ARAMID FIBER MESH-REINFORCED THIN SHEET RESPONSE TO IMPACT LOADS

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Abstract ID Number:

Keywords: Textile reinforced concrete (TRC), Impact loads, Strain rate effects, and Aramid fiber mesh.

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Presenter of the paper during the Conference: Christian Meyer

Total number of pages of the paper (this one excluded): 8

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Abstract

The response of structures to impact loads has gained considerable interest during the last few years. Whereas the design and construction of new structures to resist such loads poses not so much technical as economical challenges, this is even more true in the case of hardening and strengthening of existing structures. Thin sheets, consisting of a fine-grained cement matrix reinforced with a suitable fiber mesh made of high-performance materials such as aramid, are now being studied for their suitability in such situations. A considerable body of knowledge can be found in the body-armor literature. It is the objective of a study currently in its initial phase to combine this knowledge with the state of the art of penetration dynamics in order to determine the feasibility and effectiveness of such strengthening technology. A brief overview of the state of the art of both of these technologies is given, together with a preliminary feasibility assessment.

1. INTRODUCTION

Although aramid fibers are widely known to be the material of choice for composites used in the body armor industry [1], research on aramid fiber-reinforced composites for civil engineering applications has been rather limited. A study of thin-sheet cement composites reinforced with aramid fiber mesh at Columbia University [2, 3] has shown that such composites have a potential for various practical applications. A follow-up preliminary study has been performed to review the suitability of aramid fiber mesh as reinforcement of thin cementitious sheets subjected to impact loads [4]. Since thin concrete sheets reinforced with aramid fabrics, such as Kevlar and Twaron, have an enormous capacity of absorbing and dissipating energy, such structural components have the potential of greatly enhancing the resistance of structures to impact loads. The primary objective of the proposed research will be to study analytically and experimentally the mechanisms by which composites that consist of inherently brittle materials are capable of dissipating large amounts of energy. Especially, the strain rate effect on fine grained concrete and aramid fiber mesh will be investigated thoroughly. Based on the outcome of this research, the feasibility of using such thin sheets in civil engineering applications will be explored. Of particular interest will be the hardening or strengthening of existing structures.

2. FUNDAMENTAL RESPONSE MECHANISMS

The strain rate effect of materials is one of the major factors determining impact resistance. Its inclusion in numerical simulations requires a much larger computational effort, especially if complex nonlinear material models are involved. The concrete and steel in reinforced concrete structures subjected to such loads experience strain rates of the order of $10\,s^{-1}$ to $1000\,s^{-1}$. At these high strain rates the apparent strength of the materials can increase by more than 50 percent for the reinforcing steel, by more than 100 percent for concrete in compression, and by more than 600 percent for concrete in tension [5]. Such strain rate induced strength increases are typically expressed in terms of a Dynamic Increase Factor defined as the ratio of the dynamic response to the quasi-static response. It is well established that fiber-reinforced concrete exhibits considerably improved impact resistance compared with plain concrete. The flexural strength of steel fiber-reinforced mortar appears to be slightly more strain rate sensitive than plain mortar, which is likely to be due to the multiple cracking of the matrix [6]. The energy absorbed by steel fiber-reinforced concrete under impact loads can be about 20 to 100 times that absorbed by plain concrete. For example, it has been shown that the flexural energy absorption of fiber-reinforced concrete (FRC) beam specimens increases significantly with the strain rate – see Fig. 1, which also depicts the load-deflection curves for two extreme strain rates.

The dynamic mechanical properties of Twaron fabrics were examined by high-speed tensile tests on specimens using a split Hopkinson bar [7]. The stress-strain curves of Fig. 2 are representative of both the static and dynamic behavior of Twaron fibers. The strain rates of $495s^{-1}$ and $238s^{-1}$ are clearly dynamic, while the strain rates of $1s^{-1}$, $0.1s^{-1}$ and $0.01s^{-1}$ represent basically static loadings. The energy absorption capacity of a material, defined by the area under the stress-strain curve, is affected both by the failure strain and the maximum stress. This area is significantly smaller for the high strain rate ($\dot{\varepsilon} = 495s^{-1}$) than that for a low strain rate ($\dot{\varepsilon} = 238\ s^{-1}$), Fig. 2. If the fibers are to sustain load, they first need to be straightened and realigned due to the initial crimping. The straightening process stiffens the material and contributes to the nonlinear response. Unlike at low strain rates, there is insufficient time at high strain rates for this effect to take place. In addition, at low strain rates, intermolecular slippage in the polymer chains becomes significant. Therefore, the phenomenon involves plastic flow and deformation, which dissipates additional energy.

