FINITE ELEMENT ANALYSIS OF BALLISTIC PENETRATION OF TRACE FRAGMENTS ON ARAMID UD CLOTH

by

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The finite element method is used to analyze the failure deformation and determine the V50 value of aramid UD cloth (Uni-Directional Fabric) under 1.1 g fragment ballistic impact, and the numerical results are basically consistent with the actual experimental results. The paper concludes that the numerical method can be used to optimize the aramid UD cloth, it can more intuitively see the whole ballistic penetration process, provide accurate design methods for better applications of aramid UD cloth in the field of ballistic protection, and provide theoretical basis and data support for practical structural design.

Key words: *aramid UD cloth, 1.1 g fragmentation, target simulation*

Introduction

A large amount of data show that personal protection plays a key role in war, it can effectively reduce the casualties of soldiers, so the study of personal protection is of great significance. 1972 Kevlar (Kevlar) fiber developed by DuPont in the USA is of great significance, which marks the beginning of the transformation of protective materials from the traditional hard to soft [1].

The ballistic penetration is a hot topic in both academia and industry, and extreme research has been conducted [2, 3]. Bulletproof mechanism and ballistic properties are mainly obtained through experimental methods, theoretical model analysis and numerical simulation of three methods of approach, the previous research on ballistic penetration of fiber composites is often used in an experimental way can be the most direct penetration results, the experimental data obtained can be used to judge the accuracy of theoretical analysis and numerical simulation, so the experiments are the basis of other research methods. However, the experimental research needs to spend a lot of manpower and material resources, and the penetration effect of the projectile on the fiber composite material is completed in an instant, and a lot of experimental phenomena cannot be directly observed by the naked eye. Although the theoretical model analysis can reflect the main mechanical mechanism in the penetration problem to a certain extent, the calculation results will have a relatively large error because

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the theoretical analysis is based on a simplified analytical model. With the rapid development of computer hardware and software, numerical simulation methods are increasingly used to study the penetration problem. Compared with experimental research and theoretical analysis, the finite element numerical simulation method has its advantages, which are that it can dynamically reproduce the whole process of penetration, provide more detailed data, and observe some physical phenomena that are difficult to observe in experiments. The development of computer hardware and software has contributed to the increased use of numerical methods in the study of penetration problems. Compared with experimental and theoretical methods, numerical simulation has many advantages, but in the field of personal protection of aramid UD cloth, a complete set of models has not yet been established.

There are also many factors that affect the ballistic impact performance of woven composite materials, and the ballistic penetration process is very complex, such as the characteristics of the raw material, the structure of the fabric, the geometry of the projectile, the velocity of the projectile, the type of resin system, the angle of incidence and other factors have an impact. An important factor that limits in-depth research is that the time of the ballistic impact process is very short, and in the actual ballistic penetration test, only the incident velocity of the bullet and the residual velocity after penetrating the target plate can be obtained, and people cannot capture the information of some historical changes in the penetration of some of the penetration process, including, for example, the change of the velocity history of the projectile body, the change of the acceleration history of the projectile body, the deformation of the target plate process, and the destruction mode of the materials, *etc*. This information is very useful for analyzing the deformation and damage pattern of the target plate in the penetration process, as well as the ballistic penetration mechanism. Although high-speed camera, infrared velocity meter, laser velocity meter or micro velocity sensor have been used, these methods are far from meeting practical requirements, and the test results are often inaccurate after mathematical processing.

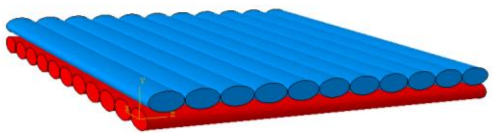

Figure 1. The schematic diagram of UD cloth

This article is based on the explicit general nonlinear finite element analysis software LS-DYNA, and takes the ballistic impact of 1.1 g fragments on aramid UD cloth as the research object. A relevant model is established, and numerical simulation is carried out. The experimental data is compared to verify the accuracy of the model. The structural schematic diagram of aramid UD cloth is shown in fig. 1.

