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Design Automation of a Laminated Armor for Best Impact Performance Using Approximate Optimization Method

Hasan Kurtaran*, Murat Buyuk*, Azim Eskandarian**

* Department of Design and Manufacturing Engineering, Gebze Institute of Technology, PK. 141, 41400 Gebze/Kocaeli, Turkey; **FHWA/NHTSA National Crash Analysis Center, The George Washington University, 20101 Academic Way, Ashburn VA 20147, USA

Abstract

Values of characteristic parameters such as thickness have big influence on the impact behavior of a laminated armor. Determination of those values for an optimum laminated armor usually requires evaluation of many computationally costly impact analyses. In this paper, automated, efficient and effective determination of design parameters in a laminated armor for best impact performance is investigated using an approximate optimization method. The approximate optimization method is generated by coupling a parametric preprocessor, finite element analysis software, response surface approximations and a numerical optimization algorithm. The whole coupling is achieved through a commercial code, ANSYS Design Optimization Module. The laminated armor of interest consists of three layers. The frontal layer is alumina ceramic, and it is supported by a 4340 steel mid-layer and a 2024-T3 aluminum rear layer. The armor is impacted by a projectile with velocities of 1000 and 2000 m/s. The surface normal of the armor has an oblique angle with the projectile's moving direction. The 3-D impact analysis of the armor is conducted using non-linear explicit dynamic finite element code ANSYS/LS-DYNA. Optimization of the armor is performed to find the best thickness values of layers and oblique (orientation) angle towards the least penetration of the projectile.

Keywords: High velocity impact, 3-D finite element analysis, laminated armor, response surface approximations, approximate optimization

1. Introduction

Armor design for high velocity impacts is often encountered in defense and aerospace applications. Materials under high velocity impacts show highly nonlinear and dynamic behavior including complex failure process. Commercial codes based on numerical methods are increasingly used for the simulation of impact analysis. A popular 3-D explicit nonlinear dynamic Finite Element (FE) code LS-DYNA [1] with advanced contact algorithms and material models was successfully used to simulate several types of armors subjected to the impact of projectiles moving at various velocities [2-4]. Success of FE codes for impact simulations enabled armor design to be done efficiently in computer environment.

Determining the appropriate values of armor parameters that ensure lightweight structure and no or little penetration of the impacting projectiles are of major goals in armor design. There are

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quite a few examples available in the literature related to armor design [5-6]. Available examples are mostly not associated with high velocities. This is due to the nature of the numerical analysis for high velocity impacts. The impact analysis carried out with explicit finite element codes requires very small integration time steps leading to high computational cost in the analysis. Another reason is that high velocity impact simulation requires advanced material models and adaptive remeshing capabilities to be implemented in the codes many of which do not have these features. Therefore, most of the high velocity impact simulations in the literature include 2-D and axisymmetric structures.

The recently popular approximate optimization method which is based on integration of analysis software, numerical optimization algorithm and approximation methods can be used for armors to automate the design process and to reduce the design time. The approximate optimization method has been recently used in the solution of several crashworthiness and impact design problems successfully [7-8] and presents a potential for armor design as well. In the approximate optimization method, armor design is formulated in the form of an optimization problem that can be solved easily by a conventional numerical optimization algorithm. Computationally expensive objective and constraint functions in the optimization problem, which often come from FE analysis results, are replaced with their approximations before the optimization problem is solved. Solution of the optimization problem leads to the optimum design.

In this paper, the approximate optimization method implemented in ANSYS Design Optimization (DO) module [9] is used to automate the design of a multi-layered laminated armor efficiently. Design optimization is carried out to find the optimum thickness and orientation angle of layers from the projectile's impact direction towards the least penetration of the impacting projectile for velocities of 1000 and 2000 m/s. Approximate optimization method through ANSYS DO module was obtained by integrating ANSYS parametric preprocessor, 3-D explicit dynamic finite element code ANSYS/LS-DYNA, ANSYS post processor, a numerical optimization algorithm based on penalty methods and response surface approximation. Details of the armor design are given in the following sections.

