EFFICIENT MODELING OF PANEL-LIKE TARGETS IN PERFORATION SIMULATION

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ABSTRACT

This paper studies the application of thin shell elements and solid shell elements in the structural modeling of panel-like targets in finite element perforation simulations. LS-DYNA is used for the present numerical investigation. By comparing the projectile residual velocities and impact pressures given by the shell element targets to those obtained form the solid element target, this work shows that the solid shell element modeling of panel-like targets can not only save a lot of computational effort, but also be able to give good results if the target panels satisfy certain conditions. Therefore, the shell element modeling of targets is an efficient model in the performance simulation of projectiles penetrating through panel-like targets. A preliminary criterion for the validity of the shell element target model is also proposed in the paper.

Keywords: Finite element modeling of panel-like targets, High velocity impact, Perforation simulation, Solid shell element, LS-DYNA.

Introduction

The prediction of perforation capability of projectiles is very important in various engineering, such as weapons effects, aerospace engineering, offshore engineering etc. In the past few decades, many analytical formulae have been proposed for the prediction of residual velocities, and the experimental research of impact mechanics has also achieved a great amount progress [vide the review paper of Ref. 1 for instance]. However, because of the complex of the impact and penetration between deformable projectiles and targets, analytical formulae can only give reasonable prediction of residual velocities when the striking velocity is much higher than the ballistic limit of the target [1]. The experimental approach can give good perforation results, but it is very expensive. On the other hand, the computer simulation has been proven to be a powerful and economical tool for the prediction of penetrations and perforations of deformable projectiles over all ranges of striking velocities.

The structure modeling of targets plays a crucial role in the finite element simulation accuracy of the projectile performance. In the computer simulations of projectile perforations, the target materials are usually modeled by the three-dimensional (3-D) elements. Even thin plate targets are also modeled by the 3-D finite elements in order to capture all the dynamic characteristics in the interactions between projectiles and targets. The 3-D model for the panel-like targets is accurate indeed. But on the other hand, the 3-D target model is very computationally expensive. The objective of this work is to explore the reliability and accuracy of the shell element modeling of panel targets in perforation simulations. Both the performance of thin shell elements and that of solid shell element, a special type of thick shell elements, in LS-DYNA are studied. Thin shell elements have been employed by few researchers to model thin plate targets [Ref. 2 among others]. But it seems that the solid shell elements have not been studied for the modeling of plate targets yet. The numerical examples studied in work include the perforations of conical nosed projectiles and flat nosed projectiles. By comparing the residual velocities and impact pressures in the projectile obtained from shell target models and solid target model, it was shown that the shell element modeling of the panel-like targets in the perforation simulation can not only save a lot of computational effort, but also give good results. A preliminary criterion for the validity of the shell model of targets is also proposed. The numerical simulation results indicate that the shell target modeling is indeed an efficient model in the performance simulation of projectiles penetrating through panel-like targets when the targets satisfy certain conditions.

Perforation Modes and Corresponding Stress State

The interaction between a projectile and target material involves contact, energy transfer, large strain, large deformation, and complex process of material failure. The material failure of the targets, or the perforation mechanism, mainly depends on following factors: the striking velocity; the material properties of targets; and the geometric aspects such as projectile nose shape as well as the ratio of projectile diameter to target thickness. Some perforation mechanism of ductile materials can be illustrated by the failure modes shown in Fig. 1 [3]. Another common failure pattern of thin plates is the petalling failure.

Corresponding to each failure mode, the stress state is different. For example, in the shear band plug failure, the perforation is caused by the shear stresses along the shear band in the direction of projectile velocity. In the ductile hole formation, the contact stresses (in the target thickness direction) play an important role. And in the dishing and petalling failure, the in-plane stretching of deformed targets is the dominant deformation mode.

The shell finite elements, in which the in-plane stresses are the dominant stresses, are efficient and accurate on modeling global responses of structures. Therefore, shell elements should be able to simulate the perforations caused by the in-plane stretching, such as dishing and petalling. Furthermore, thick shell elements are capable of accounting for the transverse shear stresses well, which corresponding to the shear band failure.