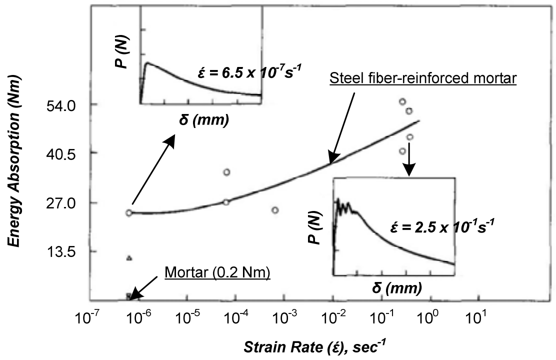

Fig. 1. Strain Rate Effect on a FRC Beam [6]

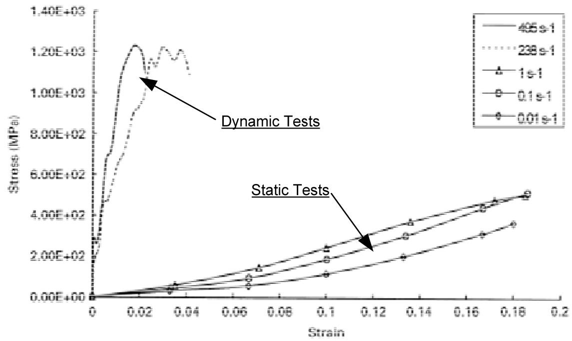

Fig. 2. Strain Rate Effect on Twaron Fibers [7]

Another parameter that determines structural response to impact loads is the kinetic energy density delivered by the projectile, which is defined as the kinetic energy of the projectile divided by its cross-sectional area. In the subhydrodynamic regime of penetration in which the kinetic energy density is low, conventional material parameters determine the penetration mechanism. However, the kinetic energy density is much higher for longer, thinner, heavier, and faster projectiles. In this case the strengths of the materials are negligible and the impact needs to be characterized as a fluid-structure interaction, governed by the laws of fluid dynamics. This is known as the hydrodynamic regime. Although fluid flow governs the interaction in the transition between two zones, with density being the dominant physical parameter, material strength still proves to be a significant factor [8].

3. ANALYTICAL / NUMERICAL APPROACH

This study will have analytical, numerical and experimental components to develop a new technology to harden or strengthen existing structures by improving our understanding of structural response mechanisms to impact loads. Once these mechanisms are understood sufficiently well, analytical models can be developed to allow the numerical simulation of material response. Such numerical simulations will be useful when identifying potential strategies to support the experimental effort.

3.1 Analytical approach

The structural response analysis to impact loads requires realistic analytical models. Several analytical and empirical models have been proposed in the body armor literature to consider the nonlinear characteristics of ballistic performance and the strain rate effect on various composite materials [9]. These are generally algebraic relations and ordinary differential equations. Most analytical penetration models are based on localized interaction models (LIM). The combined effect on the interaction between the medium and a moving projectile can be expressed as the superposition of all local interactions. It is determined both by the local geometric and kinematic parameters of the surface element and by the global parameters that take into account the integral characteristics of the medium. The typical mathematical form of LIM is expressed in Eqs. 1 and 2, Fig. 3 [9].

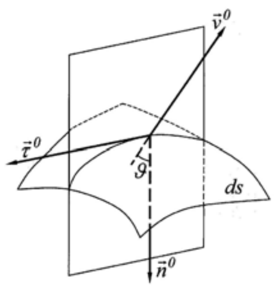

Fig. 3. Definition of LIM [9]

