TB46

19th International Symposium of Ballistics, 7–11 May 2001, Interlaken, Switzerland

BALLISTIC LIMIT OF FABRICS WITH RESIN

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Composite panels made from fabrics and resin are important components in today's light armors. Experimental work has indicated that for a few sheets of fabric, "Dry is better," meaning that fabric sheets without any resin will outperform the equivalent areal density of a fabric/resin composite. This paper examines this result. It is shown that for low relative areal densities of fabric, the loss in fabric material (by weight) by adding resin leads to a loss in performance of the armor system. However, as the relative areal density increases, the fabric/resin composite panel begins to show bending stiffness, and its performance increases. Experimentally it has been observed that the crossover in performance is in the region where the mass of the fabric material involved in the momentum balance equals the mass of the impacting bullet. As the areal density of the fabric increases beyond this point, the fabric/resin composite panel outperforms the equivalent areal density dry fabric. This paper provides an equation to predict the ballistic limit curve of the fabric/resin composite panel given the ballistic limit curve of the dry fabric. The analytic expression agrees well with experimental data.

INTRODUCTION

Fabrics are an extremely important part of modern armors. Also extremely important are composite panels made of fabric sheets stiffened with resin. At the last International Ballistic Symposium, a considerable amount of work was reported describing fabrics and fabric/resin composites (e.g., [1–8]). In particular, an analytical model was presented that predicted the ballistic limit curve of a fabric based on the elastic properties of the fiber [8]. This model analytically addressed a number of topics, such as transverse wave velocity in the fabric, which will be used below to estimate the way in which a composite panel comprised of fabric with resin responds.

Experimental work with panels made from fabrics and resin has indicated that for a few sheets of fabric, "Dry is better," [2,3] meaning that fabric sheets with no resin (hence dry) will outperform the equivalent areal density of a fabric/resin composite. For low relative areal densities of fabric, the loss in fabric material by adding resin in order to maintain the same areal density leads to a loss in performance of the armor system. However, as the relative areal density increases, the fabric/resin composite panel begins to show bending stiffness, and its performance increases. Experimentally it has been observed that the crossover in ballistic limit performance is in the region where the amount of fabric material involved in the momentum balance is equal to the mass of the impacting bullet. As the areal density of the fabric increases beyond this, the fabric/resin composite panel outperforms the equivalent areal density dry fabric. This paper provides an equation to predict the ballistic limit curve of the fabric/resin composite panel given the ballistic limit curve of the dry fabric. The equation is then compared to experimental data for Kevlar 29/resin composite panels.

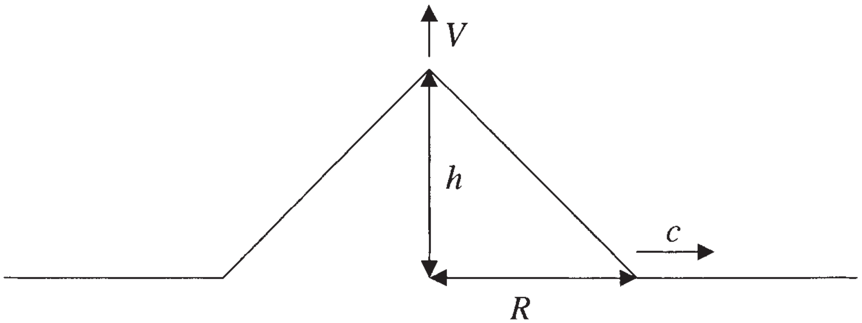

Figure 1: Geometry of deforming fabric and fabric/resin composite.

SIMPLE THEORY

When a projectile impacts a fabric, the fabric forms a pyramid with the projectile at the top apex (Fig. 1). The edges of the pyramid coming down from the top apex run in the direction of the fibers in the fabric weave. An experimentally observed fact from numerous tests is that the ratio of the height of the pyramid h to its diameter R is a constant. This ratio is directly related to the strain experienced by the fabric. To a first approximation, the strain is given by

$$\varepsilon_{xx} = \frac{\sqrt{h^2+R^2}}{R} - 1 \approx \frac{1}{2}\left(\frac{h}{R}\right)^2 \quad (1)$$

As was mentioned, this is an approximation: in reality, there is also a dependence on the ratio of the projectile diameter to the base diameter of the pyramid, and so as the penetration progresses and the base of the pyramid grows larger, the strain slowly increases until the fabric breaks (see [8] for details).