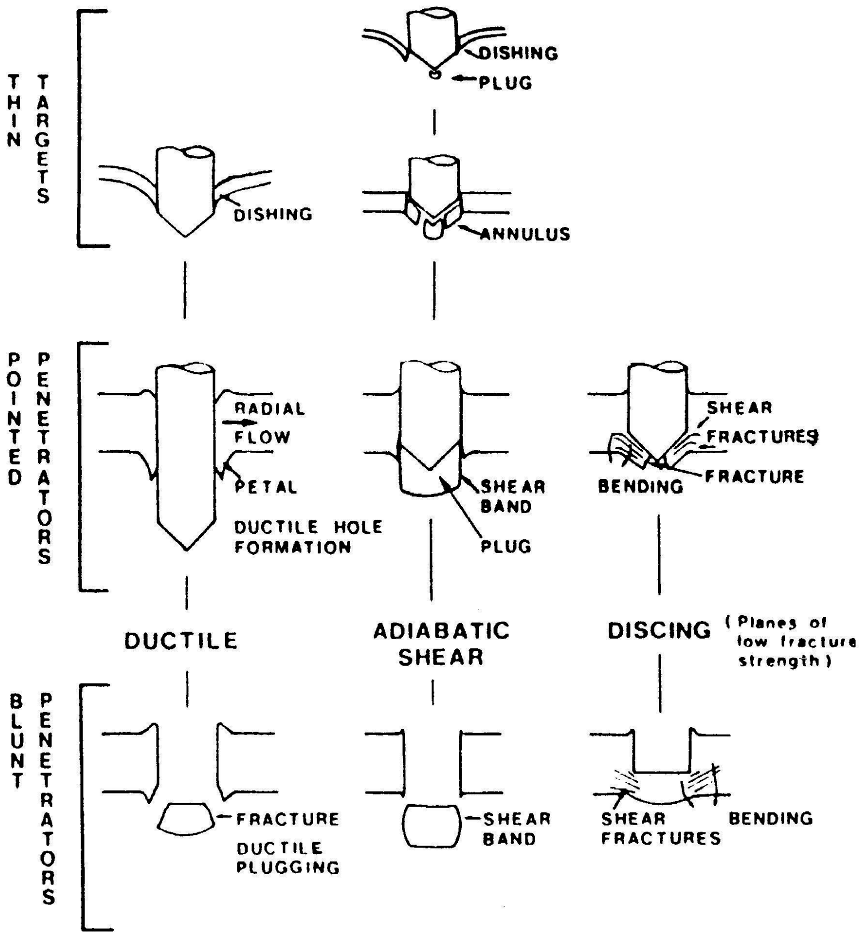


Fig. 1. Various perforation modes

Modeling of Panel-like Targets

In reality, all structures or structural members, including thin panel targets, are three-dimensional. Because of the large geometric aspect ratio, a panel-like structure can be modeled using the two-dimensional theories of plates and shells when global solutions, such as deflection, frequencies of major vibration modes are of the interests. Consequently, a panel-like target can be modeled by one layer of shell elements in the finite element modeling. The perforation process of a projectile through a target is a localized process that involves very complicated interaction between the projectile and the target material. Therefore, thin panel targets are usually modeled by three-dimensional solid elements in the finite element analysis of perforations. When solid elements are chosen, at least three layers of elements have to be used in the target thickness direction, which results in more computing time to be consumed compared to the shell element modeling. Furthermore, the solid element target model also needs much more computer memory than the shell element model.

