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FINITE ELEMENT DESIGN MODEL FOR BALLISTIC RESPONSE OF WOVEN FABRICS

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A computational capability is described for designing lightweight fabric barrier systems to protect aircraft against fragments from an engine burst. A model of the deformation and failure of yarns and woven fabric under impact was developed, using data and observations from experiments. When implemented in the shell elements of the LS-DYNA3D finite element code, the model computed residual energies of fragments accelerated against fabric targets in agreement with measurements from laboratory gas gun tests. Computational simulations with this model can assist the engineer in specifying such design variables as yarn pitch, number of fabric plies, gripping conditions, and loads applied to the supporting structure.

INTRODUCTION

Lightweight ballistic barriers installed in the fuselage wall of commercial aircraft could protect flight-critical components from uncontained engine fragments. Under Federal Aviation Administration sponsorship, SRI is evaluating several candidate materials and developing a computational capability for designing efficient barrier systems. Described here is a model to predict the response of advanced polymer fabrics to impact from fragments of various mass and velocity. The model is intended for use as an engineering design tool for engine fragment barriers.

BACKGROUND

We are aware of previous theoretical and computational models for the ballistic response of fabrics. Taylor and Vinson [1] describe a model that treats fabric as a very flexible isotropic plate. However, this formulation ignores the directional properties of the yarns. Several authors [2-4] model the fabric as an assembly of flexible fibers interconnected at nodal points. Increasingly sophisticated models of this type have been developed that include contact between plies and slippage between yarns [5]. Johnson et al. [6]

use a combination of bar and shell elements arranged in an orthogonal grid. Others have used full three-dimensional finite elements with smeared properties [7-8].

In the previous International Ballistic Symposium, we presented a micro-mechanical model that treated explicitly the deformation and failure behavior of individual yarns when the fabric was impacted [9]. To ensure the model would be true to the physical processes induced in the fabric by fragment impact, we examined yarn and fabric geometry, performed static and high-rate experiments, measured stress-strain and failure behavior, and wrote mathematical expressions describing the data and observations. The resulting model, when implemented in LS-DYNA3D, predicted the outcome of a ballistic event in detail.

Because of the detail included in the model, the results are especially useful to developers of ballistic fabrics. However, because of the large amount of computational time required to simulate impact response of a large area of fabric, the model was not practical for engineers responsible for designing barriers. Therefore, we formulated a shell element version of the model, seeking computational efficiency, but retaining the important physics. Our objective was to allow evaluation of design variables such as yarn pitch, number of fabric plies, gripping conditions, and loads applied to the supporting structure.

DESIGN MODEL DESCRIPTION

The design model uses an orthotropic continuum formulation in which the two orthogonal local coordinate directions correspond to the orientations of the yarns. We use measured values for thickness and areal density. We calculate the Young’s modulus (dyne/cm^2) in the two orthogonal directions along the yarns by taking the measured yarn load at 1% strain, multiplying by the pitch, and distributing the load over the fabric thickness. The shear modulus in all directions is assumed to be 10% of the Young’s modulus (needed for numerical stability), and the Poisson’s ratio is assumed to be zero in all directions. The fabric density is calculated by dividing the measured areal density by the measured fabric thickness. For multiple plies, the fabric thickness is the number of plies times the single layer thickness; the modulus and density values remain the same. Because of gripping considerations, this model assumes that, for a multi-ply target, the fabric yarns are all aligned in the same directions (e.g., 0 and 90 degrees). Calculated parameters for the constitutive model are listed in Table 1.

No.of Plies	Pitch (ypi)	Thickness (mm)	Areal Density (g/cm^2)	Force @ 0.01 (dyne)	Modulus (dyne/cm^2)	Density (g/cm^3)
1	30	0.15	0.0130	2.00×10^8	5.25×10^{11}	0.867
1	35	0.19	0.0158	2.34×10^8	4.84×10^{11}	0.832
1	40	0.23	0.0185	2.67×10^8	4.57×10^{11}	0.804
1	45	0.27	0.0219	3.00×10^8	4.38×10^{11}	0.811

Table 1: Model Parameters for Zylon

FAILURE MODEL

Fig. 1 shows the load-stroke response of a single ply of Zylon fabric in a quasi-static penetration test gripped on two edges. In this test, described in [10], a fragment simulator is pushed quasi-statically through a gripped specimen of fabric. The fabric demonstrates several failure mechanisms, as annotated in the figure. First, at a load of about 500 lb, yarns around the fragment rupture in what we call a “local failure” mode, resulting in a significant load drop. Next, yarns remote from the impact site begin to separate, i.e., a “remote failure” mode, which results in a steady increase of the load. Finally, yarns along the ungripped sides begin to pull out, resulting in a nearly linear load drop to zero.

