time needed to travel for 0.5mm was 0.0025ms, however; in this case blunt shock takes place; so it needed to estimate the time duration at a higher value. After the finite element model being completed; the results are stored in the special files. These files should be read by the post processing in software analysis which is known LS-PREPOST post processing. Therefore, must restore the results in the first suitable file then only run the LS-PREPOST process.

RESULT AND DISCUSSION

LS-DYNA solver used to implement the finite element analysis and the simulation of blunt trauma. This may be follow by verifying the result obtained with the experimental results. The response of body and the blunt trauma process could be specified after changing the nose shape of the projectile. After that, the results of simulation must be identified, discussed and the physical mechanism represented by blunt trauma case should be described. The response of the human thorax was evaluated by studying the acceleration-time and displacement-time curves with each different impact conditions resulting in especial response. In current study, initial velocity was chosen at 250m/s for each projectile shapes and other conditions were same such as volume and mass values.

EFFECT OF BLUNT HEAD PROJECTILE

Acceleration-Time Curve of Blunt Head Projectile

The acceleration-time curve demonstrated how much force is happened by the human thorax model. In general, the equation of motion and the acceleration of the element are proportional to resultant force apply on the element, and as well as inversely with the mass. The maximum acceleration of the human thorax was obtained and happened at the point where the muscle layer contact with the steel plate. The acceleration-time curve has been plotted in Figure 6. The maximum acceleration at velocity value of 250m/s was $0.18*10^9 m/s^2$. Maximum acceleration represented the optimum value which occurring within 0.003ms from the time.

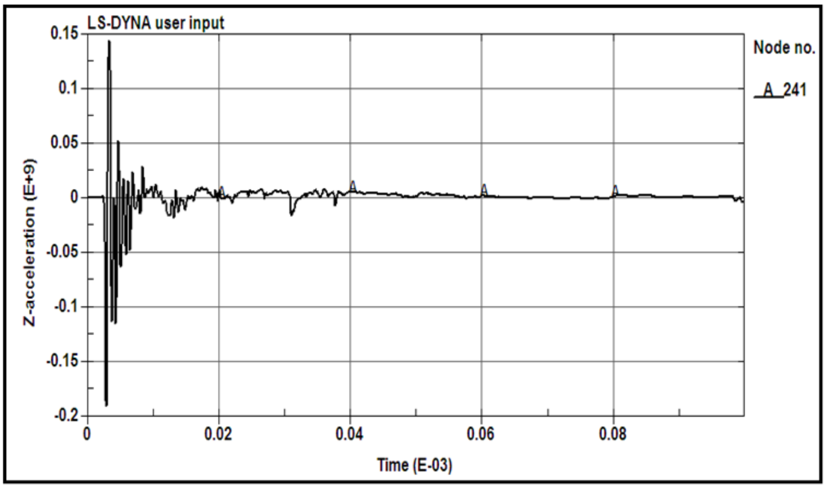


Figure 6. Acceleration-Time curve of human thoracic response for blunt head projectile

Displacement-Time Curve of Blunt Head Projectile

The displacement-time curve explains the response of the blunt projectile impact in term of distance or deflection. The displacement-time curve was plotted for the blunt projectile at 250m/s. From the simulation, data showed that the maximum displacement occurred at the point where the muscle layer contact with the steel plate, the same point where the peak force occurred. The displacement-time curve has been plotted in Figure 7. Blunt trauma of projectile at 250m/s generated a 3.4mm of maximum deflection within 0.053ms from the contact. The amplitude value of the displacements increased with the energy delivered to the body. After the 0.053ms; the displacement of the impact point was decreasing due to the rebound or go back of the elastic property of the muscle layer of thorax

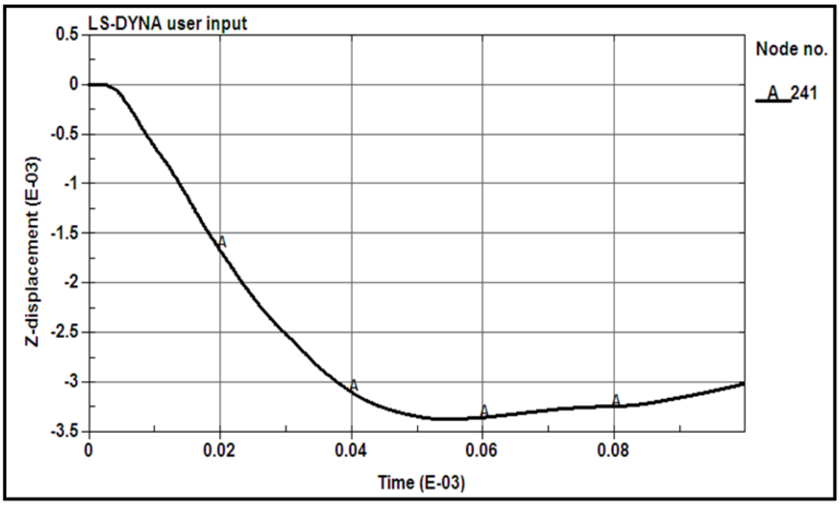


Figure 7. Displacement-Time curve of blunt head projectile

EFFECT OF HEMISPHERICAL PROJECTILE

Acceleraton-Time Cureve of Hemispherical Projectile

In spherical projectiles; a similar process to the blunt projectile being at 250m/s, the maximum acceleration of the human thorax also happened at the impact point where the muscle layer contact with the steel plate. Acceleration-time curve has been plotted in Figure 8. The maximum acceleration for hemisphere projectile at 250m/s was $45*10^6$ m/s^2. Maximum acceleration represent the peak force which occurring within 0.02ms from the time. The curve shows a fluctuating behavior along the time duration.