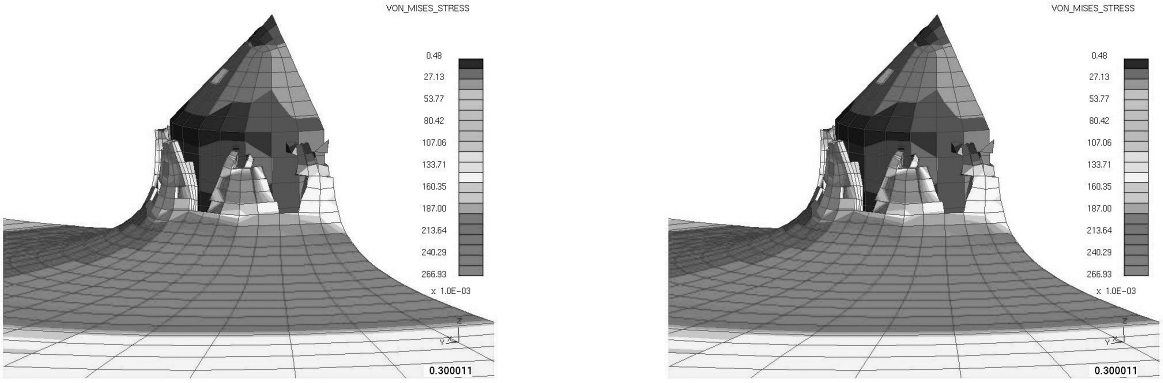
The major difference between the capability of a 3-D solid element model and that of a 2-D shell element model lies on the stress state of the material under consideration. Unlike the three dimensional stress state in a solid element, the normal stress along the thickness direction in a shell element is basically neglected. As a result, the shell elements are not capable of accounting for the stress wave propagation in the target thickness direction. When the influence of the normal stress on the target failure can not be ignored, the solid elements have to be employed. But, when the perforation of a projectile through a target is dominated by the annulus failure or the shear band plug as shown in Fig. 1, the shell elements could be able to model the material failure of the targets with good accuracy in the perforation simulations.

Simulation Results

LS-DYNA (V950.d) is employed for the perforation simulations in this numerical investigation. Material type 3 is used for all the targets in the simulations, but the strain rate is not considered. The element failure is implemented by the element erosion scheme once the equivalent plastic strain of an element reaches the given ultimate strain. In the present perforation simulation, the eight-noded brick element is used for the solid element, the S/R Hughes-Liu shell element is chosen as the thin shell element, and thick shell element is the eight-noded solid shell element. The same mesh density in the plate plane is used for all the meshes of thin shell, thick shell and brick elements. By making use of the symmetry, only a half of the projectile and target is modeled in the perforation simulations of both normal and oblique impacts.

Example 1. Cylindro-conical Steel Projectile Perforating Thin AL 2024 Plate

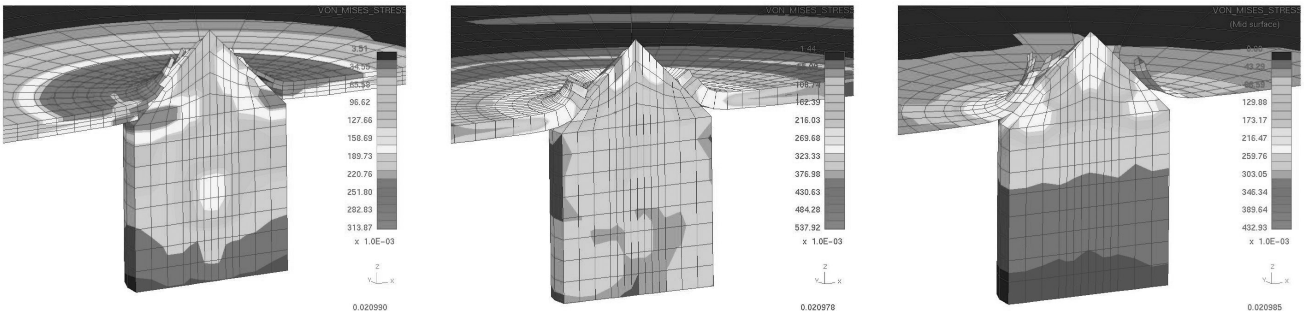
The diameter of the projectile in this example is 12.7mm. The thickness of the target is 1.27mm, and the diameter of the target is 360mm. The target is fixed along the boundary. The aspect ratio of projectile diameter to target thickness is 10. The target material is AL-2024-T3. Both experimental results and analytical solutions are available in literature for this example, and its ballistic limit is 73m/s. The residual velocities corresponding to some striking velocities given by experiments and some formulae were summarized in Ref. 1.