Finite element simulation

There are various numerical methods [4-6], among which the finite element method is the most widely used method in engineering [7, 8]. In this paper, the finite element method is used, LS-DYNA explicit solution is applied, and a subroutine is used to control the structure and performance of the single cell, and the single cell of the model is to be consistent with the real single cell structure when meshing in Hypermesh, *i.e*. the same dimensions and positions are basically the same, but in order to reduce the fluctuation of calculation results, the 1/4 model is used for modeling, taking into account the periodicity and the cost of calculation.

The performance parameters of the aramid UD cloth used in the model and the 1.1 g breaking performance parameters are shown in tabs. 1 and 2. In tab. 1, E represents the modulus of aramid UD cloth, G – the stiffness of aramid UD cloth, and Poisson ratio – the ratio of transverse normal strain to axial normal strain of aramid UD cloth under uniaxial tension. In tab. 2, E represents the modulus of the 1.1 g fragment, and Poisson ratio represents the ratio of the transverse normal strain to the axial normal strain of the 1.1 g fragment under unidirectional compression.

Table 1. The aramid performance parameters

E [GPa]	G [GPa]	Poisson ratio
80	0.29	0.4

Table 2. The 1.1 g fragmentation performance parameters

E [GPa]	Density [kgm^{-3}]	Poisson ratio
210	7.9×10^3	0.3

The theory of composite mechanics is applied in the calculation through the generalized Hooke's law, and the stiffness matrix is obtained by axis transformation according to the fine mechanics of the composite material, so as to establish the single-cell model, and the finite element mesh model is shown in fig. 2.

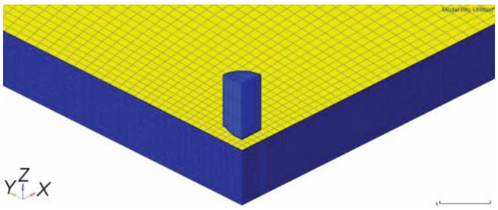

Figure 2. Schematic diagram of 1/4 model of the target

In the simulations we assume:

– The monofilaments in the yarn are continuous and parallel.
– The resin is uniformly distributed in the yarn tow, the fibers are fully infiltrated, and the fibers are perfectly bonded to the matrix.
– The effects of fiber matrix defects, cracks, and porosity, as well as residual stresses, residual strains, and environmental effects in the composite material are neglected.
– The mass of the projectile in the penetration process is assumed to be unchanged, the heat dissipated in the penetration process is negligible, the loss of kinetic energy of the projectile is assumed to be completely absorbed by the target, and the projectile is assumed to be a rigid body in the simulation process.

Since the LS-DYNA software cannot set the unit scale by itself, the unit system of each physical quantity must be harmonized or unified with each other during the numerical simulation.

The unit system of physical quantities must be coordinated or unified with each other, which really means that the known physical quantities and the physical quantities derived after the derivation must have a unit system that is unified with each other, which is necessary to ensure that the results obtained are reliable and to enable the researchers to reduce some unnecessary errors. The units used for each physical parameter in the simulation process are shown in tab. 3.

Table 3. Unit system used in this paper

Mass	Force	Length	Time	Velocity	Accelerated velocity	Modulus	Stress
[kg]	[KN]	[mm]	[ms]	[mm per ms]	[mm per ms^2]	[GPa]	[GPa]

The simulation is performed using the commercial explicit finite element software LS-DYNA. When the program calls the subroutine, the main program passes the variables such as strain increment, history variable, current time step and cumulative time to the set of equations of the constitutive relation of the subroutine for calculation. The calculated stress increment is calculated. When the program calls the subroutine, the main program passes the variables such as strain increment, history variable, current time step, and accumulated time into the subroutine's set of ontological relationship equations for calculation. The result of the calculation, such as the stress increment and the corresponding history variable, is passed to the next time step for calculation. Finally, the subroutine evaluates the strain result passed by the main program, and the mesh cell that reaches the maximum strain is deleted as soon as the material damage criterion is satisfied, thus the material is damaged. If the material is not destroyed, the displacement and stress of the material will continue to increase until the material is finally destroyed.