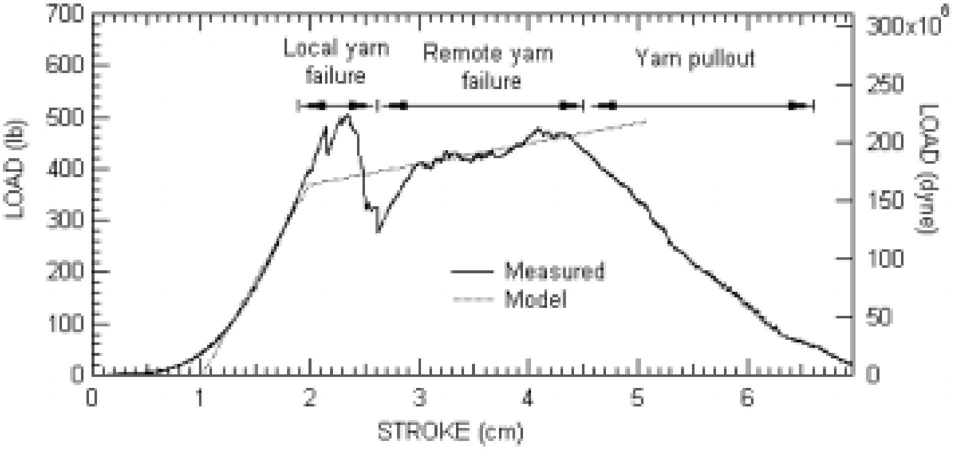

Figure 1: Fabric response in a quasi-static penetration test.

We did not attempt to model these failure mechanisms explicitly, but instead modeled the overall response with a bilinear curve, as shown in Fig. 1. We assume the response for the material is elastic-plastic with linear hardening to failure in the two orthogonal directions corresponding to the yarn directions. By fitting the results of the gas gun tests, the yield stress is set to 12.0 x 10^9 dyne/cm^2 with 20% strain hardening. The failure criterion is based on accumulated plastic strains in the two directions. The material fails when strains in both directions exceed a specified limit (i.e., yarns in both directions must fail before the fragment can penetrate). The limit values for strain, which depend on the number of plies, are listed in Table 2.

No. of Plies	1	2	3	4	5	6
Limit Strain	0.035	0.060	0.085	0.110	0.135	0.150

Table 2: Limit Values of Strain

GAS-GUN TEST SIMULATIONS

We performed simulations using the design model for 15 gas-gun tests. The tests included 15-cm-square Zylon targets from 30 to 45 yarns per inch (ypi), from 1 to 6 plies, gripped on two edges and four edges, with a range of pitch and roll angles. Table 3 lists the details of the 15 tests along with the calculated and measured residual velocities of the fragment and the energy dissipated by the target. For calculations in which the fragment did not penetrate the target, the residual velocity was set to zero. Fig. 2 shows the calculated response for Test 58, a single ply of 40 x 40 ypi Zylon gripped on two edges. The 25-g fragment simulator had an impact velocity of 80 m/s, a roll angle of 16 degrees, and a pitch of 1 degree. Fig. 2 shows snapshots of the computed response at 0.10-ms intervals. As seen in Fig. 2(c), the deformation wave reaches the target edges at about 0.20 ms. In the simulation, the left and right edges are held and the upper and lower edges are not held. As shown in Figure 2(e) the fragment begins to penetrate at about 0.4 ms and is nearly through the target at 0.5 ms, as seen in Figure 2(f). The calculated residual velocity of 38 ms is about 10% less than the measured velocity of 42 ms, indicating that the model target was stronger than the actual target.

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Table 3: Design Model Calculations

Test no.	Sides Held	Plies	Pitch (ypi)	Mass (g)	Impact Velocity (m/s)	Residual Velocity		KE total (J)	Dissipated Energy (J)		Error (% of KE)
						Test (m/s)	Model (m/s)		Test	Model	
49	2	1	35	25	52.0	0	5	33.8	33.8	33.5	-0.9
39	2	1	30	25	79.5	45	48	79.0	53.2	50.2	-3.8
47	2	1	35	25	80.0	49	52	80.0	49.7	46.2	-4.4
58	2	1	40	25	80.0	42	38	80.0	58.2	62.0	4.7
71	2	2	30	25	95.0	20	0	112.8	107.8	112.8	4.4
61	2	3	30	96	79.5	0	0	303.4	303.4	303.4	0.0
66	2	1	30	96	83.0	75	72	330.7	60.7	81.8	6.4
67	2	2	30	96	83.0	53	56	330.7	198.4	180.1	-5.5
25	4	1	35	25	77.5	59	45	75.1	31.6	49.8	24.2
13	4	1	45	25	78.0	29	35	76.1	65.5	60.7	-6.3
20	4	1	30	25	79.0	62	54	78.0	30.7	41.6	13.9
24	4	1	40	25	79.0	50	40	78.0	47.4	58.0	13.6
26	4	1	30	25	82.5	63	59	85.1	35.5	41.6	7.2
29	4	4	40	96	79.0	28	0	299.6	263.3	299.6	12.1
32	4	6	40	96	79.0	0	0	299.6	299.6	299.6	0.0