2. Design Optimization Methodology with Approximations

The impact design problems can be automated if formulated in the form of an optimization problem as following:

minimize:

$$y_0(\mathbf{x}) \tag{1}$$

subjected to:

$$y_j(\mathbf{x}) \le 0 \,, \; (j = 1,\ldots,n_c) \tag{2}$$

within the design space:

$$x_{il} \le x_i \le x_{iu} \,, \; (i = 1,\ldots,N) \tag{3}$$

where $y_0(\mathbf{x})$ is the objective function, $y_j(\mathbf{x})$ $(j = 1,\ldots,n_c)$ are the constraint functions and $\mathbf{x} = [x_1, x_2,\ldots,x_N]$ is the vector of design variables. x_{il} and x_{iu} describe physical upper and lower bounds on design variables. n_c and N are the number of constraints and number of design variables, respectively. The constraint and objective functions may correspond to weight, penetration depth, energy absorption, etc.

Solution of Eqns. (1)-(3) for impact problems can be efficiently done by replacing objective and constraint functions with their Response Surface (RS) approximations. Approximations serve as simplified mathematical models for replacing computationally costly impact analysis. Optimization with approximations is often referred to as approximate optimization in the literature. The approximate optimization method implemented in ANSYS DO module and used in this paper is shown in Fig. 1. ANSYS DO module generates and utilizes polynomial RS approximation for objective or constraint function as following [9]:

$$y(\mathbf{x}) = \underbrace{\underbrace{\underbrace{a_0 + \sum_{n=1}^{N} a_n x_n}_{linear} + \sum_{n=1}^{N} b_n x_n^2}_{quadratic} + \sum_{m=1}^{N-1} \sum_{n=m+1}^{N} c_{mn} x_m x_n}_{quadratic+crossterms} \tag{4}$$

where a, b, c are coefficients to be determined.

In design optimization process, ANSYS DO first creates N+2 design sets to construct a linear approximation. Here set indicates values of all parameters for a specific design. ANSYS DO will either generate design sets randomly or use the existing ones in the optimization database. Impact analyses are carried out at available design sets. Analysis results are then used to create linear approximations of objective and constraints. Higher order approximations such as and quadratic and quadratic with cross terms RS approximations are created using least square method when there are enough design sets in the database. The optimum design is predicted by solving Eqns. (1)-(3) with a numerical optimization algorithm based on penalty functions. The predicted optimum is verified by exact analysis (ANSYS/LS-DYNA). If the predicted objective and constraints are identical with the results from ANSYS/LS-DYNA, or the estimated optimum design is satisfactory enough, the optimization loop is stopped. Otherwise, the newly calculated results are added to the existing design sets and new approximations are created followed by the solution of the optimization problem.

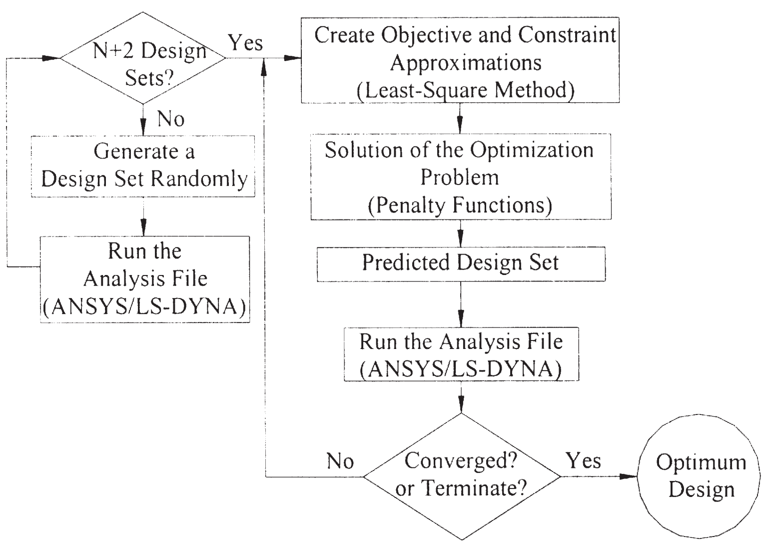


Fig. 1. Approximate design optimization process with ANSYS DO module.

