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Penetration Analysis for Composites Applicable to Military Vehicle Armors, Aircraft Engines and Nuclear Power Plant Structures

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***Abstract*—**This paper describes a method for analyzing penetration for composite material using an explicit nonlinear Finite Element Analysis (FEA). This method may be used in the early stage of design for the protection of military vehicles, aircraft engines and nuclear power plant structures made of composite materials. This paper deals with simple ballistic penetration tests for composite materials and the FEA modeling method and results. The FEA was performed to interpret the ballistic field test phenomenon regarding the damage propagation in the structure subjected to local foreign object impact.

***Keywords*—**Computer Aided Engineering, CAE, Finite Element Analysis, FEA, impact analysis, penetration analysis, composite material.

I. Introduction

COMPOSITE materials are used in various areas because of their outstanding physical properties such as light weight, high strengths and high stiffnesses. The composite exhibits not isotropic but anisotropic properties and is multilayered with various materials which make it exceptional with its physical properties. Composites are also very promising materials to protect important components, structures or even humans in the event of foreign object collisions [1]-[3]. Military vehicles and nuclear power plants are some of the fields utilizing composite materials now and in the future.

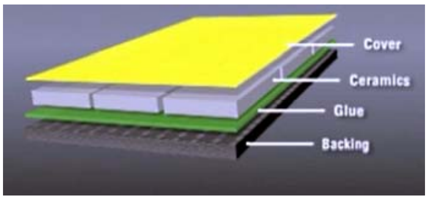

Fig. 1 An example of ceramic composite armor [9]

One of the most important requirements for military vehicles is their ability to protect their passengers or soldiers from enemy fire. Many researchers have studied to improve this protection capability of military vehicles [4], [5]. Composites are being studied as a military armor to improve the protection capabilities of military vehicles as shown in Fig. 2 [6]-[8]. In this connection, experimental methods are essential tools to design and validate military vehicle armors. However, as we know, these experimental methods are very time-consuming and their costs are high; thus, an FEA solution which is relatively economical and less time-consuming is proposed in this paper.

Fig. 2 Ceramic composite armor used for military vehicles [10]

In an aircraft engine, failure of the blade can cause catastrophic disaster in terms of human life and economical aspects. Consequently, the structural robustness of the engine in the event of blade failure has always been the long-term concern of each aero engine manufacturer so as to protect both humans and the components. This is called the “containment design”.

Composite materials are now considered for use in the fan case of the aircraft jet engine and the performance of a composite structure under blade-out loads needs to be demonstrated [21], [22]. The proposed method in this paper is efficient and reliable to design and demonstrate it in the concept design stage.

Nuclear power plants have nuclear reactors and the fuels that contain a host of radioactive materials by nature. This means that these radioactive materials should be confined inside the protecting structure under any circumstances such as foreign object collisions; for this reason, it has a containment structure as shown in Fig. 3.

Recently, a research about composite materials is growing to use them for nuclear power plant construction and nuclear reactors [11], [12].

One of the challenging nuclear power plant (NPP) engineering problems is to calculate the strengths and load-bearing capacities of the NPP structures under an aircraft crash impact, as studied and reported by some researchers [13], [14].

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However, it is virtually impossible to test them with real aircrafts. The proposed FEA method presented here is possibly applicable in the concept design stage to the analysis of NPP and nuclear reactor structures made of composite materials subjected to foreign object collisions such as airplane crash.

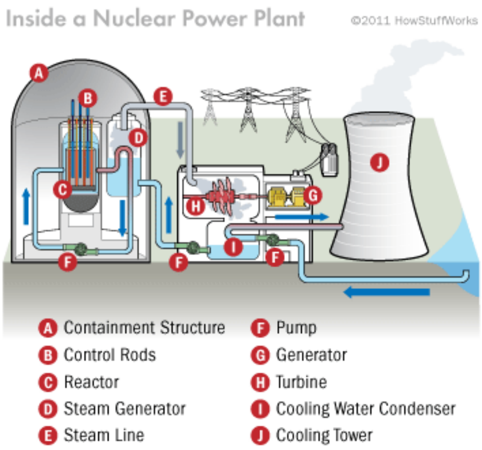

Fig. 3 Nuclear reactor overview [15]

It can be said that the aforementioned cases have the same engineering problems, in the sense that a certain protective structure should be sustained and functioning when subject to foreign or internal object impacts. This paper presents a fast and reliable FEA method and its application to a sample case.

II. Ceramic Composite Ballistic Field Test

Ceramic composite ballistic test was experimentally carried out to evaluate the protection capability. The used ceramic composite panel was multi-layered and composed of E-glass, Kevlar, EPDM, Epoxy, Al_2O_3 and S-2 glass. The given colliding bullet speed was 657 m/s ~ 668 m/s and the bullet size was 12.7 mm. Four shots were fired to the ceramic composite panel and the obtained test results are shown in Table I.

