ARAMID FIBER MESH AS REINFORCEMENT OF CONCRETE PANELS SUBJECTED TO HIGH STRAIN RATES

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ABSTRACT: Because of their high strength and energy dissipation capacity, aramid fibers are used widely as the material of choice for body armor and similar applications. Their use as reinforcement of concrete panels, whether prestressed or not, poses significant challenges because of their relatively low fiber-to-fiber friction coefficient and limited bond strength between fibers and cementitious matrix, as well as chemical incompatibility between aramid fibers and cement matrix. This paper explores the mechanisms by which more or less brittle materials embedded in body armor systems are capable of dissipating large amounts of energy, thereby preventing the penetration by armor-piercing projectiles and to determine whether such mechanisms can be reproduced with cement-composite thin sheets reinforced with similar aramid fiber mesh. A brief survey of the mathematical models available to describe such mechanisms will help determine to what extent such technology transfer is feasible.

1. INTRODUCTION

Terror attacks in recent years have raised the public awareness of the vulnerability of constructed facilities worldwide. Whereas it is the prerogative of public officials to make policy decisions regarding the level of protection that is desirable and affordable, the engineering community is called upon to provide the tools to achieve the various levels of protection. While the state of the art exists to design and build new facilities with just about any realistic level of protection, the hardening of existing buildings and facilities, representing trillions of dollars of capital investment, is a daunting task, primarily because the economic constraints are typically more severe than in the case of new construction. For this reason new technologies need to be made available that are affordable and effective in increasing the level of protection against both blast and impact loads.

This paper reports very preliminary deliberations on how to strengthen existing buildings with thin sheet concrete panels reinforced with aramid fiber mesh. Aramids or their better-known commercial variants Kevlar, Twaron, and Technora, are known to form the basis of body armor technology, and the main purpose of the work described here is to survey this mature field and investigate the potential for technology transfer to the field of textile-

reinforced concrete thin sheets. Since both applications seek to fulfill similar objectives, namely to dissipate large amounts of energy, it should be a worthwhile undertaking to determine to what extent such a technology transfer is feasible. Of particular interest will be the mechanisms by which advanced composites absorb the energies associated with impact loads and to explore the possibilities of creating similar mechanisms with textile reinforced cement composites.

2. MECHANICS OF BODY-ARMOR COMPOSITES

It is widely known that aramid fibers are the material of choice for composites used for body armor [Pho03]. In this section we shall review briefly the physical characteristics of such composites and the mechanical properties of the component materials. We are primarily interested in the mechanisms by which composites that consist of layers of various inherently brittle materials are capable of dissipating large amounts of energy. Next we shall investigate to what extent such mechanisms are applicable to composites in which such fibers are embedded within a cement-based matrix.

Aramid fibers are characterized by very high stiffness, high strength-to-weight ratio, and relatively low strains at failure. The material is essentially linear elastic in tension under both low and high strain-rate loadings, Fig. 2.1. Similarly, the ceramic materials used also display basically linear elastic behavior and brittle failure.

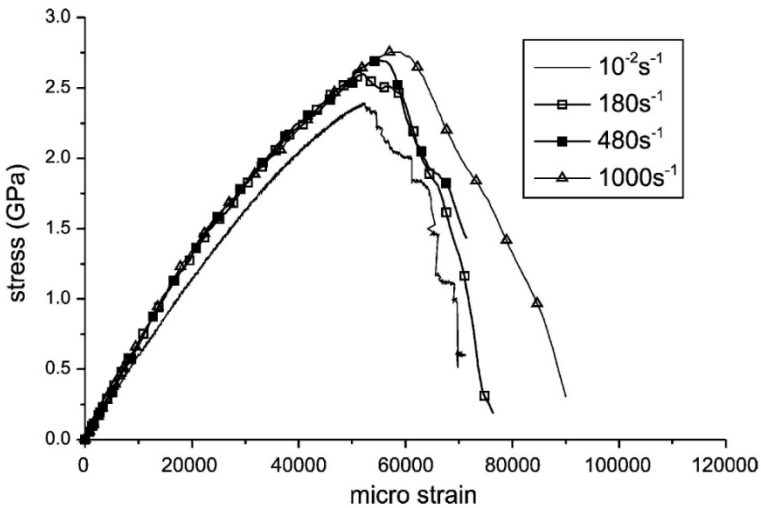


Fig. 2.1. Stress-Strain Curves for Twaron Filaments at Different Strain Rates [Gub03]