3. Finite Element Modeling of the Armor and the Projectile

In this study, 3-D finite element modeling of a laminated armor impacted by a projectile that has 7.62 mm diameter and semispherical nose shape is introduced. The armor consists of three circular layers of different thickness. In developing the model, ANSYS Parametric Design Language (APDL) [9] was utilized to further enable automatic model regeneration during the design optimization process. Components of FE modeling which are mesh generation and constitutive models are described in detail below.

3.1 Finite Element Mesh

FE mesh created for the armor and the projectile is shown in Fig. 2. The mesh is optimized for stability, accuracy and efficiency of the impact analysis. The circular layers of the armor were divided into three regions in mesh in radial direction; inner, middle and outer regions. Mesh density is gradually coarsening from inner region, which is potential impact region, to the outer region. Mesh transition between regions are good enough to prevent stress wave reflections from the boundary of regions. The armor and the projectile are meshed with explicit 8-noded hexagonal elements of varying size between 0.3 mm and 1 mm. Maximum aspect ratio of the elements do not exceed five in the mesh. The projectile has very fine mesh as well. The armor-projectile initial FE mesh (before optimization) includes total 135,984 elements; 40,000 elements for the projectile and 95,984 elements for the armor. The translational nodal degrees of freedom along the boundary of the armor layers were constrained to prevent any motion.

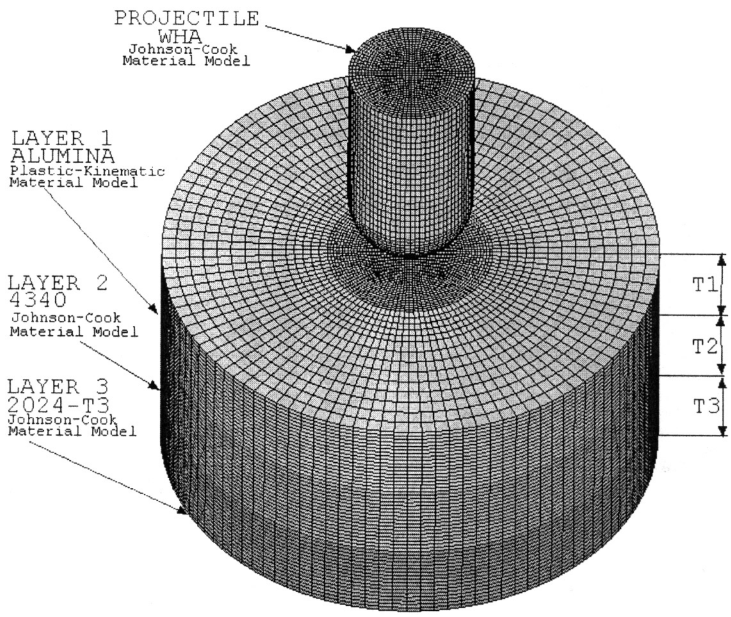


Fig. 2. FE model of the armor and the impacting projectile.

Contact behavior between the projectile and the armor mesh was simulated with eroding node-to-surface and surface-to-surface contact-impact algorithms of ANSYS/LS-DYNA. During impact simulations, some local instabilities such as the excessive motion of some nodes were observed. This was prevented by lowering the default contact stiffness scale factor f_s from 0.1 to 0.05 by trial and error. FE analysis of the mesh was performed for 10 μs on P4-IBM PC with 1.9 GHz processor and analyses took between 2 and 6.5 hours of CPU time.

3.2 Constitutive Models

Plastic kinematic hardening and Johnson-Cook constitutive models were used to simulate the behavior of the armor layers and the projectile during impacts.

3.2.1 Plastic Kinematic Hardening Model

Plastic kinematic hardening material model is a strain-rate dependent elastic-plastic model utilized to predict the response of the first layer of the armor made of alumina ceramic. In this model, strain rate is accounted for using the Cowper-Symonds model which scales the yield stress by the strain rate dependent factor as shown below [9]:

$$\sigma_Y = \left[1 + \left(\frac{\dot{\varepsilon}}{C}\right)^{\left(\frac{1}{P}\right)}\right]\sigma_0 \tag{5}$$

where σ_0 is the initial yield stress, $\dot{\varepsilon}$ is the strain rate, C and P are the Cowper-Symonds strain rate parameters. If C and P values are equal to zero, strain rate effects are not considered in the formulation. Fracture is simulated by removing elements that reach a user-defined value of equivalent plastic strain (erosion strain). Fracture strain is assumed to be 0.12. Plastic kinematic model constants for alumina ceramic is given in Table 1.