The impact velocity of the 1.1 g fragment is 529 m/s, and the aramid woven fabric is 29 layers, after setting the material parameters and boundary conditions, the finite element analysis simulation is carried out, and the calculation cloud of the target destruction in different time periods is shown in fig. 3. From fig. 3, it can be seen that throughout the impact penetration process, the units are gradually destroyed and the stiffness is subsequently reduced, and as the bullet penetrates further into the material, more units are subsequently destroyed due to the gradual reduction of stiffness. The aforementioned series of diagrams is a top view of the impact during the bullet penetration process, from which it can be seen that the lateral propagation of the stress wave, the destruction of the single cell, and the formation of a tiny bulge at the time of the exit surface.

In the process of penetration, the fiber aggregate and matrix bearing is the main way of composite material resistance to damage, the projectile and composite material contact, the first failure and destruction of the unit near the point of elasticity, with the continuation of the penetration process, the projectile and composite material in the fiber and matrix contact the more, the more the unit of failure and destruction, the gradual formation of bullet holes. At the same time, in the target plate from the shooting surface will see some bulging bulge, which is matrix This is the matrix cracking, the target material back by the tensile deformation results.

The final damage obtained by finite element simulation is shown in fig. 4, from which it can be seen that the projectile impact velocity is 529 m/s, and the fragmented projectile finally stays in the UD cloth target body, staying in the penultimate layer, which is considered to be the V50 value of such material in the simulation, and the actual test of hitting the target is the 29-layer aramid UD cloth, and the V50 value of 1 g fragmentation is 538 m/s, which can be seen in tab. 4, where the two data are within 2% of each other. The 1 g fragmentation is 538 m/s, as shown in tab. 4, where the two data are within 2% of each other. As can be seen from tab. 4, the error between the two data is within 2%, and the data from the finite element simulation and the actual test are basically in agreement.

Table 4. The V50 value of 1.1 g fragment in actual ballistic test

	1	2	3	4	5	6	7	9
Incident velocity	490	590	573	553	561	574	557	595
Penetration	No	Yes	Yes	No	No	Yes	No	Yes
V50 value of 1.1 g fragment is 538 m/s								

