

MULTI-SCALE MODELING AND LARGE-SCALE TRANSIENT SIMULATION OF BALLISTIC FABRIC

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ABSTRACT

Ballistic fabrics such as Kevlar and Zylon are finding new uses not only as shielding for personnel but also in commercial and military aircraft protecting flight-critical components in the event of a high-speed ballistic impact. Since experimental tests on these materials are often expensive and time consuming, a computational model amenable to large-scale numerical simulations on massively parallel processors would provide an ideal alternative. To this effect, a novel multi-scale approach has been developed for modeling ballistic fabric that extracts information from the micro-scale fibril material properties to build the macro-scale sheet. This approach incorporates the stochastic nature of the material due to the random variations in the yarn caused by the weaving process. Representing these variations is critical to capturing the heterogeneous damage and failure of the material as confirmed by experimental tests. A parallel implementation of the proposed multi-scale method has been developed with particular attention to the contact problem. The paper will focus on all of these issues and report on massively parallel large-scale computations for large sheet applications with both performance and validation results.

1. INTRODUCTION

For decades, ballistic fabric has been a primary ingredient in lightweight protection of personnel and structures from incoming high-speed fragments. For example, in law enforcement and military applications the objective is to develop lightweight body armor. In the aircraft industry, the objective is to develop lightweight shields for structures. In order to design such systems, computational sciences and high-performance computing can play a pivotal role in ensuring the success of such efforts. Through high-fidelity modeling and simulations, they enable the

rapid assessment of current technologies and performance improvement of current designs. Recent research has already shown that dramatic improvements in blast resistance can be made while paying attention to the weight issue, by exploiting structural fabric concepts. However, the effective incorporation of these concepts into shielding systems requires specific knowledge of their response to impact in each specific application.

The main objective of this paper is to harness the significant increases in widely available scientific computing to simulate realistic responses of structural fabric, starting directly at the microscale where relatively simple descriptions of the material are possible, in order to gain further insight in their behavior and pave the way for the optimization of their designs for specific applications. By employing enough of these simple structural elements, an entire macroscale sheet of structural fabric can be built. The advantage is that relatively simple microscale models can be used, with the burden of the analysis being shifted to rapid, efficient computation. The immediate benefit is the rapid optimization and deployment of new lightweight fabric materials for engineering designs.

2. MULTI-SCALE MODEL

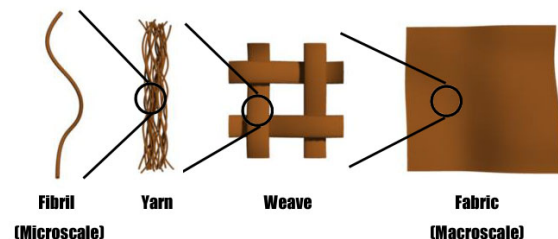


Fig 1. Multi-scale nature of structural fabric.

In order to accurately capture the behavior of structural fabric without having to resort to phenomenological modeling, a multi-scale approach to

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fabrics is employed. A single sheet of fabric is woven from hundreds of yarns which are themselves comprised of hundreds of micro-scale fibrils, figure 1. The model for the macro-scale sheet is based on fabric geometry and the micro-scale model of the fibrils. This approach allows for a model based entirely on the micro-scale fibril information and thus no macro-scale phenomenological parameters are introduced.

2.1 Micro-scale Model

For structural fabric, a typical quantity of interest is the global, tensile, force-deflection response. The compressive response is usually of little interest, in particular if information on fabric rupture is sought. Therefore, analyses based on so-called relaxed theories of perfectly flexible solids are employed, which consist of enforcing a zero stress state for any compressive strains. Pipkin (1986) appears to have been the first to have shown that such a model is compatible with the conventional theory of elastic surfaces by considering a minimizing sequence for an associated variational problem, and that such sequences have a structure similar to observed wrinkling in thin elastic sheets. These types of approaches have been adopted by numerous researchers for the elastostatic analysis of structural fabric; for example Buchholdt et. al (1968), Pangiotopoulos (1976), Bufler and Nguyen-Tuong (1980) and Cannarozzi (1985, 1987). Steigmann and coworkers (Steigmann (1990), Haseganu and Steigmann (1994-1996) and Atai and Steigmann (1997, 1998)) have developed a variety of theoretical results and elastostatic solution techniques based on pseudo-dynamic relaxation methods, such as those found in Papadrakakis (1980). A crucial theoretical result proven by Steigmann and coworkers is that a necessary condition for the existence of energy minimizers in elastostatics is for structural members to carry no load in compression. This relaxed requirement is adopted for the microscale fibrils in the upcoming dynamic analyses. This approach has been applied to the dynamic analysis of structural fabric and other materials in Zohdi (2002), Zohdi and Steigmann (2002), and Zohdi and Powell (2006).