Table 1. Plastic kinematic hardening material constants for alumina ceramic (Al_2O_3)

Modulus of Elasticity (MPa)	*Density (Kg/m^3)*	*Poisson Ratio*	*Yield Stress (MPa)*	*Tangent Modulus (MPa)*	*Strain Rate Parameters*		*Failure Strain*
E	ρ	ν	σ_Y	E_T	C	P	ε_f
370,000	3960	0.22	200,000	0	0	0	0.12

3.2.2 Johnson-Cook Material Model

Johnson-Cook (JC) is a strain-rate and temperature-dependent (adiabatic assumption) viscoplastic model. It is employed to describe the response of 4340 steel and 2024-T3 aluminum layers of the armor and the projectile made of tungsten heavy alloy (WHA). The JC model represents the flow stress with an equation of the form [9]:

$$\sigma_Y = \left(A + B\varepsilon^n\right)\left(1 + C\ln\dot{\varepsilon}^*\right)\left(1 - T^{*m}\right) \tag{6}$$

where σ_Y is the effective stress, ε is the effective plastic strain, $\dot{\varepsilon}^*$ is the normalized effective plastic strain rate (typically normalized to a strain rate of 1.0 s^{-1}), n is the work hardening exponent and A, B, C and m are constants. The quantity T^* is defined as:

$$T^* = \frac{T - T_{room}}{T_{melt} - T_{room}} \tag{7}$$

where T_{room} is the room temperature, T_{melt} is the melting temperature and is typically taken as the solidus temperature for an alloy. Fracture in the JC material model is based on a cumulative damage law:

$$D = \sum \frac{\Delta \varepsilon}{\varepsilon_f} \tag{8}$$

in which:

$$\varepsilon_f = \left[D_1 + D_2 \exp(D_3 \sigma^*)\right]\left[1 + D_4 \ln \dot{\varepsilon}^*\right]\left[1 + D_5 T^*\right] \tag{9}$$

where $\Delta\epsilon$ is the increment of effective plastic strain during an increment in loading and σ^* is the mean stress normalized by the effective stress. The parameters D_1, D_2, D_3, D_4 and D_5 are fracture constants. Failure of elements is assumed to occur when $D = 1$. The failure strain ϵ_f and thus the accumulation of damage is a function of mean stress, strain rate, and temperature. Failed elements are removed from the FE model.

The JC material model was used in conjunction with Mie-Gruneisen equation of state model [9]. Johnson-Cook and Mie-Gruneisen EOS material constants for WHA, 4340 and 2024-T3 are given in Table 2 [10-14].

Table 2. Johnson-Cook and Mie-Gruneisen material constants for WHA, 4340 and 2024

Parameter	*Notation*	*WHA*	*4340*	*2024-T3*
Strength Constants				
Density (Kg/m^3)	ρ	17670	7850	2770
Poisson Ratio	v	0.28	0.33	0.33
Modulus of Elasticity (MPa)	E	347,000	210,000	72,400
Static Yield Limit (MPa)	A	926	792	264
Strain Hardening Modulus (MPa)	B	843	510	426
Strain Hardening Exponent	n	0.4	0.26	0.34
Strain Rate Coefficient	C	0.0385	0.014	0.015
Thermal Softening Exponent	m	0.5727	1.03	1
Reference Temperature (K)	T_{room}	300	300	300
Melting Temperature (K)	T_{melt}	1723	1793	775
Specific Heat (J/Kg K)	c_P	134	477	875
Fracture Constants				
D_1		0	-0.8	0.13
D_2		0.33	2.1	0.13
D_3		-1.5	-0.5	-1.5
D_4		0.042	0.002	0.011
D_5		0	0.61	0
Mie-Grunesien EOS Constants				
S_1 (MPa)		304	164	200
S_2 (MPa)		331	294	300
S_3 (MPa)		201.8	500	500
γ_0		1.58	1.16	1.02

4. Optimization Problem Formulation for the Armor Design

Design of the laminated armor is of interest to prevent full penetration of the projectile impacting at velocities of 1000 m/s and 2000 m/s. Thickness of layers and orientation of the armor with the projectile's moving direction as shown in Fig. 3a are considered to affect the penetration performance and selected as design variables. The displacement of the projectile into armor is utilized to derive the objective and constraint functions.

