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# A continuum shell finite element model for impact simulation of woven fabrics

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**Abstract**

A new computational approach is developed to predict the impact behaviour of fabric panels based on the detailed response of the smallest repeating unit (unit cell) in the fabric. The unit cell is constructed and calibrated using measured geometrical (weave architecture, crimp, voids, etc.) and mechanical properties of the fabric. A pre-processor is developed to create a 3D finite element mesh of the unit cell using the measured fabric cross-sectional micro-images. To render an efficient method for simulation of multi-layer packs, these unit cells are replaced with orthotropic shell elements that have similar macroscopic (smeared) mechanical properties as the unit cell. The aim is to capture the essence of the response of a unit cell in a single representative shell element, which would replace the more complicated and numerically costly 3D solid model of the yarns in a crossover. The 3D finite element analysis of the unit cell is used to provide a baseline mechanical response for calibrating the constitutive model in the equivalent shell representation. This shell element takes advantage of a simple physics-based analytical relationship to predict the behaviour of the fabric's warp and weft yarns under general applied displacements in these directions. The analytical model is implemented in the commercial explicit finite element code, LS-DYNA, as a user material routine (UMAT) for shell elements. Layers of fabric constructed from these specialized elements are stacked together to create fabric targets that are then analysed under projectile impact. This approach provides an efficient numerical model for the dynamic analysis of multi-layer fabric structures while taking into account several geometrical and material attributes of the yarns and the fabric.


*Keywords:* Fabric modelling; Unit cell approach; Ballistic impact; Finite element analysis

## 1. Introduction

High-performance fabrics are extensively employed in ballistic and impact protection applications. Over the past two decades, many researchers have endeavoured to capture the behaviour of fabrics using analytical and numerical approaches. Despite all such efforts, the design of fabric armour systems is still largely empirical based due to a lack of reliable and robust analysis tools. To reduce the reliance on time consuming and costly tests it is desirable to have efficient analysis tools that can provide insight into the impact phenomenon and

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thus aid in the optimum design of fabric armours. Recent advances in textile production and manufacturing have placed a demand for more realistic and sophisticated models that can be used as effective design tools in the ballistics industry. Although numerous studies have been conducted to date, many of these are either based on oversimplifying assumptions on the mechanics of fabrics or use detailed 3D finite element models that are computationally impractical for analysing multi-layer and real size fabrics under dynamic loading conditions. In this paper we introduce a numerical approach that takes into account the important characteristics of the woven panels in an efficient computational environment.

Finite element models based on pin-jointed orthogonal strings (cables) have been the most widely utilized approaches by various researchers over the past couple of decades. Studies performed by Roylance and Wang [1], Shim et al. [2], Lim et al. [3], Shahkarami et al. [4], Johnson et al. [5], and Billon and Robinson [6] are examples of such numerical techniques. The pin-jointed approach has proved to be very efficient in approximating the dynamic behaviour of woven fabrics; however, the discrete nature of such models has inherent oversimplifications that somewhat limits their predictive capability. In particular, these models do not effectively take into account the important details associated with the weave architecture; yarn-to-yarn contact conditions (or intra-layer interactions, e.g., surface finish and friction); and layer-to-layer contact conditions in multi-layer fabrics (or inter-layer interactions, e.g., friction, bonding, stitching and spacing effects). To this end, more detailed modelling techniques have appeared in the literature, such as the work by Shockey et al. [7] and Duan et al. [8], among others. These full blown 3D continuum models provide useful tools in capturing the detailed dynamic response of fabrics on a small scale but are computationally demanding when applied to the industrial size fabric armours with thicknesses of practical relevance (i.e., 30–50 ply fabric packs which are typically used as armour).

Unit cell approaches have been used extensively in the analysis of fibre and textile composites. In 1973, Kawabata et al. [9–11] presented simple analytical models to capture the uniaxial, biaxial and shear behaviour of fabrics. Ivanov and Tabiei [12] developed a micro-mechanical model of a woven fabric for non-linear finite element impact simulations. In their model, they considered the motion of the crossover point and calculated its equilibrium position under the applied strains, assuming a visco-elastic constitutive behaviour for the yarns. King et al. [13] presented a continuum model to analyse and predict the behaviour of fabrics based on the properties of the yarns and the weave. In their approach, an energy minimization scheme was employed to relate the configuration of the fabric structure to the microscopic deformation of its components. Similar shell-based models have been developed by other researchers, e.g., Boisse et al. [14] and Peng and Cao [15], that are also based on the continuum modelling of the unit cell to track the deformation of fabrics during the forming process as they undergo large displacements and shear distortions.

Recent developments in numerical modelling of fabrics have provided sophisticated tools to analyse the performance of these systems, however, most of these models either lack efficiency or fail to capture many realistic features of the structure and/or the dynamic event. The study presented here focuses on developing an efficient shell-based meso-mechanical model that captures the essential components of plain woven fabrics. This equivalent (smeared) shell element uses an analytical constitutive model similar to that proposed by Kawabata et al. [9], that takes into account the interaction of warp and weft yarns. Multi-layer fabric panels under projectile impact are then discretized entirely using these representative shell elements, resulting in a highly efficient computational analysis. The following sections present the details of this approach.

## 2. Overall approach

Every single layer of the fabric consists of an assembly of yarns crossing over one another according to a specific weave pattern. The presence of these crossovers and the resulting interaction between the orthogonal yarns give rise to a bi-axial response of the fabric. The current approach uses the material and geometrical properties of the fabric panels to provide a predictive tool based on the interaction of the yarns in a unit cell of a fabric with specific weave architecture.

The unit cell approach proposed here is based on the numerical study of the smallest repeating unit of the fabric. The objective is to recreate the membrane response of a fabric unit cell in a single representative shell element. This shell element takes advantage of a simple mechanistic constitutive relationship to estimate the tensile forces in the warp and weft yarns subjected to arbitrary biaxial (in-plane) displacements.