The micro-scale analysis begins with a *purely one-dimensional* description of the tensile deformation of the micro-scale fibril. As the fibrils are extremely thin, roughly the width of a human hair, one may assume a uniaxial-stress type condition. Axial strains for a structural fabric are expected to be in the range of 2 %-10% prior to rupturing. For example, a Zylon fibril ruptures at approximately a 3 % strain (Toyobo, 2001). Due to the same small strains, a simple Kirchhoff-St. Venant material model for the fibrils is reasonable. The stored energy of a single fibril is given by $W = \frac{1}{2} \mathbf{E} E^2$, where \mathbf{E} is Young's modulus, where $E \stackrel{\text{def}}{=} \frac{1}{2}(C - 1)$

is the Green-Lagrange strain, where $C \stackrel{\text{def}}{=} F^2$ is the right Cauchy-Green strain, where $F = \frac{dx}{dX}$ is the deformation gradient, where X are referential coordinates and where x are current coordinates along the axis of the filament. For detailed information on this model please see Zohdi and Powell (2006).

The overall response of the yarn is determined by summing the response of each of its individual micro-scale fibrils. For Zylon, a single yarn is made up of 350 individual fibrils. At the micro-scale, unavoidable fibril misalignment occurs due to the weaving process. This misalignment is highly advantageous from the stand point of rupture resistance. Should all the fibrils be perfectly aligned, a state that is almost impossible to attain, then one would get instantaneous rupture of the yarn once the critical strain was reached. With misalignment, the axial directions of the fibrils and the yarn are no longer aligned. As such, the rupture of many fibrils will be delayed and the yarn as a whole fails gradually, not suddenly. Another important consequence of the random misalignment of the fibrils is that it is a source of statistical variation for the yarn properties. As the misalignment differs from yarn to yarn, so do the yarn properties. Since each yarn is made up of many fibrils, 350, and not just a few, the differences between yarns tend to be somewhat small. However, the inclusion of these statistical variations due to the micro-scale fibril misalignment is critical for accurately capturing the macro-scale behavior.

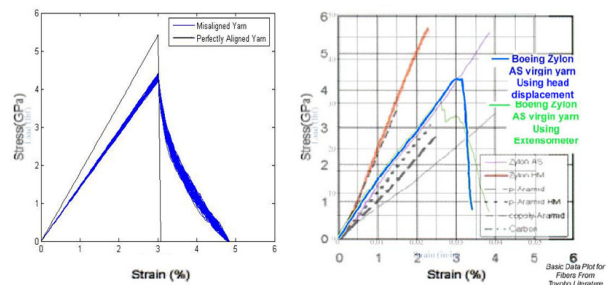


Fig 2. Left: Simulated response of 100 yarn based on randomly oriented micro-scale fibrils and one yarn with perfectly aligned fibrils. Right: The blue line is the stress-strain response for a Zylon yarn as measured by the Boeing Corporation.

In Figure 2 one can see the response of 100 simulated yarn with random misalignment of the fibrils and one yarn with no misalignment (ie all fibrils perfectly aligned). It is clear that including the micro-scale fibril misalignment is essential to accurately modeling the macro-scale fabric sheet. The material has a more gradual, realistic rupture behavior which is a natural result of the multi-scale model. Furthermore, this misaligned response is in excellent agreement with the experimental results furnished by the Boeing Company, shown on the right of figure 2. The resulting stiffness, failure stress, and general failure behavior are all in good agreement with Boeing's tests on actual Zylon yarn segments.