a. Brick element target b. Thick shell element target

Fig. 2. The perforations of cylindro-conical projectile into AL-2024 plate at V0 = 90m/s

Both thin shell elements and the eight-noded solid shell element are used in the present modeling of the target plate. Five integration points across the target thickness are used in the shell elements. Four layers of elements are used along the target thickness direction in the 3-D solid modeling. The failure modes corresponding to V0 = 90m/s given by the brick element and the thick shell element are depicted in Fig. 2, where the stress unit is GPa. The figures show that the perforation process corresponding to this low velocity impact is a dishing resulting from the contact at the interface of projectile to target and a petalling by the in-plane stretching. The perforations corresponding to V_o = 330m/s given by the brick element as well as the thick and thin shell elements are shown in Fig. 3.



a. Brick element target b. Thick shell element target c. Thin shell element target

Fig. 3. The perforations of conical projectile into AL-2024 plate at V0 = 330m/s

The residual velocities of the projectile obtained from different element modeling of the target for striking velocities V_o = 90m/s, V_o = 250m/s and V_o = 300m/s are tabulated in Table I. These velocities are the averaged values of the projectile. Equation (28) in Ref. 1., which gives good velocity prediction, is a special formula that makes use of the ballistic limit obtained from experiment.

Table I. The residual velocities of 12.7 diameter cylindro-conical projectile

Solution Method	Residual velocity (m/s)		
	V_o=90	V_o=250	V_o=300
Thin shell element	51.5	238.4	288.4
Thick shell element	63.0	239.4	289.8
Brick element 1x1 Gauss integration	52.2	238.5	289.2
Brick element 2x2 Gauss integration	61.6	241.4	292.1
Eq. (28) in Ref. 1	55	239.1	290.8
Experimental results (Ref. 1)	58	238.8	

The integration scheme of Gaussian quadrature for the brick elements could affect the simulation results. Therefore, both one point integration and 2x2x2 integration are used for the brick elements. The results in the table show that the one point integration for the brick elements gives lower residual velocity than the 2x2x2 integration. When there is no material failure involved, one knows it from the finite element theory that the selection of numerical integration scheme affects the resulting element stiffness matrix, and the full integration of Gaussian quadrature for displacement-based elements overestimates, in general, the resulting element stiffness. But when the elements undergo material failure and erosions by element elimination, the selection of integration points will affect the element stiffness in a different way. The one point integration could underestimate the plastic deformation development and material failure in solid elements. Consequently, the residual velocity should be between the values given by the brick element model using the one point integration and the full integration as indicated by the experimental results.

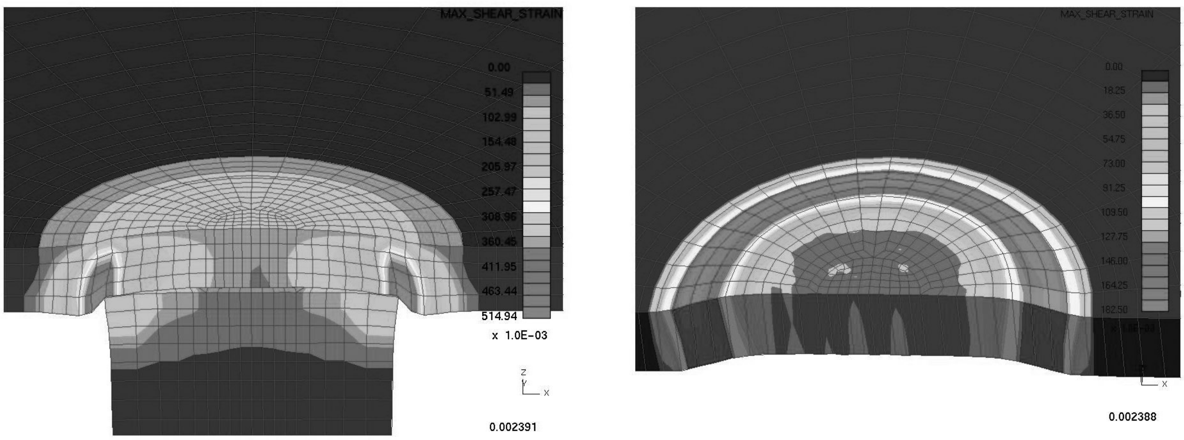
Table I indicates that both thick and thin shell elements give good results when the striking velocity is much larger than the ballistic velocity limit. But in general, the thick shell element yields better results than the thin shell element even in the case where the striking velocity (V_0 = 90m/s) is close to the ballistic limit (Vb = 73m/s).