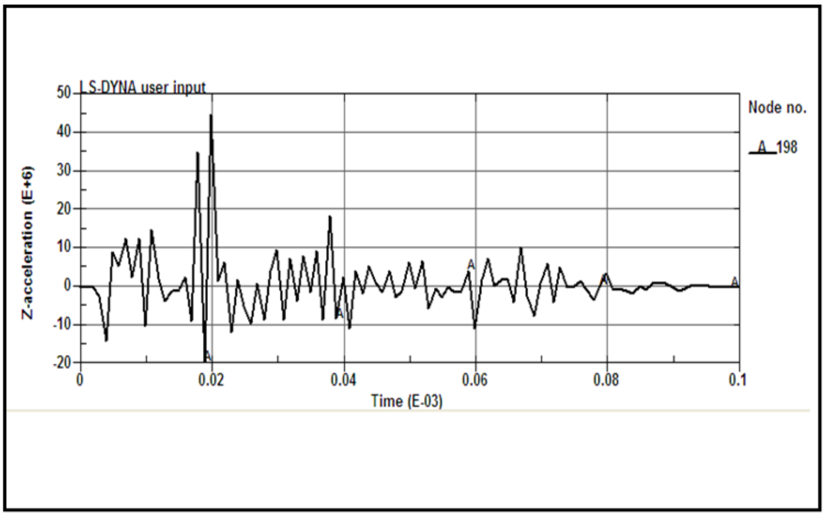


Figure 8. Acceleration-Time Curve of Hemispherical projectile

DISPLACEMENT-TIME CUREVE OF HEMISPHERICAL PROJECTILE

The displacement-time curve was plotted for this projectile at 250m/s. The maximum displacement occurred at the impact point where the muscle layer contact with the steel plate, the same point where the peak force occurred. The displacement-time curve has been plotted in Figure 9. Blunt shock of hemispherical projectile at 250m/s caused a $0.022*10^{-3}$m of displacement or deflection within 0.063ms from the time. After that, the displacement of the impact was decreased due to the elastic property of the muscle layer of human thorax.

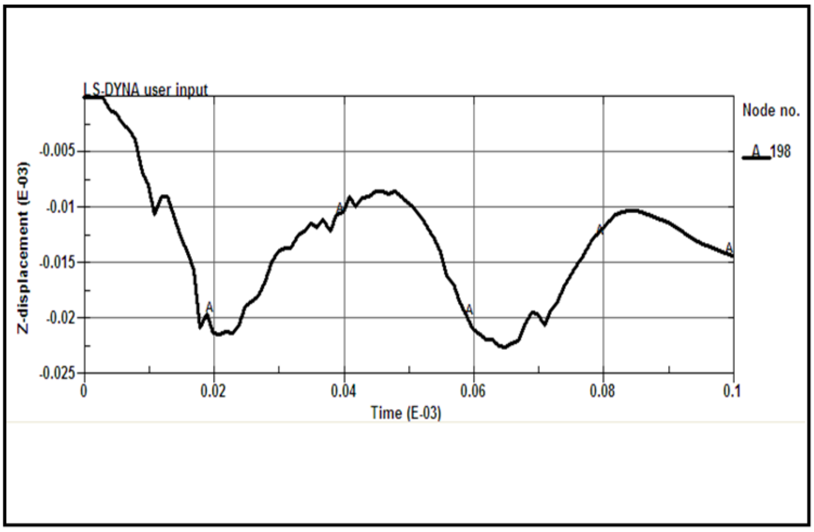


Figure 9. Displacement-Time curve of hemispherical projectile

EFFECT OF CONICAL PROJECTILE

Acceleration-Time Curve of Conical Projectile

As mentioned earlier; the maximum acceleration of the thorax was obtained from the simulation. It was happened at the point where the muscle layer contact with the steel plate. The acceleration-time curve has been shows in Figure 10. The maximum acceleration for conical projectile at 250m/s was $69*10^6$ m/s^2 within 0.033ms.