The goal and the requirements are expressed in the form of an optimization problem as following:

find:

$$\mathbf{x} = \{T1, T2, T3, \alpha\} \tag{10}$$

to maximize:

$$(U2 - U1) \tag{11}$$

subjected to:

$$\left.\begin{array}{c} U1 \leq U2 \\ 0.5\text{ mm} \leq T1 \leq 5\text{ mm} \\ 0.5\text{ mm} \leq T2 \leq 5\text{ mm} \\ 0.5\text{ mm} \leq T3 \leq 5\text{ mm} \\ 0.0^0 \leq \alpha \leq 20^0 \end{array}\right\} \tag{12}$$

where U1 is the displacement of the reference point at the back face of the projectile. U2 corresponds to the distance between the reference point and the back face of the armor. Penetration distance is measured using the distance between the projectile back face and the armor back face as (U1-U2) since the nodes/elements on the projectile's nose fail and are removed from the FE model during impact. Eqn. (11) indirectly enforces minimum penetration while Eqn. (12) puts a limitation on the penetration depth into the armor not to exceed the total thickness. Eqn. (12) also indicates the range within which design parameters can be adjusted to satisfy the objective and constraints. T1, T2, T3 are thicknesses of the layers and α is the orientation angle. Initial values of design parameters were taken as T1 = 2 mm, T2 = 4 mm, T3 = 1 mm and $\alpha = 5^0$. Derivation of objective and constraint function is shown in Fig. 3b.

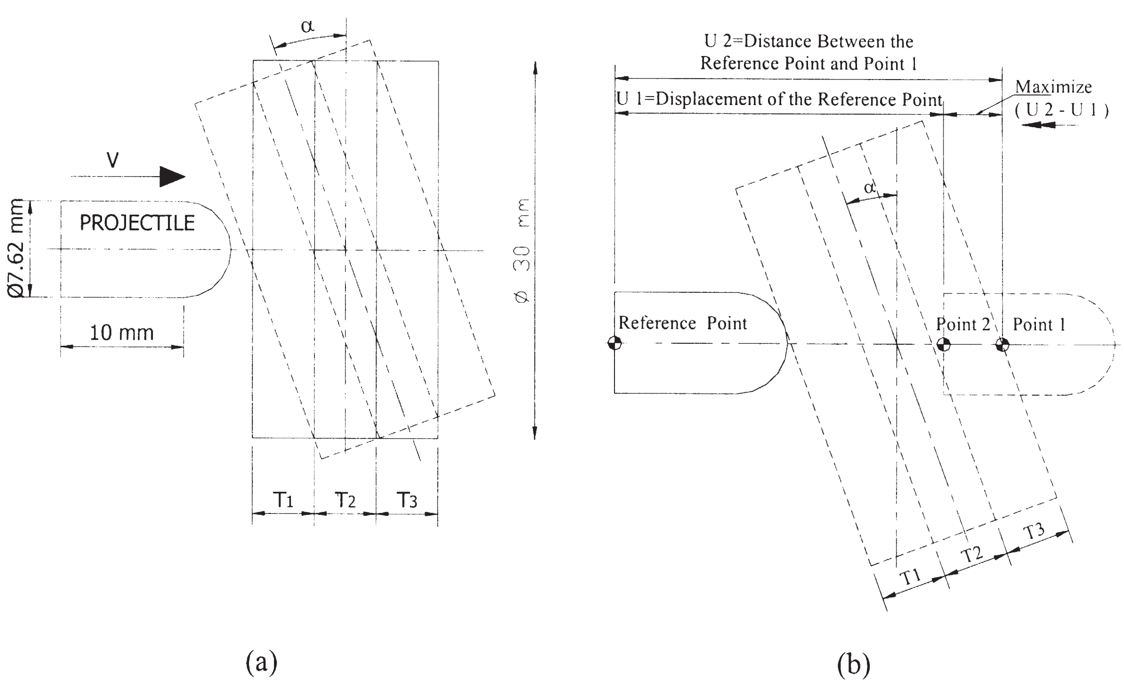
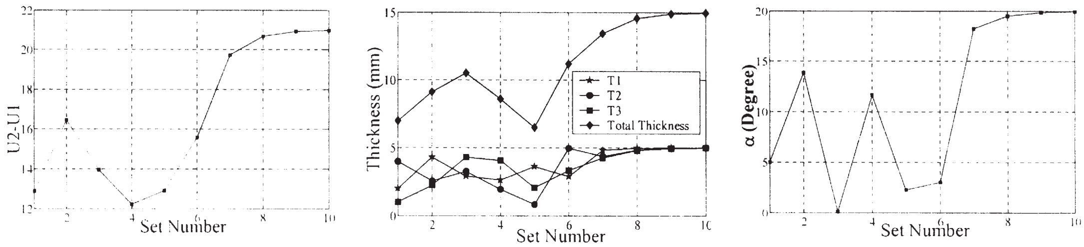


