Research Progress of Numerical Simulation Method Based on the Protection Performance of STF-Kevlar Fabric Liquid Armor Composites

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Abstract. In this paper, the numerical simulation method for the protection performance of liquid armor based on STF can be roughly summarized into two ways, containing the shell element simulation method based on the inter-yarns friction coefficient and the coupled Euler-Lagrangian simulation method. The shell element simulation method of inter-yarns friction coefficient has a single consideration for STF performance, but it has high calculation efficiency and low calculation cost. The coupled Euler-Lagrangian simulation method fully considers the shear thickening characteristics of STF, and comprehensively considers the characteristics of STF. The simulated performance gets closer to the actual situation, and it can also reveal the effect of STF in improving the protection performance.

1. Introduction
Shear Thickening Fluid (STF) is a type of fluid with a certain viscosity under normal conditions. When the shear rate or the applied external force increases, the microscopic particles will be quickly aggregate, showing impact resistance new materials in solid form. And elastic fiber such as aramid fiber fabric (Kevlar fabric) is widely used in energy absorption field due to its advantages of high strength, lightweight, impact resistance, high temperature resistance and chemical resistance. Although the quality of the Kevlar fabric after the STF solution immersion treatment is reduced, the comfort and impact resistance is significantly enhanced, and the application prospect is broad.

In recent years, many researchers have carried out a large number of studies on the impact resistance of STF-Kevlar fabric. Zhang et al. conducted a comparative study on the performance of Kevlar fabric treated with STF and pure fabric. It is shown that the stab resistance of STF-Kevlar fabric was considerably better than that of pure fabric, and the cutting resistance was also slightly increased. Tan et al. used graphene to enhance STF and found that yarn slippage can be better prevented, and the single yarn pull-out force is almost 5 times that of pure STF. STF has the effect of increasing the yarn count of the fabric and reducing the movement of the yarn in the impact area. Haris et al. found that fabric treated STF not only has the effect of bulletproof protection, but also has potential applications to reduce shock waves. Yeh et al. found that shear thickening fluid (STF) can effectively improve the energy absorption capacity of Kevlar fabric. Riaan et al. tested the resistance ability of Kevlar with different grams per square meter. Majumdar et al. studied and analyzed the main factors affecting the impact resistance and energy absorption of STF-Kevlar fabrics. The results show that SiO2 concentration, solvent ratio, and STF dilution ratio is the main influence items of...
impact energy absorption. Khodadadi et al. found that by increasing the nano-silica loading, the energy absorption of the composite material increased, but under the high loading of nano-silica, the effectiveness of STF decreased. Li et al. found that the concentration and particle size of STF significantly affect the puncture resistance. Liu et al. found that when the solid content of SiO₂ is 35%, the adhesion effect is the best and uniformly dispersed; it is the best effect when the immersion time is 30 min in STF. Cao et al. found that STF plays a role in the sliding and deformation parts mainly by enhancing the friction between the fabric yarns and preventing the fabric yarns from sliding.

It can be seen from the aforementioned literatures that most of the research are based on experimental methods. However, more accurate test results are limited by factors such as short test time and high test cost. In this case, the numerical simulation for STF-Kevlar composites has greater benefits and prospects. Comparatively speaking, there is few numerical simulation researches on the protective performance of STF-Kevlar fabrics. This article summarizes the numerical simulation method of the protective performance of STF-Kevlar fabric composite.

2. Numerical simulation methods based on STF liquid armor protection performance

Compared with the numerous experimental studies on the protective performance of STF-Kevlar fabrics, there are fewer numerical simulation studies based on the protective performance of STF-Kevlar, but in these few simulation studies, two methods can be summarized. It is summarized as follows.

2.1. The simulation method of shell element based on inter-yarn friction coefficient

It is believed that the performance enhancement provided by STF is due to the increased frictional interaction between the impregnated fabric yarns. The experimental results of the yarn pull-out test are utilized to characterize the friction performance of the STF impregnated fabric. Therefore, in this simulation method, the yarn uses shell elements, and the effect of STF is realized by considering the higher coefficient of friction between the yarns. The advantages of this simulation method are low computational cost and high efficiency. But at the same time, the main limitation of this method is that it does not include the rate-dependent viscous effect of colloidal fluid (ie STF), so it is impossible to fully understand the deformation, failure mechanism and energy distribution characteristics of Kevlar-STF composites.