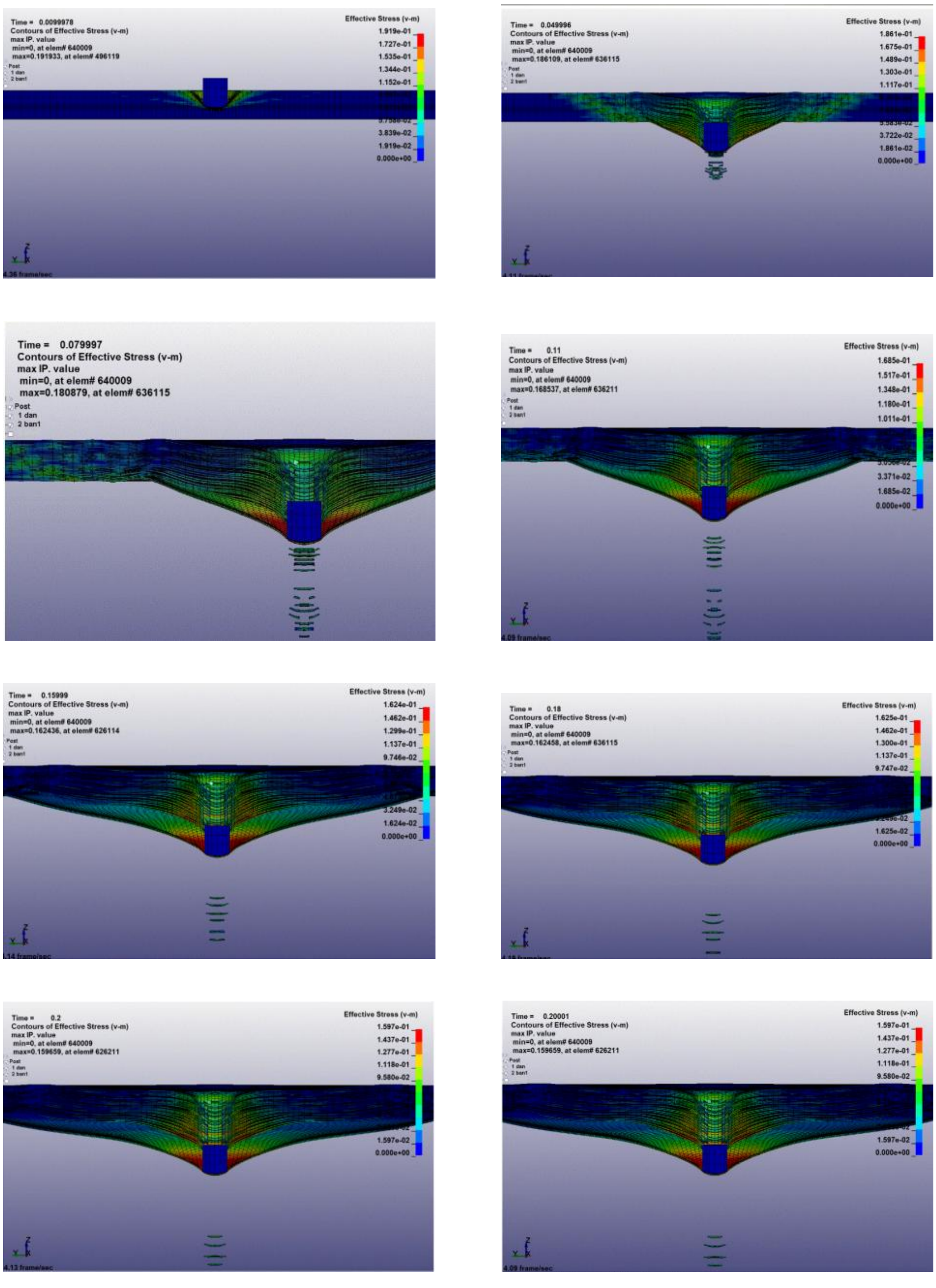

Figure 3. Cloud diagrams of target damage calculation in different time periods

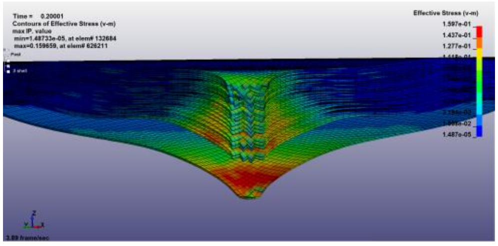

Figure 4. Final damage diagram of the target

Conclusions

This paper analyzes the structure of aramid UD cloth, establishes a fine structural single-cell model, uses commercial finite element software LS-DYNA combined with the user-defined material subroutine VUMAT to perform ballistic impact intrusion finite element simulation for the ballistic stability of aramid UD cloth, obtains the residual velocity and deformation morphology of the target plate after the projectile penetrates the target plate, and compares the calculated results with the actual ballistic test results of fragmentation. Based on the real structure of aramid woven fabric, the corresponding finite element model is established. As far as possible, the model structure of the composite material is consistent with the real physical structure. The mesh division of the material is as far as possible to make it consistent with the real single cell, and numerical simulation calculations are carried out by the finite element software LS-DYNA and the VUMAT subroutine written in FORTRAN language, which can simulate the process of penetration of the 1 g fragment into the aramid UD cloth with a high degree of accuracy, and simulations are carried out. The 1 g fragment into the aramid fabric with a high degree of accuracy, and simulations are obtained to obtain the residual velocity, residual energy, residual energy, and residual energy of the target body. Residual velocity, residual energy, target deformation, *etc.*, the simulation results and the actual experimental results are in good agreement, indicating that the finite element analysis method has the effectiveness and feasibility of the single-cell model and the corresponding user subroutine can be borrowed and applied to other dynamic impact analysis. The simulated 1.1 g fragmentation resistance of 29-layer aramid UD cloth has a certain deviation from the actual experimental data, but it is within the acceptable range of experimental error, and the single-cell model can simulate the ballistic stability of aramid UD cloth more accurately.

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