Fig. 3. Design variables (a) and the measurement of penetration in the armor (b).

5. Armor Optimization Results

Optimization problem expressed by Eqns. (10)-(12) was solved using quadratic with cross terms approximations through ANSYS DO module. Optimization results for 1000 m/s of the projectile impacting velocity are as following. The change of objective function, thickness and orientation angle of layers with optimization set number is demonstrated respectively in Fig. 4. It will be useful to remind that optimization process starts after N+2 design sets. That is, for our case design set numbers bigger than 6 reflect optimization results in Fig. 4.



(a) (b) (c)

Fig. 4. The change of objective function (a), thicknesses of the layers (b), and orientation angle (c) with optimization set number (projectile velocity is 1000 m/s).

Simulations for initial and optimum designs under the impact of the projectile moving at velocity of 1000 m/s are compared in Fig. 5.

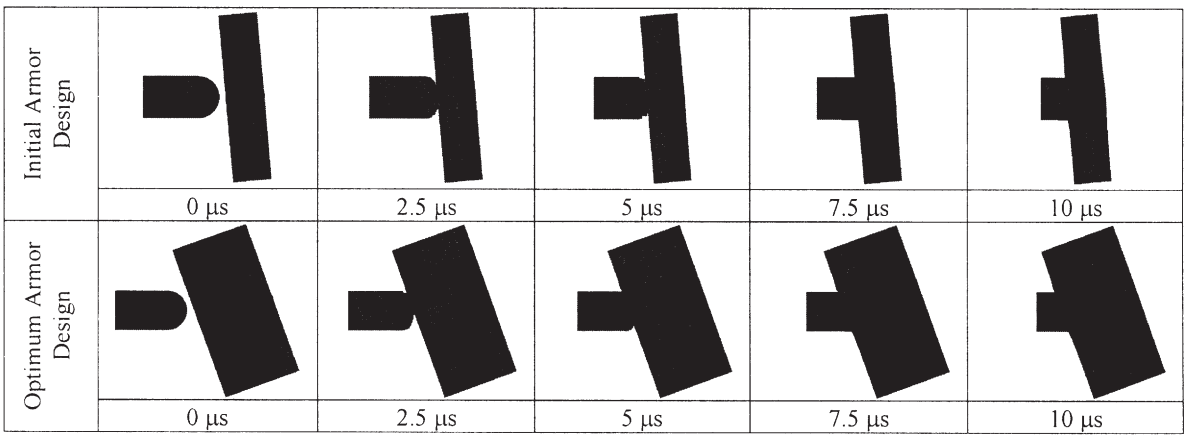
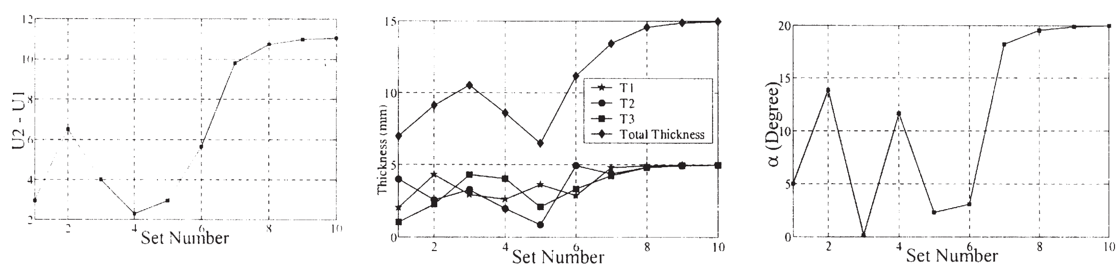


Fig. 5. Deformation of initial and optimum armor impacted by the projectile moving at velocity of 1000 m/s.