2.1.1. Kevlar fabric target model

In order to properly model the Kevlar fabric, the microstructure of the fabric presents a plain weave structure composed of crisscrossed yarns. Depending on the above structure, it is more suitable to use shell elements for modeling. Shell elements are a fabric modeling method that can better solve contact problems and lateral pressure loads, and can fully represent the impregnation effect of STF. Kevlar fabric is composed of multiple yarns, and each yarn can be modeled as a discrete continuum. The SEM image of the STF impregnated fabric shows that the silica nanoparticles adhere to the surface and the fiber content in each yarn, but each fiber is distinguishable. Therefore, it is assumed in the simulation that the role of silica nanoparticles can be applied to the fabric yarn model through appropriate characteristic parameters without the nanoparticles being physically modeled.
2.1.2. STF simulation

The research of Lee et al. believes that the most noticeable difference between pure Kevlar fiber and STF impregnated Kevlar is the static and dynamic coefficient of friction. The static and dynamic coefficient of friction are tested by fiber pullout test. Zhao Xudong proposed Equation (1) to indirectly obtain the friction coefficient between the warp and weft using the tension-displacement curve.

\[
F = C \times \text{Count} \times 4 \times \text{Diameter}^2 \times \text{Modulus} \times \text{Waviness} \times \text{Friction}
\]  

(1)

Where \( F \) is the tensile force; \( C \) is constant value based on the coefficient of friction of Kevlar fabric - 0.573; Count is the number of fabrics per inch of yarn - 17/in.; Diameter is the diameter of a single fiber contained in a single yarn - 1.2x10^{-5} m; Modulus is the elastic modulus of the yarn along the axial direction (the direction consistent with the direction in which the yarn is pulled out), in Pa; Waviness is the thickness of the yarn — 7x10^{-5} m;

The following formula can be used in LS-DYNA to achieve the Coulomb friction coefficient of STF impregnated Kevlar

\[
\mu = \mu_d + (\mu_s - \mu_d) e^{-|\nu_{rel}|}
\]

(2)

\( \mu_d \) is the dynamic friction coefficient, \( \mu_s \) is the static friction coefficient, and \( e \) is the exponential decay constant, assuming that the friction coefficient depends on the relative speed of the contact surface \( \nu_{rel} \). Write the above formula into the LS-DYNA code and combine the drawnwork test to achieve STF impregnation of Kevlar fabric to achieve the purpose of simulation.

2.1.3. Material properties

During the simulation, the Material cards in LS-DYNA were chose to use add_erosion (ball, fabric), orthotropic_elastic (fabric), rigid (ball). Other material parameters used are E11, E22, E33, G13, G23, G12, Poisson’s ratio, Failure stress, Failure strain, Shell thickness, Integration points, Boundary conditions, Contact cards, Static coefficient of friction, Dynamic coefficient of friction and Exponential decay coefficient.

2.1.4. Research progress on this method

Mahdi et al. and Mirrahimi et al. used the above method to extend STF-Kevlar to the study of high modulus polypropylene woven (HMPP) fabrics, and studied the impregnated shear thickening fluid through experiments and numerical simulation techniques (STFs) high modulus polypropylene woven (HMPP) fabric impact resistance. They use LS-DYNA to simulate the impact of the end projectile on the four-layer fabric. It is shown that STF impregnation improves the ballistic properties of the woven fabric. These studies considered the friction between the yarn and its intersections generated by STF impregnation. Meanwhile, the impact of the friction between the projectile and the fabric during the impact on the fabric was considered in their studies.

Liu studied the mechanism of the friction coefficient and failure stress between yarns on the energy absorption of STF-Kevlar fabrics, and found that the shear thickening liquid has a significant enhancement effect on the energy absorption of Kevlar fabrics; failure stress significantly affects the fabric absorption ability, the greater the failure stress, the more energy absorption. The friction coefficient indirectly affects the energy absorption capacity of the fabric by affecting the number of participating yarns. The higher the friction coefficient, the less energy is absorbed.

2.2. The simulation method of Coupled Eulerian–Lagrangian (CEL) approach
According to Section 2.1, the shell element simulation method based on the friction coefficient between yarns has the high calculation efficiency and low calculation cost, but the characteristics of STF liquid cannot be considered in the simulation, especially the shear rate dependence and shear thickening effect. Therefore, the effect of shear thickening liquid on the protective performance of liquid armor containing Kevlar fabric cannot be completely simulated in the above method. In response to the above problems, Sen et al.\textsuperscript{0} carried out the study of coupled Euler-Lagrangian simulation method, which the above problem can be effectively solved.

2.2.1. Kevlar fabric target model
The Kevlar fabric finite element model was used by a mesoscopic model based on the yarn scale of the membrane. The membrane unit is used to discretize the yarn and eliminate the rotational degrees of freedom. Only three translational degrees of freedom are active, so the effect of the small bending stiffness of the yarn is ignored by the model. This approximation reduces the calculation cost and the ballistic performance measurement parameters (ie the remaining speed of the back surface deformation) without affecting the calculation accuracy. This modeling method first simulates a single yarn into a belt-shaped membrane unit, and then combines multiple yarns into a membrane unit fabric. M3D4R of Abaqus finite element (four-node membrane element with simplified integral) was used to divide the geometric model. The numerical simulation of multi-layer fabrics involves stacking multiple single-layer membrane in a certain direction.