2.2 Macro-scale Model

For the coarse weave of many structural fabrics, treating the sheet as a continuum is not a valid approximation. In this case, the diameter of the projectile used in testing done by D. Powell at the University of California, Berkeley is less than 20 yarns across. Thus the choice was made to model the yarn discretely as continuous truss elements connecting a network of lumped masses (figure 3). The macro-scale model begins with an initially undeformed two-dimensional network of yarn made up of micro-scale fibrils. The yarns are pinned together at nodes. In reality the yarn are tightly woven, not pinned. The nodes are placed at every criss-cross contact junction between the warp and the fill of the weave.

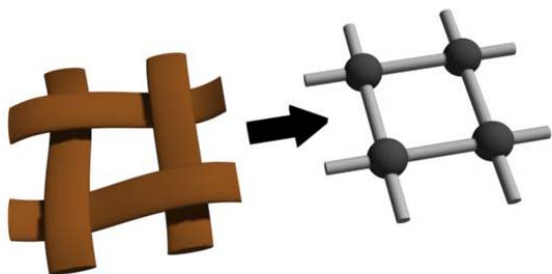


Fig 3. Truss network with lumped mass nodes representing the yarn of the macro-scale fabric sheet.

This approach was implemented in FEM, a finite element program in use at Stanford University, using simple truss elements. The response of each of these truss elements is determined by running the micro-scale simulation described above. The equations of motion are solved using an explicit central difference time integrator.

2.3 Contact

For structural fabrics such as Zylon, a typical problem of interest is the response to the impact of a small projectile. As such, an appropriate algorithm to search for contacting entities and enforce the contact constraints needed to be included. To do this, the Sandia's ACME contact library was added to FEM. A dynamic 2-configuration search was used to identify elements in contact. Contact is frictionless and enforced using a Lagrange multiplier method. As the equations of motion are solved with an explicit method, a predictor-corrector approach is taken to calculate the contact forces.

3. RESULTS

As in the experimental tests performed at the University of California, Berkeley, a 50 caliber (0.0127 m or 0.5 inch diameter) cylindrical projectile was simulated. The projectile has a mass of

0.036 kg and a length of 0.0381 meters (1.5 inches). A range of initial velocities were examined and the residual velocity was recorded for each shot. An initially planar, square, fabric target with dimensions 0.254×0.254 meters (10×10 inches) was chosen. The fabric was assumed to have no tension in the yarn prior to impact nor any slack. This is of course an idealization, as any fabric sheet in an actual experiment would have some tension or some slack. However, as the experiments attempted to minimize both slack and tension, it is a reasonable approximation. The fabric was set to have 35×35 yarn per square inch or $1,378 \times 1,378$ yarn per square meter (standard for Zylon). Consequently 350×350 lumped mass nodes and $3 \times 350 \times 350 = 367,500$ degrees of freedom or unknowns were needed for the computation. Each of the 350 fibrils that make up the yarn is estimated to be 0.02 mm in diameter. Thus each yarn would have a cross-sectional area of $1.075 \times 10^{-7} \text{ m}^2$.



Fig 4. Resulting deformation predicted by numerical simulation.

A typical boundary condition examined in the experiments was fabric pinned at the corners. In experiments, a small hole is cut near the corner of a square 10 inch sheet of fabric, 1.5 inches from either edge. A bolt was slipped through the hole and the fabric was held in place by a two inch diameter washer placed on either side of the hole. In the simulation, every node within the pinned region was restricted from moving. Some sliding would normally occur in the experiments but this slipping was assumed to be small and was neglected by simulation. Figure 4 shows the response of fabric pinned at the corners as predicted by the simulation. Just as seen in the experimental results, failure occurs at the boundaries. It should also be noted that failure does not occur simultaneously at each attachment. This effect is caused by material variation in the yarn and is also seen in the experiments.