Optimization problem expressed by Eqns. (10)-(12) was resolved for the impact velocity of 2000 m/s of the projectile to investigate the influence of the impact velocity on the optimum design. Results for design variables, objective function and constraint with respect to optimization set number are illustrated in Fig. 6.



(a) (b) (c)

Fig. 6. The change of objective function (a), thicknesses of the layers (b), and orientation angle (c) with optimization set number (projectile velocity is 2000m/s).

Simulations for initial and optimum designs under the impact of the projectile moving at velocity of 2000 m/s are compared in Fig. 7.

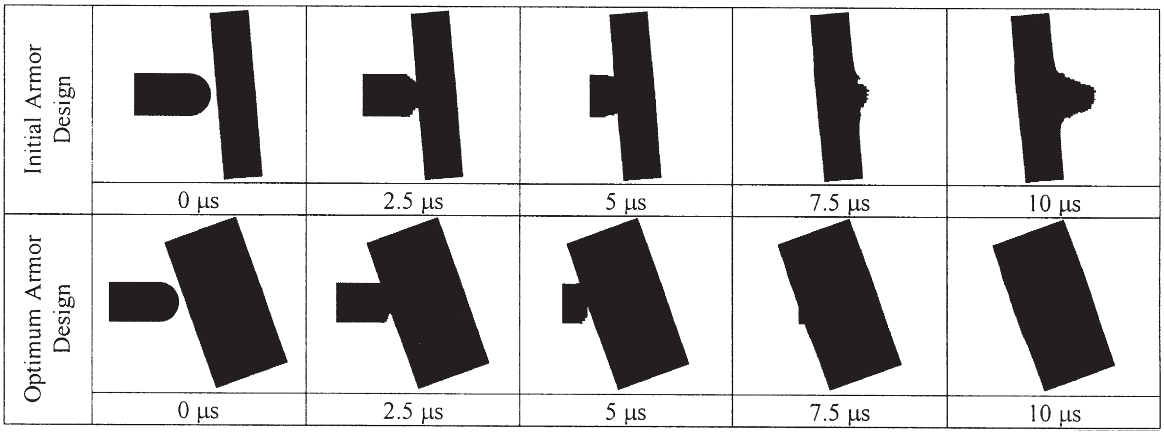


Fig. 7. Deformation of initial and optimum armor impacted by the projectile moving at velocity of 2000 m/s.

The change of the objective function with impact velocity is demonstrated in Fig. 8. As seen from Fig. 5 and Fig. 7, the approximate optimization method reduced the penetration depth significantly by increasing the layer thicknesses and changing the orientation angle with only 10 FE analyses. Design variables converged to their upper limits.

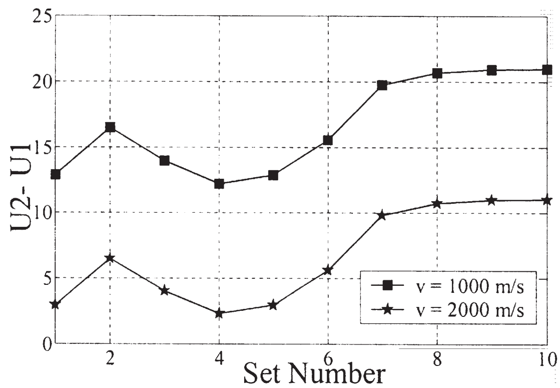


Fig. 8. The change of the objective function with impact velocity.