Example 2. Blunt-nosed Steel Cylinder Impacting on AL 6061-T6 Plate

Li and Goldsmith studied, both experimentally and analytically, the perforation of the steel rod against AL 6061-T6 plates with various thickness [4]. The projectile is a 12.7mm diameter cylinder with an aspect ratio of 3. The target is of 360mm diameter with fixed boundary. The strain rate effect was not taken into account in Ref. 4. Hence the strain rate effect is also ignored in the present study. The material properties are summarized in Table II.

Table II. The material properties of steel projectile and aluminum target

Material	Density(kg/m^3)	Dynamic yield stress (GPa)	Ultimate shear strength (GPa)	Ultimate tensile strain (%)
Projectile	7977	1.393	0.804	--
AL 6061-T6	2780	0.295	0.190	18



a. Brick element target b. Thick shell element target

Fig. 4. The shear bands evaluated by the solid and thick shell elements

Two thickness $h = 3.2mm$ and $h = 4.8mm$ for the targets are considered in the present simulations, which corresponds to the aspect ratios of projectile diameter to target thickness 3.97 and 2.65 respectively. Both the normal and oblique impacts are studied for the target of *3.2mm*. The one point integration scheme is used for the brick elements. The maximum shear strains in the 3.2mm plate given by the solid element and thick shell element modeling are depicted in Fig. 4. The figure shows that the thick shell modeling is capable of modeling the shear band given by the 3-D target modeling, although the shear band is a constant value across the target thickness.

The residual velocities obtained from the finite element analysis with different target modeling and those given by Li and Goldsmith [4] are listed in Table III. It is worth to point out that the model of eight layer solid elements for the target gives the same results as the four layer element model of the target.

Table III. Perforation results of 12.7 cylinder impacting on Al 6061-T6 plate

Target thickness	**Initial condition of projectile**			**Residual velocity** (m/s)	
	velocity	oblique angle	yaw angle	Solution method	Velocity
4.8mm	565m/s	0	0	Thin shell element	525.1
				Thick shell element	531.5
				Brick element	536.1
				Analytical [Ref. 4]	538
				Experimental [Ref. 4]	535
3.2mm	557m/s	0	0	Thin shell element	527.8
				Thick shell element	533.2
				Brick element	537.6
				Analytical [Ref. 4]	540
				Experimental [Ref. 4]	535
3.2mm	685m/s	4^{o}	4^{o}	Thin shell element	657.2
				Thick shell element	657.6
				Brick element	661.2
				Analytical [Ref. 4]	660
				Experimental [Ref. 4]	653

It can be seen from Table III that, in the case of normal impact, the thin shell element target model results in a much larger difference than the thick shell element modeling of target if taking the residual velocities given by the solid element target model as a reference.