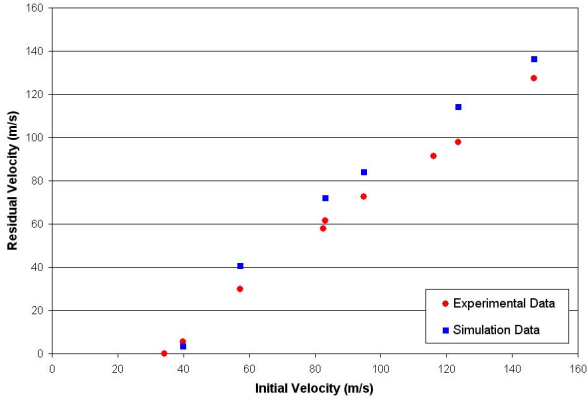


Fig 5. The residual versus initial velocity for cylindrical projectile impacting a sheet of fabric clamped on two sides. Both experimental and numerical results are shown, all values are in feet per second and degrees.

Figure 5 shows a plot of the residual velocity versus the initial velocity for a .254 meter (10 inch) square sheet of Zylon with two of its sides clamped. Both simulated results and experimental results are shown. At higher velocities, where penetration occurs easily, the simulation tends to over-predict the residual velocity. Alternatively it could be said that the simulation under-predicts the amount of energy absorbed during impact. However, at lower velocities, between 30-45 meters per second (100-150 feet per second), the simulation and the experimental results converge. This region is where the ballistic limit lies. The ballistic limit is defined as the transition velocity below which penetration does not occur and above which the projectile does penetrate the fabric. Based on a calculation of the energy absorbed during impact in this range and the assumption that the energy absorbed is independent of the initial energy, the ballistic limit estimated by the experimental results is 39.3 meters per second (129 feet per second) and from the simulated results is 39.6 meters per second (130 feet per second). Quantitatively, the two are in very good agreement.

4. PARALLEL COMPUTATIONS AND SCALABILITY

Until now, all simulations have been run in serial. However, to tackle even larger problems involving multiple sheets, the algorithm must be run in parallel so results can still be calculated in a reasonable amount of time. As the implementation in FEM uses an explicit method for the time integration, the majority of the algorithm is trivially parallelizable. For that reason, this section will be focused on the contact search and enforcement portion of the algorithm, as that is where the majority of the difficulty in parallelization lies.

Sandia's ACME contact library is designed for parallel codes, so the majority of our work centered around measuring and attempting to improve the

scalability of the contact search. According to the authors of ACME, the choice of subdomains is critical to optimizing the performance of the contact search. The standard approach to creating subdomains results in elements from different bodies being placed in different subdomains and therefore on different processors. In this approach, if elements A and B are in contact, the data regarding their positions will be stored on separate processors. As a result, a significant amount of data must be passed between processors during each contact search and the entire algorithm takes more time. An alternative approach would be to place elements into subdomains based on their spatial proximity to one another. In this approach, if elements A and B are in contact, their data will most likely be stored on a single processor, reducing the communication time for the algorithm. Figure 6 shows how a problem involving 3 sheets and a projectile would be divided up into 4 subdomains using each of these approaches.

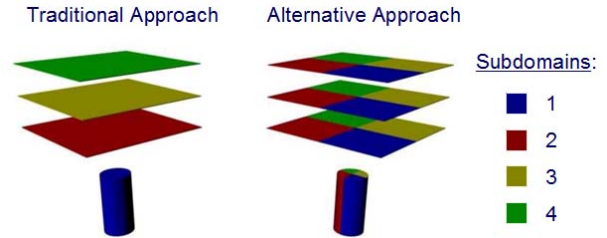


Fig 6. Two approaches to creating subdomains in a multi-sheet problem. Left is the traditional approach and right is the alternative approach idealized for contact.

The problems shown so far involve a small projectile impacting a single sheet of ballistic fabric. In this type of problem, the localized nature of the contact event causes a new difficulty in optimizing the scalability of the contact algorithm. Since only a small number of elements are in contact, as the number of processors is increased it becomes difficult to share the workload between all of the processors. Once the number of processors increases beyond 10, little improvement is seen in the scalability of the algorithm, figure 7.