TABLE I
BULLET FIELD TEST RESULTS

Shot number	Penetration
1	No
2	Yes
3	Yes
4	Yes

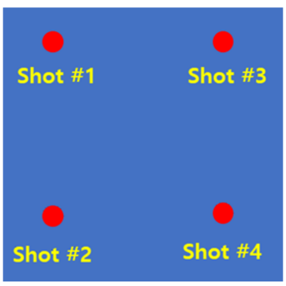

Fig. 4 The location of shots on the panel

Note that only the first bullet did not penetrate and that all subsequent shots penetrated into the panel. To find out the reason for this phenomenon, a simulation-based approach was performed.

III. Finite Element Modeling for the Penetration Analysis

LS-DYNA, which is one of the explicit FEA programs developed by LSTC, was used in this analysis to find out the reason of the phenomenon that happened in the field test. Fig. 5 shows a mesh model to study the penetration of ceramic composites. Only shot #1 and shot #2 were performed in this analysis.

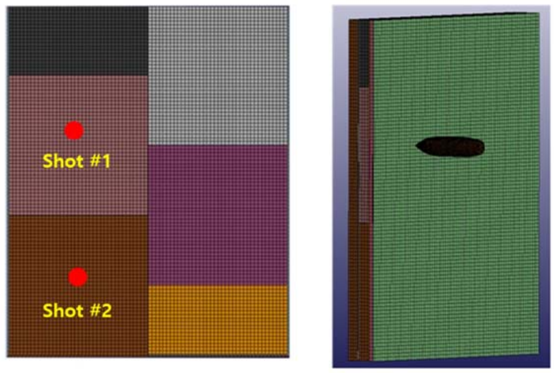

Fig. 5 The mesh model for ceramic composite plate penetration analysis

For the analysis of penetration, it is important to define proper material properties since we are dealing with a nonlinear phenomenon where the material undergoes plastic deformation as well as penetration. LS-DYNA provides an available input card for various material properties for metal, composites, ceramics, etc. Out of the many material input cards, the MAT_PIECEWISE_LINEAR_PLASTICITY card was used for E-glass, Kevlar, S2-glass, epoxy and bullet and the MAT_JOHNSON_HOLMQUIST_CERAMICS card was used for the ceramic. The material properties are given in Table II and Table III. These are from [16]-[20].

TABLE II
MATERIAL PROPERTIES FOR MAT_PIECEWISE_LINEAR_PLASTICITY

Properties	Units	E-glass	Kevlar +EPDM	S2-glass +Epoxy	Bullet
Density	kg/m^3	2,154	1,000	2,000	7,850
Young's Modulus	Pa	1.21E+10	2.34E+9	1.05E+10	2.1E+11
Poisson's Ratio	N/A	0.1	0.3	0.1	0.3
Yield Stress	Pa	5.17E+8	5.17E+7	5.17E+8	5.0E+9
Elongation at Failure	%	15	10	10	20

One of the key concepts in this penetration analysis is to demonstrate how to model or represent the conditions of contact and penetration between two objects in collision. For this, LS-DYNA provides rich choices of input cards representing a variety of contact scenarios.

TABLE III
MATERIAL PROPERTIES FOR MAT_JOHNSON_HOLMQUIST_CERAMICS

Properties	Units	Ceramic (Al_2O_3)
Density	kg/m^3	3,800
Shear Modulus (Pa)	Pa	1.2E+11
Intact strength constant 1	N/A	0.9
Intact strength constant 2	N/A	0.45
Strain constant	N/A	0.035
Fracture strength constant 1	N/A	0.53
Fracture strength constant 2	N/A	0.60
Reference strain rate	N/A	1.0
Maximum tensile pressure strength	Pa	3.32E+8
Maximum normalized fractured strength	N/A	1.0
Hugoniot elastic limit	Pa	5.0E+9
Pressure component at the Hugoniot elastic limit	Pa	1.46E+9
Bulking pressure	N/A	1.0
Parameter for plastic strain to fracture	N/A	0.0085
Parameter for plastic strain to fracture (exponent)	N/A	0.85
First pressure coefficient	Pa	1.81E+11
Second pressure coefficient	Pa	-8.0E+10
Third pressure coefficient	Pa	1.334E+12
Failure criteria (effective plastic strain)	N/A	0.70

CONTACT_ERODING_SURFACE_TO_SURFACE is selected to describe the contact between the bullet and the ceramic composite in this paper, in which the penetration phenomenon is implemented as follows:

1. When the two elements (the blade and the panel elements) are in contact, calculate the strain rate for the two elements due to the induced contact force.
2. If the calculated strain rate is higher than the threshold strain rate which is one of the parameters defined in the LS-DYNA, the element (usually the panel element) would disappear in the FEA model.
3. Then, the non-disappearing element (usually in the blade) would move toward the adjacent panel element to make contact and then calculate the strain rate again for the new element.

The penetration phenomenon was described and implemented this way.