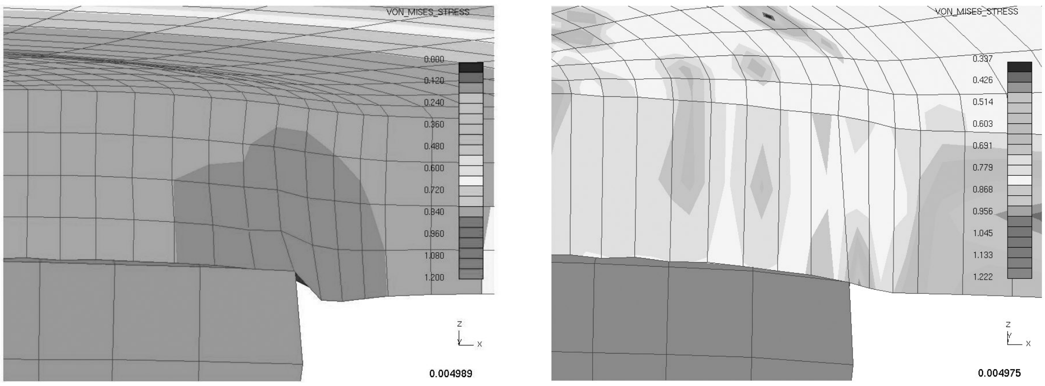
Example 3. Blunt-nosed 4340 Steel Rod Perforating HY-100 Steel Plate

The perforations of the steel rod of diameter 30.8mm into HY-100 plates with thickness *h = 5.3mm* and *h = 10.5mm* were studied experimentally by Forrestal and Hanchak [5]. The material properties used for the present simulations are listed in Table IV, where the material data of HY-100 steel are different from those given in Ref. 5 as the present data were used in the numerical simulations of other researchers.

Table IV. The geometric and material properties of steel rod and HY-100 steel plate

	Diameter	Yielding stress	Tensile strength
Projectile 4340 R_c 38 steel	30.8mm	1.179GPa	1.240GPa
Target HY-100 steel	305mm	0.800GPa	0.980GPa

In the present example, the strength ratio of 4340 steel projectile to HY-100 steel is close to unity, and the aspect ratio of projectile diameter to target thickness is 5.81 for the 5.3mm target. The residual velocities after perforating the 5.3mm steel plate are evaluated using the solid element target model and shell element target model. The results given by the shell element modeling of 5.3mm target are quite different from that given by the solid element target although the aspect ratio of projectile diameter to target thickness in this example is larger than those in the previous example. This is because the influence of the normal stress in the target thickness direction on the equivalent stress in the present example can not be neglected as depicted in Fig. 5.



a. Brick element target b. Thick shell element target

Fig. 5. The influence of the transverse normal stress on the Von Mises stress (h=5.3m

The plate thickness is reduced to h = 2mm and the length of the steel rod is 134mm in the present simulation. The time histories of residual velocities given by thin shell, thick shell and brick elements are illustrated in Fig. 6. The figure shows that the simulated projectile velocities given by the shell element target decrease slower than that given by solid element target during the perforation process, but their final residual velocities are quite close.

In many perforating cases, the pressures in the projectile induced during the perforation process are also a major concern for the interaction between the projectile and target. The contact stresses at the contact interface given by the shell element target modeling are certainly different from those given by the brick element model of the target. The pressure histories of a point inside the projectile given by the three different target modeling are given in Fig. 7. The pressure figures indicate that the shell elements are able to give reasonable pressure propagation inside the projectile.