Since it is observed that the h/R ratio is constant, it is legitimate to determine the value of h/R early in the impact event. At early time, the height is growing at a velocity V, where V is given by the momentum balance between the initial momentum of the projectile being set equal to the combined momentum of the projectile and the amount of fabric set in motion:

$$V = \frac{m_p}{m_p + \beta A_p \tilde{\rho}} V_s \quad (2)$$

In this expression, V_s is the striking velocity, m_p is the projectile mass, A_p is the presented area of the projectile, β is a multiplier to give the area of fabric inertially involved in the motion (an approximation), and $\tilde{\rho}$ is the areal density of the fabric (and below, fabric and resin). Experimentally $\beta \sim (1.6)^2 = 2.56$. The base radius of the pyramid is growing at a velocity c. This latter wave speed is a transverse wave speed, and dimensional analysis gives it a form of (or see [8] for a derivation)

$$c = c_1 c_f^{\alpha} V^{1-\alpha} \quad (3)$$

Here, c_f is the wave speed in the fiber, given by the square root of the elastic modulus divided by the density. However, any modulus related to the fabric would do, from the dimensional analysis point of view. For the fabric model presented in [8], a taught fabric has $\alpha = 1/2$. A loose fabric or crimp leads to a larger α (though still less than 1).

With Eq. (3) giving the transverse wave speed, it is possible to calculate h/R, since for early time $h = Vt$ and $R = ct$:

$$\frac{h}{R} = \frac{1}{c_1}\left(\frac{V}{c_f}\right)^{\alpha} \quad (4)$$

Thus, the strain in the fabric is determined by the competing rates of increase in the height and base diameter of the pyramid.

It is possible to explicitly estimate the magnitude of the change in ballistic limit velocity by assuming the fabric breaks at a failure strain ε_f and setting this equal to the strain in Eq. (1):

$$\frac{h}{R} = \sqrt{2\varepsilon_f} \quad (5)$$

Use of Eqs. (2) and (4) then gives

$$V_{bl} = \frac{m_p + \beta A_p \tilde{\rho}}{m_p} c_f \varepsilon_f^{1/2\alpha} (c_1\sqrt{2})^{1/\alpha} = (1 + \beta X) c_f \varepsilon_f^{1/2\alpha} (c_1\sqrt{2})^{1/\alpha} \quad (6)$$

This expression uses the nondimensional measure of the relative areal densities of the fabric and projectile $X = \tilde{\rho} A_p / m_p$ introduced by Phil Cunniff. (For comparison, the model presented in [8] yields the ballistic limit as

$$V_{bl} = \frac{9}{2}(1+\beta X) c_f \varepsilon_f \left\{ \left(\frac{R_{bl}}{R_p}\right)^{2/3} - 2\left(\frac{R_{bl}}{R_p}\right)^{1/3} + 3 \right\}^{-1} \quad \text{where} \quad \frac{R_{bl}}{R_p} = \sqrt{\frac{9\pi}{8}\left(\frac{1}{X} + \beta\right)} \quad (7)$$

thus giving $\alpha = 1/2$ and $(c_1/\sqrt{2})^{1/\alpha} \sim 1.8$. The more complicated expression of Eq. (7) captures the curvature in the ballistic limit curve, while the simple expression of Eq. (6) does not.)

When a small amount of resin is added to a fabric, to maintain the same areal density some of the fabric must be removed. Since the mass in the fabric/resin system is the same, the rate of growth of the height of the pyramid is also the same (Eq. (2)). The transverse velocity, however, does change due to the decrease in fabric and hence modulus:

$$c_f = \sqrt{\frac{E_f(1-r)}{\rho}} \tag{8}$$

Here, r is the mass fraction of resin in the system: $r = 0$ is dry fabric, and $r = 1$ is pure resin. Combined with Eq. (6), this implies that the new ballistic limit upon the addition of resin is

$$V_{bl}(X,r) = \sqrt{1-r}\, V_{bl}(X,0) \tag{9}$$

Thus, if all the addition of resin did was add mass, then the result would be that the ballistic limit is always decreased by the addition of resin. For example, 18% resin would decrease the ballistic limit velocity by 9.5% for all areal densities.

Such a reduction is not observed. Though a reduced ballistic limit is seen for smallX (low areal densities of fabrics), for larger X the ballistic limit of the fabric/resin composite panel exceeds the ballistic limit of the dry fabric.

ADDITIONAL EFFECTS OF ADDING RESIN: ROLE OF BENDING STIFFNESS

There are four other mechanisms that come into play as resin is added to fabric:

1) the increase in resin leads to a resistance to bending in the fabric/resin composite (as opposed to the dry fabric that only has tensile membrane stresses), thus increasing the panel's resistance to deformation and thus increasing the ballistic limit;
2) the newly acquired bending strength leads to an increase in the transverse wave speed, thus reducing the strain and increasing the ballistic limit;
3) the now harder panel deforms the projectile, leading to an increase in the presented area of the projectile and thus leading to an increase in the ballistic limit;
4) it is possible that for larger amounts of resin the harder panel will rigidly hold the fabric, allowing the fibers to be sheared by the projectile rather than failing in tension (their optimal failure mode), thus leading to a reduction in ballistic limit.