Figure 2. Single-layer Kevlar fabric modeling\textsuperscript{[24]}. 

Figure 3. Multi-layer Kevlar fabric modeling\textsuperscript{0}. 

2.2.2. Kevlar-STF Composite Target Model

The Kevlar-STF composite target plate model adopts the coupled Euler-Lagrangian approach, because Euler material can interact with the Lagrangian element through Euler-Lagrangian contact. This simulation method can consider the characteristics of STF liquid, especially the shear rate dependence and shear thickening effect, and can avoid the element distortion caused by the traditional Lagrangian method to lead the analysis failure. At the same time, this method can solve the problem which causes the element boundary exceeds the material boundary leading the failure of simulation due to large deformation mismatch with the material boundary of the traditional Euler model. CEL analysis includes a Lagrangian step followed by a remapping step. The first step is similar to the Lagrangian analysis. In this step, the mesh deformation will deform with the material. In the remapping step, the nodes will return to the initial position where they were calculated and the flow will be generated from this position. Two steps are repeated in each explicit time increment until the simulation is finished. The interaction between Lagrangian and Euler element (fluid-structure interaction) can be defined using the general contact function of Abaqus/Explicit. By default, this universal contact ensures that tensile stress is not transmitted through the Euler-Lagrangian contact interface, and the interface friction coefficient is zero. Specifying universal contacts in the entire Euler-Lagrangian model will allow interaction between all Lagrangian structures and all Euler materials in the model. The Kevlar model adopts the model of 2.2.1, and the STF adopts a simplified integral eight-node hexahedral isoparametric solid element (EC3D8R of Abaqus).

![Euler-Lagrangian coupling simulation steps](image)

**Figure 4. Euler-Lagrangian coupling simulation steps.**

(a) model (b) Lagrangian incremental step (c) Euler incremental step.

2.2.3. Material Properties of the Coupled Euler-Lagrangian Simulation Method

(1) Kevlar Fabric Material Properties

Kevlar yarns mostly exhibit linear elastic behavior without significant plastic deformation. When the stress reaches a critical value, the yarn will suddenly break, similar to brittle fracture. The material properties used in Kevlar fabric include density, Young’s modulus, Poisson’s ratio, limits strength, and coefficient of friction inter-yarns.

(2) STF Material Properties

The mechanical properties of STF use the Mie-Grüneisen equation of state, and the equation is as follows

\[
p = \rho_0 C_0^2 \chi \left(1 - \frac{\Gamma_0 \chi}{2}\right) + \Gamma_0 E
\]

In the formula, \(p\) is the pressure, \(C_0\) is the speed of sound in the medium, \(\chi = 1 - (\rho / \rho_0)\), \(\rho_0\) is the initial density, \(\rho\) is the current density, \(\Gamma_0\) is a material constant, \(s\) is a linear hugoniot slope coefficient, \(s = dU_s/dU_p\), \(U_s\) is the vibration wave velocity, \(U_p\) is the particle velocity, \(E\) is the unit reference volume.
internal energy. The material performance parameters in the simulation include the viscosity value of the critical strain rate value, the $\Gamma_0$ value, the $s$ value, the sound velocity in the medium $C_0$, etc.

2.2.4. Research situation of this method
The research results using this simulation method show that the ballistic response of the STF-Kevlar composite material including lateral deformation, energy distribution, and ultimate velocity has been greatly improved, compared with the multilayer pure Kevlar target. About 75% of the energy are consumed in the STF's viscous dissipation. However, if the STF exhibits thinning behavior again after thickening, the effect of STF is observed to be negligible in the simulation, which provides a theoretical basis for the preparation of STF in liquid armor research.

3. Conclusions
(1) The shell element simulation method based on the friction coefficient inter-yarns believes that the performance of STF-Kevlar fabric the composite material the be enhanced due to the increase in the frictional interaction between the impregnated fabric yarns. The simulation depends on the experimental results of the yarn pull-out test. The advantages of this simulation method are low computational cost and high efficiency. The disadvantage is that the characteristics of STF cannot be considered.

(2) Used coupled the Euler-Lagrangian simulation method, the Kevlar yarn is modeled by Lagrangian membrane elements, and the STF is embedded in the Euler grid. The interaction between Kevlar and STF is established through the contact algorithm. Kevlar assumes a linear elastic constitutive, and it will show brittle failure if the critical strain is exceeded. STF was used in the Us-Up equation of state and the velocity-dependent viscosity curve. This method fully considers the shear thickening characteristics of STF, and the simulated performance gets closer to the actual situation, and it can also reveal the effect of STF in improving the protective performance.

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