Armor systems have been made traditionally of thick and monolithic materials such as steel with high hardness, but nowadays the use of non-metallic materials like ceramics and fibrous composites has led to the development of more efficient lightweight systems [Faw04]. In particular, ceramics have become widely used because of their low density, high hardness, high rigidity and strength in compression. However, the low facture toughness of ceramics and their response characteristics under high strain rates led to the development of ceramic-faced plates which are backed by more ductile materials such as fibrous materials or polymeric composites with higher tensile strengths. As a result, in the present body armor systems most fibrous materials designed to resist penetration by armor-piercing projectiles are comprised of multi-layered fabrics or flexible fibrous composites placed behind a hard ceramic strike face to blunt the projectiles and still satisfy the demand for light weight. When a projectile impacts onto such a composite material system, it first shatters or is blunted by the rigid ceramic plate and the load is distributed over a larger area. The backing plate deforms to absorb the projectile's remaining kinetic energy, thereby delaying the initiation of tensile failure of the ceramic and backing materials. A typical example is shown in Fig. 2.2, where a bullet traveling from right to left penetrates a multi-ply fabric system shown in black. Fig. 2.3 presents a schematic penetration sequence for a hypothetical layered fibrous composite system [Pho03].

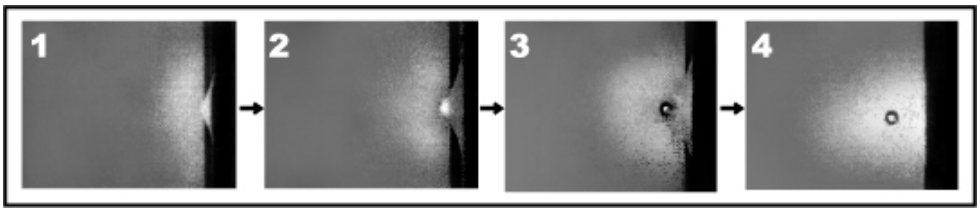


Fig. 2.2. High-Speed Photograph of Penetration Process [Mor00]

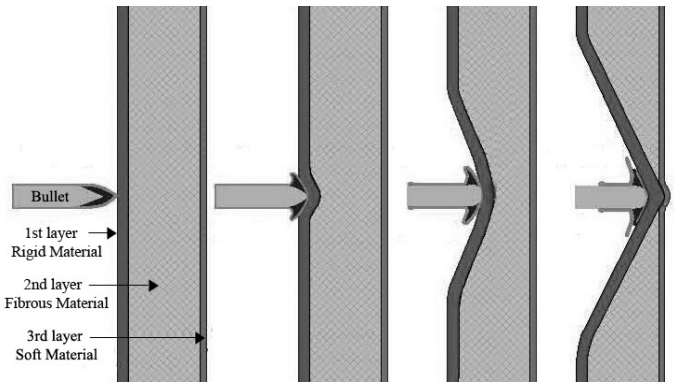


Fig. 2.3. Penetration Sequence in a Hypothetical Layered Fibrous System [Pho03]

As mentioned earlier, a ceramic strike plate can be used as the first layer to enhance the energy dissipation capacity, and the panel can be replaced by alternate materials to improve the performance and efficiency of the overall system. It is one objective of the study described herein to investigate the feasibility of replacing the rigid ceramic face layer by a thin cementitious layer with aramid fiber mesh reinforcement.

To understand the mechanism of energy dissipation in a fibrous composite system, consider a simple case of transverse impact on a single fiber, Fig. 2.4. There are two waves propagating from the point of ballistic impact, a longitudinal and a transverse wave [Che03]. The longitudinal tensile wave travels along the fiber axis. As it propagates away from the point of impact, the material behind the wave front flows toward the impact point, which is deflecting in the direction of motion of the moving projectile. This transverse movement of the fiber initiates the transverse wave.