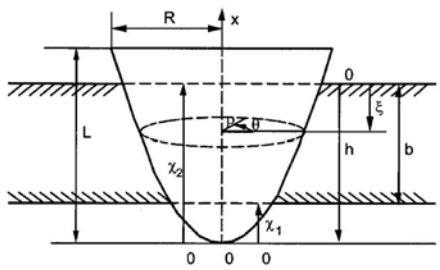

Fig. 4. Coordinates and Notations [9]

$$\begin{cases} d\vec{F} = [\Omega_n(\vec{a};u,v)\vec{n}^0 + \Omega_\tau(\vec{a};u,v)\vec{\tau}^0]ds & if \quad 0 < u < 1 \\ d\vec{F} = \Omega_n(\vec{a};1,v)\vec{n}^0\, ds & if \quad u = 1 \\ d\vec{F} = 0 & if \quad u \le 0 \end{cases} \tag{1}$$

$$\vec{\tau}^0 = -(\vec{v}^0 + u \cdot \vec{n}^0)/\sqrt{1-u^2} \quad \& \quad u = -\vec{v}^0 \cdot \vec{n}^0 = \cos\theta \tag{2}$$

where $d\vec{F}$ is the force acting on the surface element ds of the projectile. $\vec{n}^0$ is the inner normal unit vector and $\vec{\tau}^0$ is the inner tangent unit vector. $\vec{v}^0$ is a unit vector of the projectile velocity $\vec{v}$. θ is the angle between $\vec{n}^0$ and -$\vec{v}^0$. Ω_n and Ω_τ are the functions which determine the projectile-medium interaction. In general, it is assumed that $\Omega_\tau = 0$ or $\Omega_\tau = k\Omega_n$, where k is the coefficient of friction between the impactor and the shield. $\vec{a}$ is a vector with components which characterize the properties of the host medium.

The analytical model for a shield with a finite thickness (SFT) is shown in Fig. 4 [9]. The projectile is represented in the cylindrical coordinates x, ρ, θ, and the shape of the projectile is determined by the equation of $\rho = \Phi(x, \theta)$, where, Φ is a function which determines the shape of the impactor, b is the thickness of the shield, L is the impactor's nose length, and h is the penetration depth. In both a shield with finite thickness (SFT) and a semi-infinite shield (SIS), the total force $\vec{F}$ is determined by integrating the local force over the impactor-shield contact surface. The drag force is expressed as $D = \vec{F} \cdot (-\vec{v}^0)$, which is a function of $\vec{a}$, h, and v. The equation of motion of an impactor with mass m can be represented by Eq. 3.

$$mv\frac{dv}{dh} + D(\vec{a};h,v) = 0 \tag{3}$$

In a SFT, the ballistic limit velocity v_{bl} is defined as the initial velocity of the impactor required to emerge from the shield with zero velocity. In a SIS, the depth of penetration h is usually considered as a characteristic parameter. These two primary penetration factors are obtained by solving a first-order ordinary differential equation, Eq. 3.

For nonhomogeneous or layered shields with different material properties such as reinforced concrete panels strengthened by thin cementitious composites, $\vec{a}$ can be expressed as a function of the depth of the shield, ξ. The LIM is very useful to investigate impact dynamics problems because it can consider the interaction between various shapes of the projectile and the medium as well as simulate the motion of an impactor in a shield.

3.2 Numerical approach

The failure process on the macroscopic scale is comprised of several local damage and failure mechanisms at the lower scales. The fundamental mechanisms at the micro-scale are the rupture of single filaments and their debonding from the matrix. These changes in the material micro-structure propagate to the meso-scale in the form of yarn damage and yarn debonding, as well as crack initiation. These effects explain the macroscopically observable effects like delamination of the textile layer. It is assumed that the cementitious matrix is homogeneous, which means that no distinction is made between the cement paste and sand aggregate.

In general, the complex damage and failure processes call for micromechanical models, which may require a great amount of computational effort. In order to avoid this problem, textile reinforced concrete (TRC) components can be modeled on the macroscopic scale and simplified as two-dimensional elements since they are generally used for thin-walled structural elements or for hardening / strengthening of existing planar structures. Therefore, layered shell and layered folded plate elements can be employed in the modeling on the macroscopic scale [10]. The Microplane-Damage-Model, e.g., is available for the layered shell model [11]. The effect of textile reinforcement has been included at the material point level in the form of a direction-specific damage law and tension-stiffening effect associated with differently oriented microplanes. An alternative model to represent a specific multi-layer continuum by introducing an extended layered model is the Multi-Reference-Plane Model [12], which includes regular concrete layers, steel reinforcement layers, strengthening layers with textile reinforcement, and interface layers.