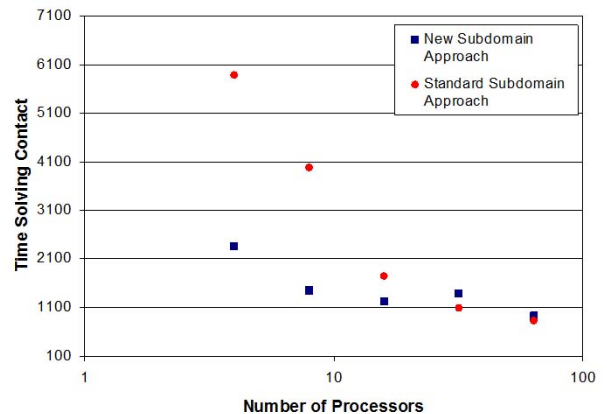


Fig 7. Time spent in the contact portion of the

algorithm plotted as a function of the number of processors. Both the new approach for creating subdomains and the standard approach are shown.

This represents the performance of the algorithm at one extreme. A problem of two sheets impacting each other represents the other extreme, contact distributed evenly across the entire problem. In this case, the algorithm scales well until the number of processors increases to beyond 200, figure 8. This problem involved approximately 1 million degrees of freedom. As the number of degrees of freedom per processor is reduced, the performance of the algorithm suffers. At around 50,000 dofs per processor, the algorithm loses optimal scalability. This is to be expected of any approach, as a certain amount of overhead is created when dividing a problem between different processors.

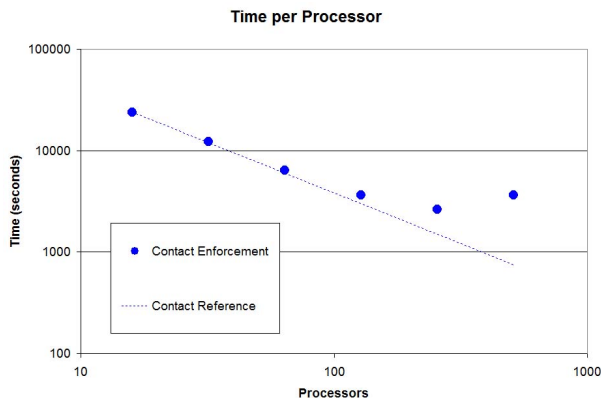


Fig 8. Time spent in the contact portion of the algorithm plotted as a function of the number of processors. The reference line represents the idealized case where doubling the number of processors reduces the time by a factor of 2.

It is expected that the majority of problems that are of interest to the users and producers of ballistic fabric will involve a mixture both localized as well as more distributed contact events. For that reason, the scalability of this algorithm should fall somewhere between these two extremes.

CONCLUSIONS

Presented in this work is a simple and efficient approach to modeling ballistic fabric. The model uses a micro-scale representation of the fibrils to calculate the yarn properties. These properties are then fed into a macro-scale simulation where the fabric weave is modeled as a simple network of trusses. This approach allows for the discrete modeling of the yarns in the fabric while not requiring an overly large number of elements. Because each yarn is modeled independently, a much more realistic failure behavior is captured by this method. The material variation in the fabric sheet, due to the misalignment from the weaving process, is also critical to producing realistic failure behavior. The model is based entirely

on information about the micro-scale fibrils. This information can be obtained from the manufacturer and is easy to test and verify. No phenomenological parameters are introduced at any point. As a result, one can have confidence in this model in a wide range of applications. Using test data from the University of California at Berkeley, good agreement is seen between the numerical model and the experimental test results, both qualitatively and quantitatively.

The basic explicit model is extremely simple parallelize, however the parallelization of contact is more difficult. Using Sandia's ACME contact library helped parallelize this portion of the algorithm, however significant work still needed to be done so that the algorithm scaled correctly. The correct choice of subdomains was critical to improving the performance of the code in parallel. Using domains that were designed for problems involving contact, the code scaled very well in the case of contact distributed across the body. In the problem of local contact, more work needs to be done. Even so, as such a small number of elements are in contact, there is limited room for improvement. In real combat systems, a combination of materials are used in shielding on both personnel and in vehicles. As the impacts are more complicated, one can assume that both local contact events will be present as well as more distributed contact events. Therefore, one can assume the scalability of this problem to lie somewhere in between the two extremes presented.

As fabrics are used as ballistic shielding in more and more applications, there is a greater need for fast and accurate numerical models. This multi-scale approach, based entirely on micro-scale information about the fibrils, has great potential to fill this need.

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