6. Conclusion

In this paper, an automated approach with approximate optimization method was applied to design a three-layer laminated armor to resist the impact of a projectile moving at several high velocities. Design automation was achieved through ANSYS DO module that integrates ANSYS parametric preprocessor, 3-D explicit dynamic finite element analysis code ANSYS/LS-DYNA, ANSYS post processor, a numerical optimization algorithm based on penalty methods and response surface approximation. Armor was designed for minimum penetration subjected to a constraint on maximum penetration distance. Thickness and orientation angle of the armor layers were considered to influence the design objective and constraints and therefore they are taken as design variables. ANSYS DO module was able to reduce the penetration into the armor systematically and efficiently. Optimum design was obtained with limited number of FE analysis.

The challenge in design optimization with ANSYS DO module comes from the difficulty in parametric modeling of the structure of interest and the capability of the analysis code ANSYS/LS-DYNA. ANSYS/LS-DYNA has quite a few advanced material models such as

Johnson-Cook. However, it does not include the recent ones such as Holmquist [10] which are considered successful in simulating ceramic behavior. Also ANSYS/LS-DYNA does not have adaptive remeshing capability to overcome the mesh distortion problems that arise in high velocity impacts. A future work may include the implementation of the aforementioned features to ANSYS/LS-DYNA. Design optimization of the armor with different objective and constraint functions such as weight can also be a future research topic.

References

[1] Hallquist, JO. *LS-DYNA Theoretical Manual*, Livermore Software Technology Corporation, Livermore, CA, USA, 1997.

[2] Mahfuz H, Zhu Y, Haque A, Abutalib A, Vaidya U, Jeelani S, Gama B, Gillespie J, Fink B. Investigation of high-velocity impact on integral armor using finite element method, *Int. J. of Impact Engineering*, 2000; **24**: 203-217.

[3] Borvik T, Langseth M, Hopperstad OS, Malo KA. Ballistic penetration of steel plates, *Int. J. of Impact Engineering*, 1999; **22**: 855-886.

[4] Borvik T, Hopperstad OS, Berstad T, Langseth M. Perforation of 12 mm thick steel plates by 20 mm diameter projectiles with flat, hemispherical and conical noses Part II: Numerical simulations, *Int. J. of Impact Engineering*, 2002; **27**: 37-64.

[5] Chen SY. An approach for impact structure optimization using the robust genetic algorithm, *Finite Elements in Analysis and Design*, 2001; **37**: 431-446.

[6] Ben-Dor G, Dubinsky A, Elperin T, Frage N. Optimization of two component ceramic armor for a given impact velocity, *Theoretical and Applied Fracture Mechanics*, 2000; **33**: 185-190.

[7] Kurtaran H, Omar TA, Eskandarian A. Crashworthiness design optimization of energy-absorbing rails for automative industry, *Proceedings of 2001 ASME International Mechanical Engineering Congress and Exposition*, New York, NY, 2001.

[8] Yamazaki K, Han J, Ishikawa H, Kuroiwa Y. Maximization of crushing energy absorption of cylindrical shells-simulation and experiment, *Proceedings of the OPTI-97 Conference*, Rome, Italy, 1997.

[9] Kohnke P. *Ansys User Manual*, release 5.7., Ansys Inc. Houston, Pennsylvania, 1999.

[10] Holmquist TJ, Templeton DW, Bishnoi KD. Constitutive modeling of aluminum nitride for large strain, high-strain rate, and high pressure applications, *Int. J. of Impact Engineering*, 2001; **25**: 211-231.

[11] Zukas JA. *High Velocity Impact Dynamics*, John Wiley & Sons Inc., NY, 1990: p. 228-230.

[12] Johnson Gr, Cook WH. A constitutive model and data for metals subjected to large strains, high strain rate and high temperatures, *Proceedings of the Seventh International Symposium on Ballistics*, The Hague, 1983.

[13] Gama BA, Bogetti TA, Fink BK, Yu CJ, Claar TD, Eifert HH, Gillespie Jr JW. Aluminum foam integral armor: a new dimension in armor design, *Composite Structures*, 2001; **52**: 381-395.

[14] Lesuer DR. Experimental investigations of material models for Ti-6Al-4V Titanium and 2024-T3 aluminum, Final Report, Contract no: DTFA03-97-Z-90007, DOT/FAA/AR-00/25, *Department of Transportation, Office of Aviation Research*, Washington, DC, USA, 2000.