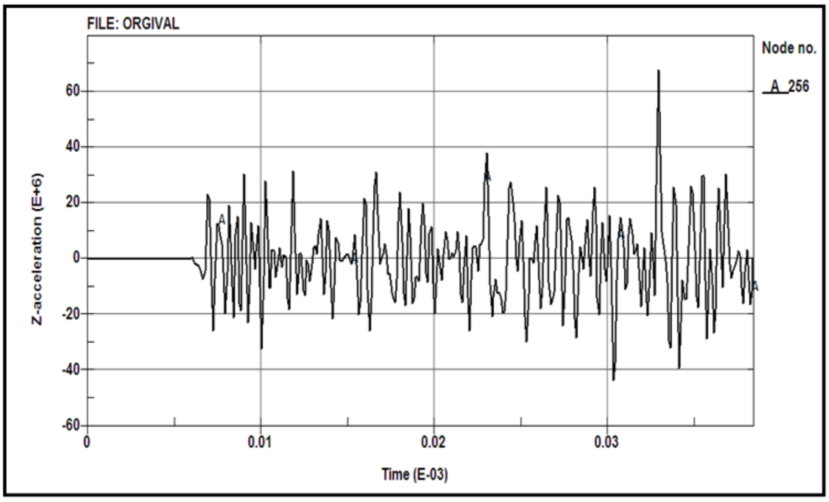


Figure 10. Acceleration-Time curve of conical projectile

DISPLACEMENT-TIME CURVE OF CONCAL PROJECTILE

The displacement-time curve was plotted for the conical projectile at 250m/s. it has been plotted in Figure 11. Blunt shock of conical projectile produced $46*10^{-6}$m of deflection within 0.04ms from the time.

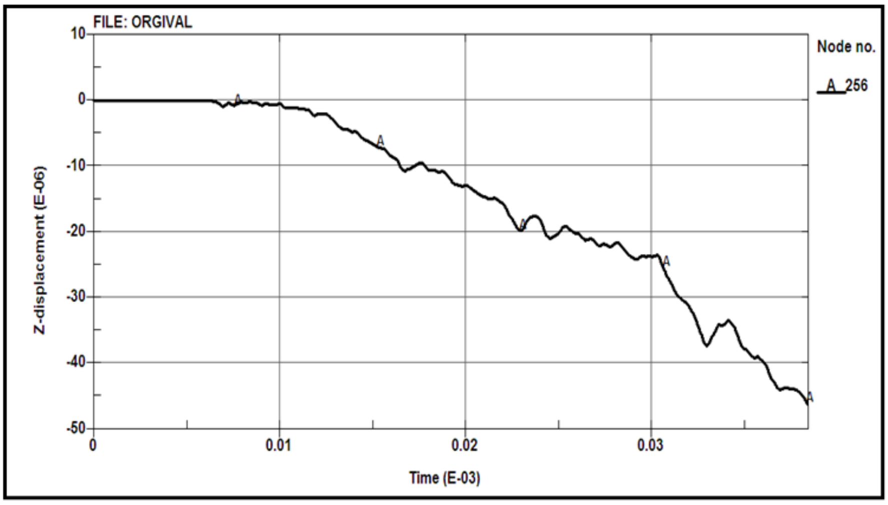


Figure 11. Displacement-Time curve of thoracic response for conical projectile

From all the previous Figures, The relevant amounts or quantities that may vary from one projectile to other one are initial position and initial velocity, so; the results of finite element analysis and objects simulation of strong shock or blunt trauma of the human thorax impacted by the different nose projectiles show various results in acceleration, displacement and time values between the blunt head, hemispherical and conical projectile, these results can be noticed by study the acceleration-time and displacement-time curves for each one. The fluctuating of plotted curves for hemispherical and conical projectiles caused by the plastic material which is assigned to the model and its motion of particles, some of these materials didn't include the failure mechanism because of the most of elements in the model not failed or failure mode didn't give a clear picture. Anyway, in the steel plate, the fracture and deformation not occur in one direction but also may be in other direction such as x and/or y direction. At the same value of velocity (250m/s) the maximum acceleration of blunt head projectile was $180*10^6$ m/s^2, while the maximum acceleration of the spherical and conical projectile was $45*10^6$m/s^2 and $69*10^6$ m/s^2 respectively. If we notice to the displacement or deformation of blunt trauma projectile at 250m/s was $3.4*10^{-3}$m, while, the displacement or deformation of spherical and conical projectile at 250m/s were $0.022*10^{-3}$m and $0.046*10^{-3}$m respectively. That is means the acceleration and the displacement for model impacted by hemispherical and conical projectiles has lower maximum acceleration and maximum displacement if comparing with model impacted by blunt projectile. The initial or primary slope represents the inertia force required to accelerate the model mass to the velocity

CONCLUSION

The current study introduced a numerical method to analysis the human thorax response and effect of blunt trauma of projectile impact without using the actual samples such as dead body. Through the current study, the results achieved from the simulation of the human thorax model subjected to impact projectile were various values of acceleration and displacement curves with impact time and it was fluctuated path. This investigation and analysis is limited to structural modeling to which never includes any thermal properties in the material model. Actually, the thermal properties will affect the model accuracy because of the adiabatic shearing process and thermal softening in the penetration process. This model is using the plastic kinematics material without failure strain. In the real case, it will be more accurate to use the material piecewise linear plasticity with the failure strain, this is because the impact of high velocity of the projectile definitely will give the penetration to the steel plate.

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