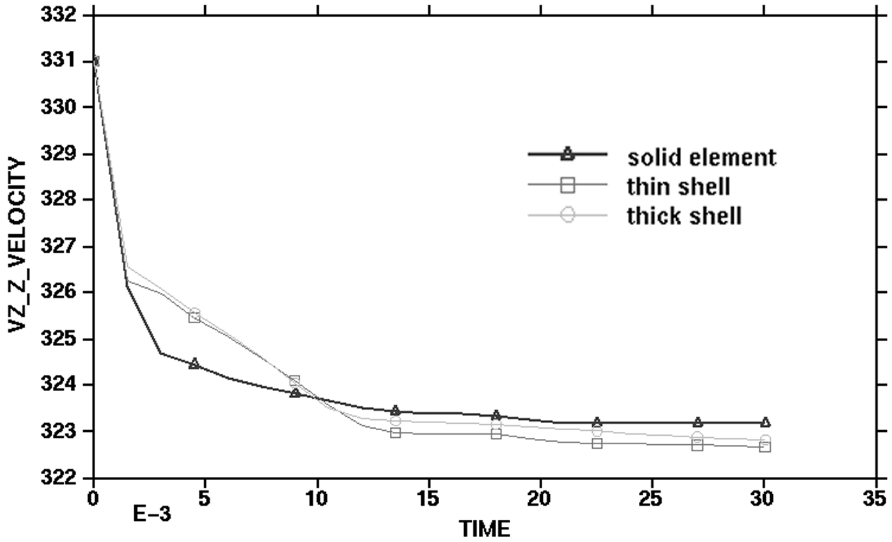


Fig. 6. Residual velocity curves given by different modeling of targets (h=2mm)

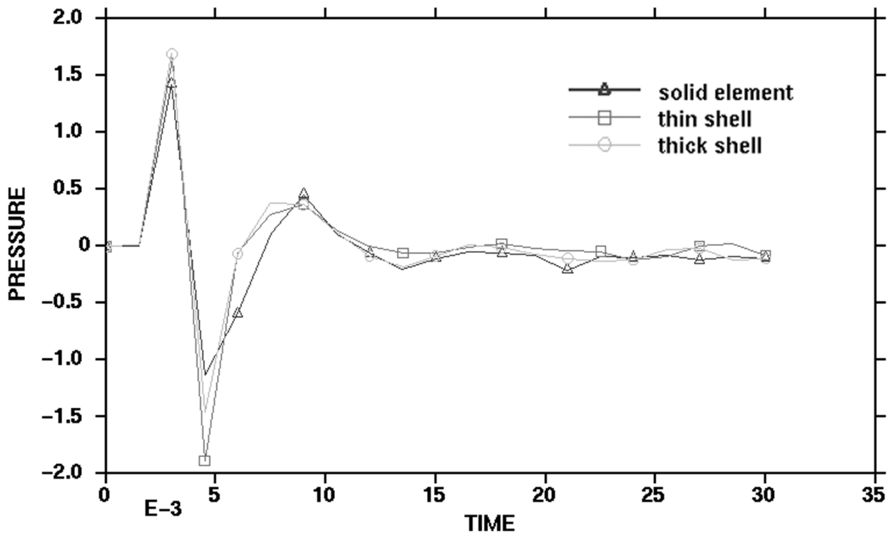


Fig. 7. Pressure curves given by different modeling of targets (h=2mm)

Discussion and Closing Remarks

This paper studies different finite element modeling techniques of panel-like targets in the perforation simulations. The perforation simulation performances of eight-noded brick element, four-noded quadrilateral thin shell element and eight-noded solid shell element were numerically investigated. In general, the liability and accuracy of the shell modeling of targets in the panel-like target perforation simulation are controlled by the influence of the transverse normal stress and the wave propagation in the target thickness direction on the failure mechanism of target materials. And this influence, in turn, is controlled by the aspect ratio of projectile diameter to target thickness and the stiffness/strength ratio of projectile to target.

The following conclusions can be drawn from the present perforation simulations of panel like targets.

1. The conditions that a panel can be considered as a 'thin' panel depend not only on the geometric aspect ratio between the projectile to target, but also on their material aspect ratio.
2. When the target panels satisfy certain conditions, the 'thin' panel targets can be modeled by shell elements in the residual velocity evaluation of plate perforations. The shell element model of the targets can not only save computing time as well as computer memory, but also yield reasonable results compared to the solid element modeling of targets.
3. In general, the thick (solid) shell element modeling of target gives better results than the thin shell element. Therefor The thick shell element is an efficient alternative for the modeling of target materials in the perforation simulations of projectiles against thin panel targets

Based on the above discussion, a preliminary criterion that governs whether a panel-like target can be modeled by shell elements may be characterized as:

$$\frac{D_p . \sigma_{yp}}{h . \sigma_{yt}} > 15$$

where D_p is the projectile diameter, h is the target thickness, σ_{yp} and σ_{yt} are the yielding stresses of projectile and target materials respectively.

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