These mechanisms all have a role, but this paper will focus on mechanism #1, where it is possible to quantitatively estimate the magnitude of the effect.

Resistance to bending in beams and plates is proportional to the moment of inertia of the beam or plate, which for a constant cross section is proportional to the cube of the thickness. For the fabric with resin, the thickness of the plate will be assumed proportional to the areal density, and so it is possible to write heuristically the increase in stiffness of the plate in the form

$$E = E_f(1-r)(1+\gamma(r)X^3) \tag{10}$$

In this equation, γ is a function of r that is to be determined. Experimentally, the ballistic limit of the fabric with resin and the dry fabric often occurs in the vicinity of $X = 0.3$ to 0.5, and so here it will be approximated by $X = 1/\beta = 0.39$. (This is an intriguing assumption, since it says that the crossover in ballistic limit behavior occurs when $\beta A_p\tilde{\rho} = m_p$, i.e. that it occurs at the point where the mass of the fabric or fabric/resin panel inertially involved in the impact event equals the mass of the projectile.) These assumptions give

$$\gamma(r) \quad = \quad \frac{r}{1-r}\beta^3 \tag{11}$$

Placing this result into the expression for ballistic limit velocity gives

$$V_{bl}(X,r) \quad = \quad \sqrt{1-r+r(\beta X)^3}\, V_{bl}(X,0) \tag{12}$$

Equation (7) and Eq. (12) applied to Eq. (7) are shown in Fig. 2 for 1000 denier Kevlart®29, $cf = 7400$ m/s and $\varepsilon_f = 3.25\%$ [3], and the composite panel is 18% resin ($r = 0.18$). The curves agree well with the data taken from [3]. The experimental degradation in ballistic limit velocity is greater than predicted for small X. Also shown is a curve with $r = 0.4$, to give an idea of the mass fraction required to match the small X ballistic limit data. Overall, the agreement is good.

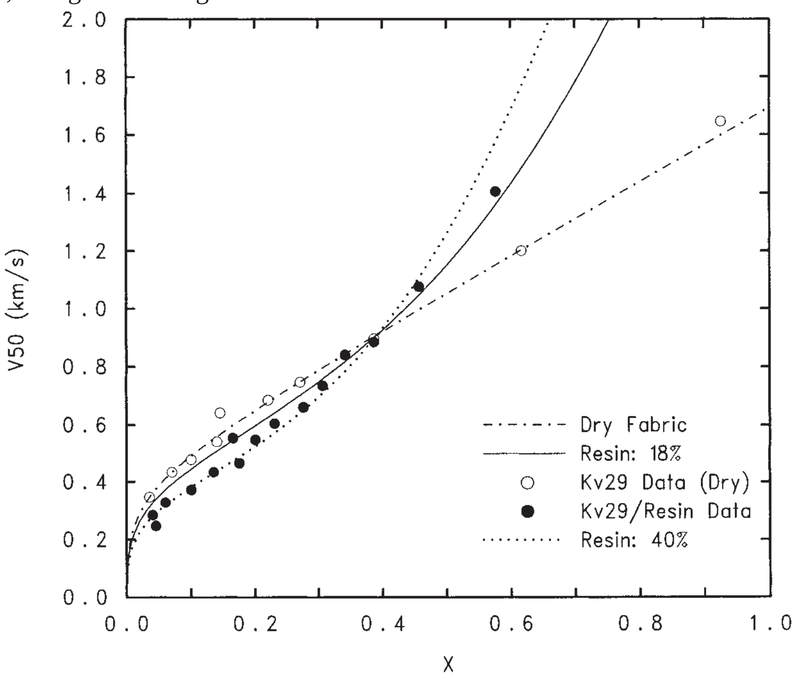

Figure 2: Ballistic limit curves for dry Kevlar 29 fabric and Kevlar 29/resin composite pamel; points are data from [3]: curves are from Eqs. (7) and (12).

CONCLUSIONS

It has been shown that "Dry is better" for relatively low areal densities of fabric because of the loss of fabric mass and thus tensile strength while adding resin and maintaining the same areal density. However, as the relative areal density increases, the composite fabric/resin panel begins to show bending stiffness, and the increase in deformation resistance due to bending strength soon compensates for the loss of fabric material, and in fact as the relative thickness of the composite panel increases, there is an increase in the ballistic limit of the fabric/resin system, as compared to the dry fabric for the same areal density. An equation to predict the ballistic limit curve of the fabric/resin composite panel given the ballistic limit curve of the dry fabric was produced. The analytic expression agrees well with experimental data.

ACKNOWLEDGEMENTS

I would like to acknowledge helpful discussions with Phil Cunniff of the U.S. Army at Natick, and with Charles E. Anderson, Jr., Donald J. Grosch, Drew Goodlin and Dick Sharron at Southwest Research Institute, in San Antonio, Texas.

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