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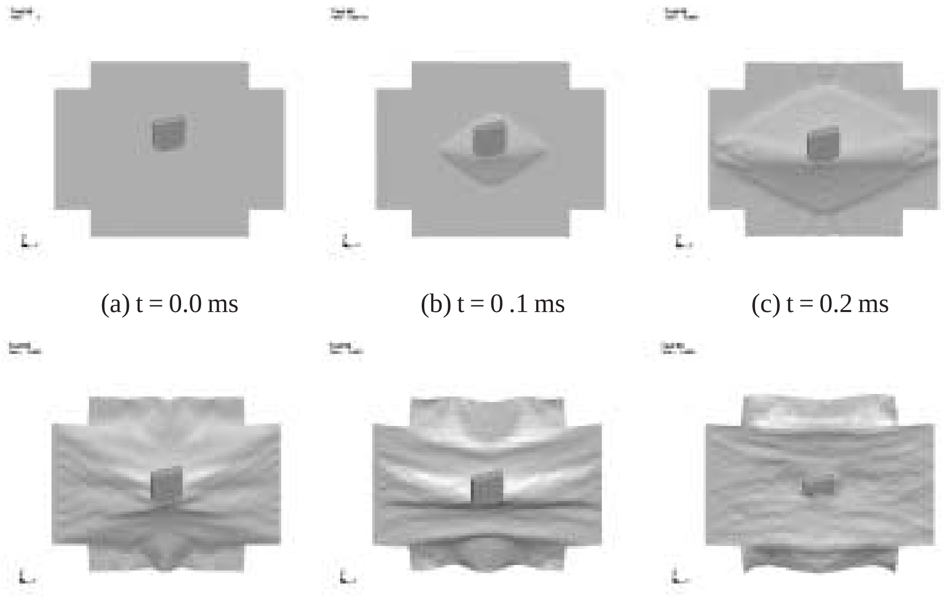

(a) t = 0.0 ms (b) t = 0 .1 ms (c) t = 0.2 ms

(d) t = 0.3 ms (e) t = 0.4 ms (f) t = 0.5 ms

Figure 2: Design model simulation for gas gun test 58.

The last column in Table 3 is the error in energy absorbed for the simulation, calculated by normalizing the difference in the calculated and measured dissipated energy by the total kinetic energy of the fragment. The average of these errors is 4.4% with a standard deviation of 8.7%. The design model provides a close estimate of the dissipated energy, but tends to overpredict results for tests with four edges gripped. Fig. 3 compares the calculated and measured energy dissipated in all the tests. A linear fit through the data passing through the origin gives a slope of 1.03 and an R_2 value of 0.98.

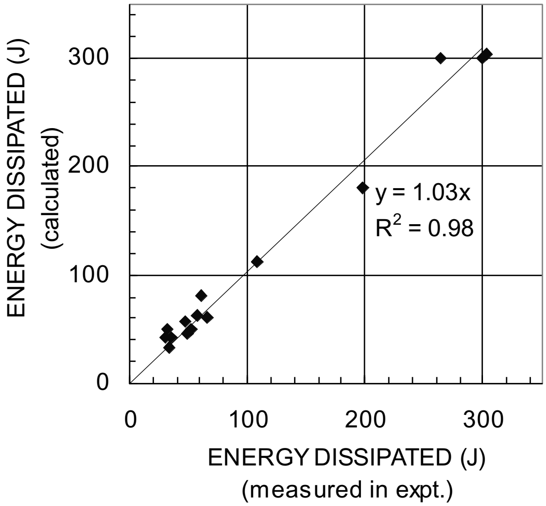

Figure 3: Comparison of measured and calculated dissipated energy.

LARGE-SCALE TESTS

We are currently evaluating the model's ability to simulate full-scale ballistic tests of fragments impacting fabric barriers in the fuselage wall. The barriers are approximately 50-cm-square sections of Zylon fabric, held to the aircraft frame and longerons by mounts at the four corners. As shown in Fig. 4, the fabric in the tests is draped as it would be when installed in the interior structure of an aircraft. Sharp titanium fragments approximately 8 x 10 x 0.6 mm and weighing 175 g are launched at velocities up to 200 m/s. Fig. 3 shows an example of the calculated response of the fabric barrier for one test configuration. The fabric causes the fragment to tumble and prevents penetration. Comparisons are being made between the measured and calculated fragment/fabric interaction, including deformation and failure of the fabric and the tumbling and trajectory of the fragment.

Figure 4: Simulated response of fabric for full-scale fragment impact test.

SUMMARY

The model simulates well the response of the fabric to impacting fragments in the set of gas gun tests described, but does not account for failure mechanisms such as yarn slippage in the fabric or fabric pull-out at attachments. We are currently evaluating the ability of the model to simulate full-scale tests of fabric barriers. When fully developed, the model will serve as a time- and cost-efficient tool for the engineer in designing lightweight barrier systems for commercial aircraft.

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