4. TRC-STRENGTHENED COMPOSITES

Strengthening methods using aramid fiber mesh-reinforced thin cementitious sheets have the potential to be superior over other strengthening technologies because of their mechanical properties and relative ease of application. It is one of the objectives of the proposed research to verify such intuitive conjecture. TRC exhibits a high degree of heterogeneity for the matrix and the reinforcement. As a result, the damage localization processes of TRC are comprised of interactions between elementary failure mechanisms within the matrix, the reinforcement, and those along their interfaces controlled by bond behavior. Due to these damage interactions, existing models for concrete and composites are not directly applicable to TRC. When TRC-strengthened thin composites are subjected to impact loads, a projectile will be blunted by the strike plate comprised of aramid fiber mesh-reinforced thin sheets, and the load induced by the projectile is distributed over a larger area. Subsequently, the backing material deforms to absorb the projectile's remaining kinetic energy by delaying the initiation of tensile failure of the TRC and backing materials.

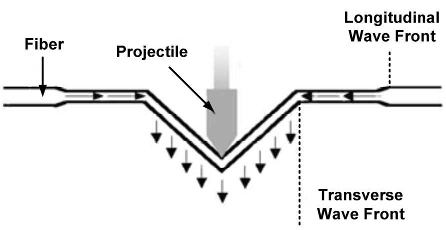

Fig. 5. Transv. Impact on a Single Fiber [13]

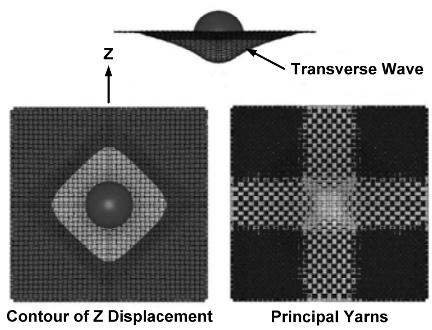

Fig. 6. Transv. Impact on a Single Ply [13]

To understand the mechanism of energy dissipation in such composite systems, consider a simple case of transverse impact on a single fiber, Fig. 5 [13]. There are two waves propagating from the point of ballistic impact, a longitudinal and a transverse wave. 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. This observation can be expanded to the transverse impact on a single ply of fabric mesh, Fig. 6. When a projectile strikes the fabric, it causes a transverse deflection of the yarns that are in direct contact with the projectile, defined as principal yarns. The impact also generates longitudinal strain waves, which move along the axes of the yarns. Subsequently, the orthogonal yarns, which 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 [13]. In this study, both reinforced concrete (RC) panels and other composites strengthened on one or both sides with aramid fiber mesh-reinforced thin sheets will be analyzed as shown in Fig. 7 and the effects of the strengthening measures will be evaluated.

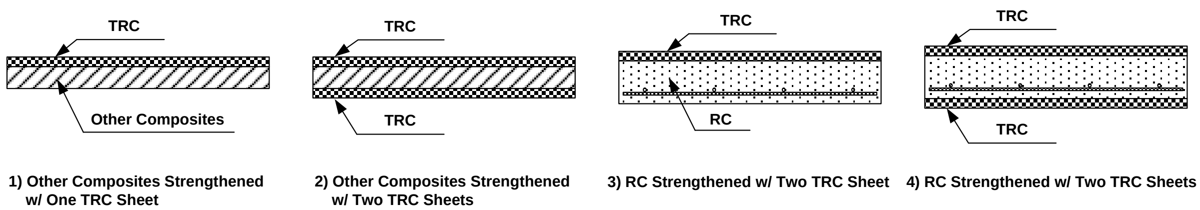

Fig. 7. TRC-Strengthened RC and Other Composites

5. CONCLUSIONS

The body-armor products and impact-resistant thin cementitious composites are similar in that inherently brittle component materials are combined to form composites that are capable of dissipating large amounts of energy. The main difference between these two types of applications appears to be the material selected for the outer face such as strike plates. Only a minimum of ductility is required for both the strike face materials in body-armor composites and the cement-based thin sheet panels. 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. It will be the challenge for the development of impact-resisting panels to fully exploit such mechanisms.

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