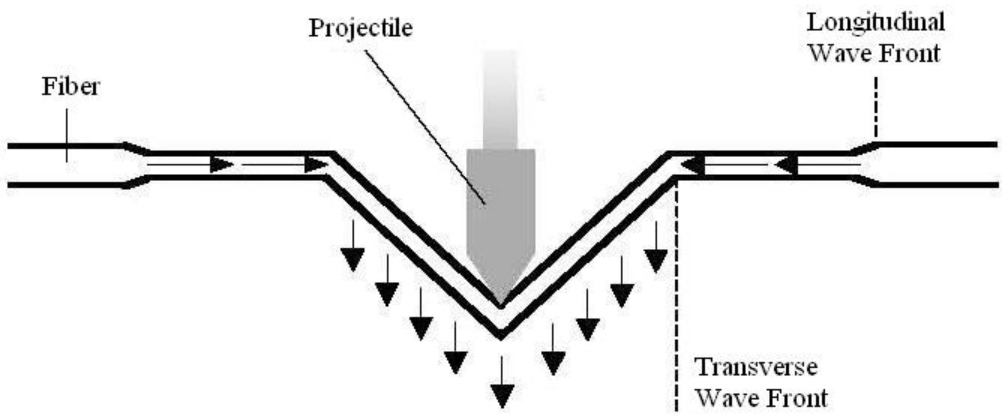
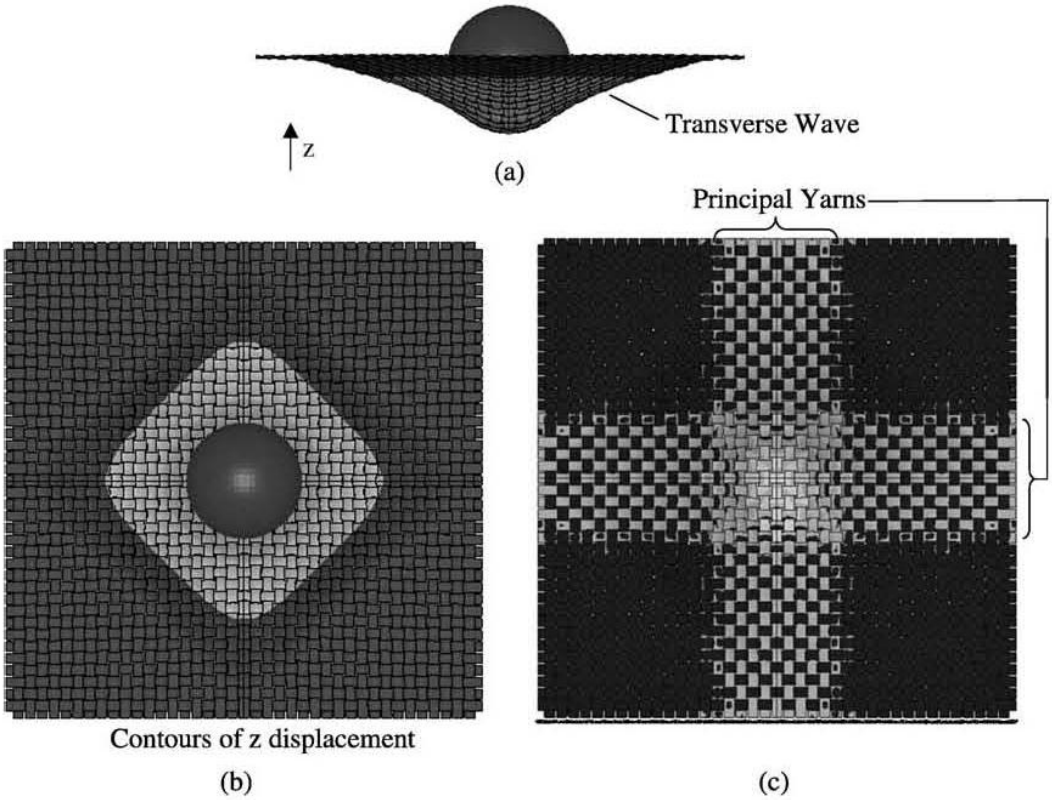


Fig. 2.4. Transverse Impact on a Single Fiber [Che03]

This observation can be expanded to the transverse impact of a single ply of fabric mesh as shown in Fig. 2.5. When a projectile strikes the fabric, it causes a transverse deflection of the yarns that are in direct contact with the projectile. These are defined as principal yarns. The impact also generates longitudinal strain waves, which move along the axes of the yarns [Che03]. Subsequently, the orthogonal yarns, defined as those yarns that intersect the principal yarns, are pulled out of the original fabric plane by the principal yarns. These orthogonal yarns undergo large deformations and develop their own strain waves. Most of the kinetic energy of the projectile is transferred to the principal yarns as strain and kinetic energy, whereas the contribution of the orthogonal yarns to energy absorption is relatively small.



(a) side view (b) displacement contours in the z direction (c) principal yarns

Fig. 2.5. Transverse Impact on a Single Ply of Fabric [Che03]

There are three significant sources of energy dissipation by fibrous composites [Mor03]. These can be classified as follows: 1) the energy absorbed in tensile failure of primary yarns, 2) the energy converted into elastic deformation of secondary yarns, i.e. all other yarns, 3) the energy converted to kinetic energy of the moving portion of the composite.