IV. RESULTS FROM THE PENETRATION ANALYSIS

The obtained results are discussed in this section. Fig. 6 shows the results of the first shot. The bullet did not penetrate the ceramic composite as it did not in the field test. Fig. 7 shows the results for the second bullet. The bullet penetrated the composite as it happened in the field test. Fig. 8 shows the kinetic energies of the first and the second bullets. The kinetic energy of the second bullet was not absorbed completely while that of the first bullet was absorbed completely during the impact. To find this discrepancy between the capabilities of composite before and after the first shot, we investigated the plastic strain (deformation).

Fig. 9 shows the damage (which is plastic strain) after the first shot obtained from this analysis. It was found that the damage of the ceramic block hit by the first bullet was propagated into the adjacent ceramic block as shown in Fig. 8. It means that the damage due to the bullet collision was not isolated in the block.

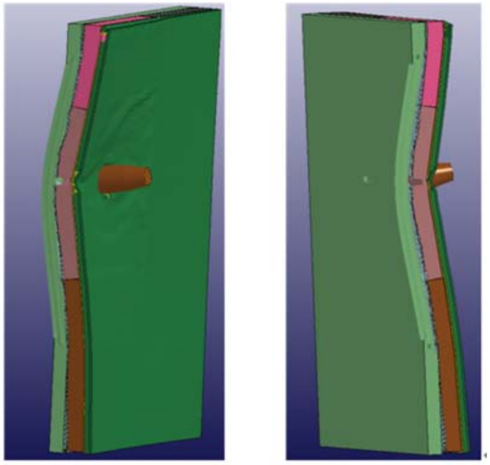

Fig. 6 Result for the first shot

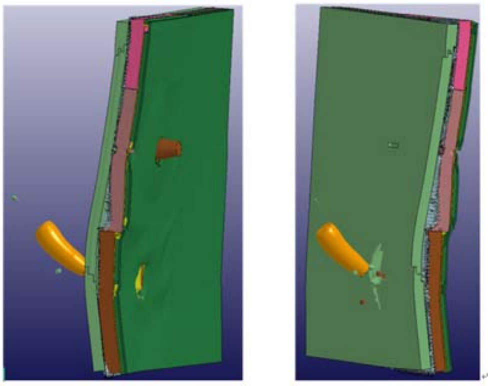

Fig. 7 Result for the second shot

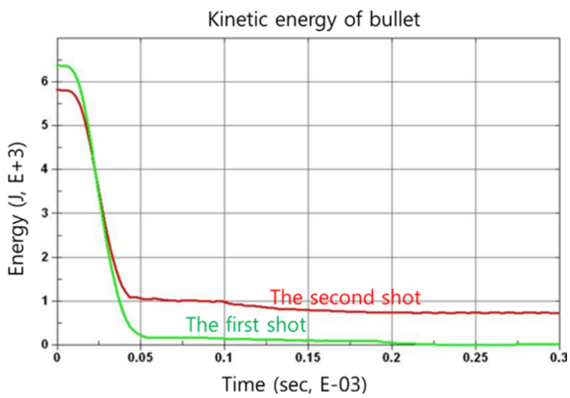

Fig. 8 Kinetic energy comparison between the first bullet and the second bullet

In summary, the reduced strength of the composite panel after the first shot was because the damage due to the first shot was propagated to the neighboring ceramic block. In order to prevent this propagation, it is recommended to place gaps between the adjacent blocks so that local damage can only occur in the target block.

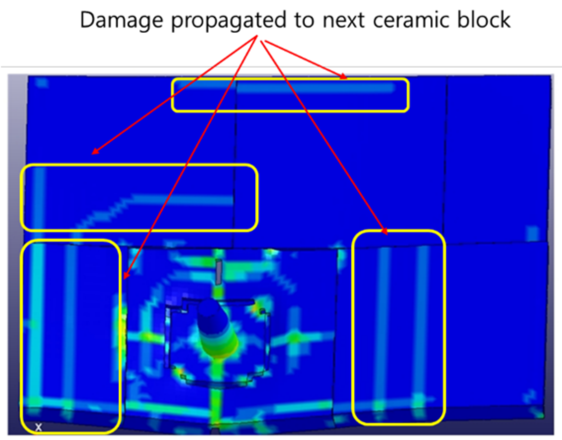

Fig. 9 Damage propagated form the damaged ceramic block to next ceramic block

V. Conclusion

An analysis was proposed in this paper based on explicit nonlinear FEA. The proposed method seems promising in the early design stage of military vehicle armor or NPP structures. The results from this FEA technique are in good agreement with the penetration field test but the FEA gives greater flexibility in dealing with the complex structural problems under dynamic and foreign object impact conditions without going into the cost and limitations of the experimental methods. This paper includes the modeling method, numerical results and a comparison of analysis and test. It is concluded from this study that local damage in ceramic composite transported to the neighboring ceramic block can easily reduce the integrity of the structure subjected to local foreign object impact.

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