Although the mechanisms under ballistic impact loading are not completely understood, it is known that the primary parameters that influence ballistic performance are associated with the material properties of the yarns, the fabric structure, the projectile geometry, impact velocity, the layer-to-layer interaction in multi-layered systems, the boundary conditions, and the friction between the yarns themselves and between the yarns and the projectile.

The material properties such as tensile strength, modulus and strains at failure play a major role in ballistic perforation [Che03]. In addition, the material properties and fabric geometry parameters are usually coupled. The two main properties of fabric structures are the cover factor and crimp. The cover factor can be determined from the width and pitch of the warp

and weft yarns and gives an indication of the percentage of gross area covered by the fabric. The crimp is defined by the undulation of the yarns due to their interlacing in the woven structure. The shape of the projectile head may be flat, hemispherical, ogival, or conical and has a significant effect on penetration performance of fibrous composite systems, as does the impact velocity of the projectile. Because damage is localized the fabric can fail if not enough transverse deformation develops. Sharp-edged high-velocity projectiles can penetrate a fabric by shearing its yarns. In multi-layered composites, the layers closest to the impact surface behave inelastically, whereas the layers toward the back remain elastic. This leads to layer-to-layer interaction. In general, the performance of the entire system is governed by its inelastic behavior. The size of the composite specimen and the support conditions obviously play a role as well. It has also been observed that the ballistic performance can be improved if the aramid fibers are prestressed [Che03]. Friction between the projectile and the yarns and the yarns themselves may affect how much energy is absorbed under ballistic impact.

A wide range of analytical models is available to describe the characteristics of ballistic performance. Ben-Dor et al [Ben05] have presented a partial review of the literature with 280 citations. Most models are based on algebraic relations and ordinary differential equations and can be classified in three main classes.

Most penetration models are referred to as localized interaction models (LIM). The integral effect of the interaction between the host medium and a moving projectile is described as the superposition of the independent local interactions of the projectile's surface elements with the medium. Each local interaction is determined by the local geometric and kinematic parameters of the surface element - the angle between the velocity vector and the local normal vector to the projectile surface - and some global parameters that take into account the integral characteristics of the medium such as hardness and density. A second widely used category of models are referred to as spherical and cylindrical cavity expansion approximations. The spherical cavity expansion approximation is widely used to construct impactor-shield interaction models for semi-infinite shields. The cylindrical cavity expansion approximation is applied typically to model both penetration into a semi-infinite shield and perforation of a shield with finite thickness. Lambert and Jonas formula was proposed for the reduction of ballistic impact data [Ben05]. Many other empirical and semi-empirical models have been formulated in a similar format, particularly models based on energy and momentum conservation. The Lambert and Jonas formula is generally the preferred form to reduce experimental data.

3. ARAMID-TEXTILE REINFORCED CONCRETE

Although the field of textile reinforced concrete is not as mature as that of body-armor composites, a considerable body of knowledge exists in this emerging technology as well. A comprehensive report summarizing the state of the art is currently in preparation [RIL06]. The fibers most commonly used in prior studies and applications are made of the high-performance materials AR-glass, carbon or aramid. Two noteworthy major studies are currently underway in Germany, one based at the University Aachen [Bra03,Heg02], and one at the Technical University Dresden [Cur98,Cur02]. The material of choice in both of these projects is AR-glass. The primary objective of the research project in Aachen is the development of new thin-sheet applications such as large concrete panels, lost formwork etc, whereas the researchers in Dresden concern themselves primarily with the strengthening or retrofitting of existing structures. Aramid fiber mesh, both prestressed and nonprestressed, has been used in research projects of more limited scope [Vil03,Krü04].

The challenges faced by body-armor products and blast and impact resisting concrete panels are similar in that inherently brittle component materials are combined to form composites that are capable of dissipating large amounts of energy. The basic fiber reinforcement material is the same in both applications and characterized by the linear-elastic brittle stress-strain behavior, Fig. 2.1. Like the other component materials in body-armor composites, also the cement-based matrix in thin sheet concrete panels displays only a minimum of ductility. Therefore, any nonlinear behavior displayed by a fiber reinforced composite derives from the irreversible slippage of individual fibers within a roving as well as large-deformation effects, which can be magnified by prestressing the fiber mesh, Fig. 3.1.

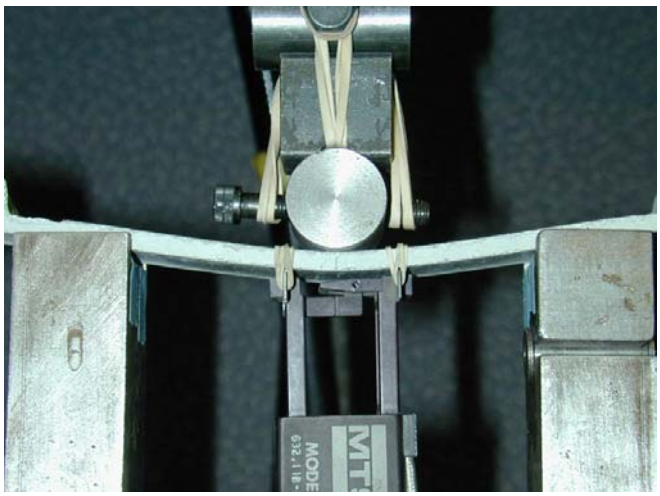
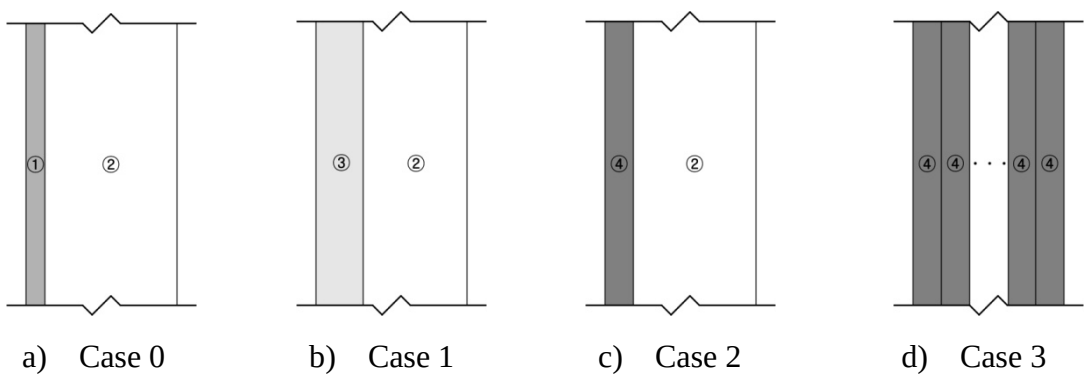


Fig. 3.1. Thin Concrete Specimen Prestressed with Aramid Mesh [Vil03]

It will be the challenge for the development of blast- and impact-resisting panels to fully exploit such mechanisms. An additional challenge will be to solve the problem of chemical incompatibility between aramid fibers and cement matrix, because the alkalinity of the pore solution in cement composites is known to affect the mechanical properties of aramid fibers. Relatively little information is available on textile reinforced concrete thin sheets subjected to blast and impact loads. Both experimental and theoretical studies will be needed to expand our knowledge of fundamental constitutive behavior of such composites in the high strain rate regime.

4. CONCLUSIONS

Applications of aramid-reinforced composites in the field of body armor are widespread, as the technology is relatively mature, and a wide variety of mathematical models are available to simulate the behavior of such composites under impact loads. It is the purpose of the study reported herein to explore the feasibility of transferring this knowledge into the field of textile reinforced cement composites. The ultimate purpose is the development of thin sheet panels that can be used to harden existing buildings against loads with high strain rates. The main difference between these two types of applications appears to be the material of choice for the strike face. Whereas body armor materials are subject to weight limitations which call for thin strike plates made of ceramic materials, specifications for building applications should be less stringent in this respect so that it should be possible to replace the brittle ceramic material face by a similarly brittle cement-based layer whose thickness is determined by specific performance criteria.



where, ① Ceramic Strike Face ② Aramid Fibrous Composite or Polymer Composite
③ Plain Cement Matrix ④ Aramid Textile Reinforced Cement Composite

Fig. 4.1. Armor Systems

Fig. 4.1 illustrates the typical body-armor system (Case 0) and three proposed options for the armor system that deserve to be explored (Cases 1 to 3). The ceramic strike face is replaced by a layer of plain cement matrix (Case 1). Because of the basically similar material characteristics of ceramics and cement-based matrices, it should be possible to replicate the energy dissipation mechanisms described in Chapter 2 with such a cement composite. If it is determined that the required thickness of the cement-based strike face is unreasonably large, such a face layer may be reinforced with additional layers of aramid fabric (Case 2). As a third alternative, a number of layers of aramid mesh are embedded within a cement matrix throughout the thin sheet composite (Case 3). In all three cases, the bulk of the kinetic energy of the projectile will be dissipated by the aramid fabrics, although the multiple cracks produced throughout the cement matrix should increase such energy dissipation capacity by a large extent.

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