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A Study of a Steel Right Circular Cylinder (RCC) Striking 23 Plies of KM2 Fabric Using the LS-DYNA Lagrangian Hydrocode

by Dennis S. Pritchard

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A Study of a Steel Right Circular Cylinder (RCC) Striking 23 Plies of KM2 Fabric Using the LS-DYNA Lagrangian Hydrocode

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Abstract

A study was conducted to examine the terminal effects of a 1.0-g steel RCC impacting 23 plies of KM2 fabric using the LS-DYNA Lagrangian hydrocode. The simulated impact velocities were 200, 400, 600, 800, 1000, 1200, and 1400 m/s. The fabric was a plain weave of 850 denier yarn. The LS-DYNA-simulated V_s versus V_r data points generated at the U.S. Army Research Laboratory (ARL) were compared to both experimental data and EPIC-generated data. Also, the LS-POST software package was used to view the simulated physical descriptions of the penetrator and target at various stages of the penetration process.

Acknowledgments

This work was supported in part by a grant of computer time from the DOD High Performance Computing Modernization Program at Aberdeen Proving Ground, MD. Mr. D. Grove is gratefully acknowledged for his efforts in support of the work reported here.

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1. Introduction

A study was conducted to examine the terminal effects of a 1.0-g steel right circular cylinder (RCC) impacting 23 plies of KM2 fabric. Simulations and analyses were conducted using the LS-DYNA Lagrangian hydrocode* in support of the Science and Technical Objective (STO) titled "Ballistic Protection for Improved Individual Survivability." This joint STO between the U.S. Army Research Laboratory (ARL) and the Natick Soldier Center is advancing materials technology to improve the protection of personnel armor systems against current and emerging fragment and bullet threats. The STO is also providing tools to benefit the development, design, and acquisition of personnel armor.

2. Review and Analysis

Experimental V_s (striking velocity) versus V_r (residual velocity) data and hydrocode simulations using LS-DYNA and EPIC are discussed in the following sections.

2.1 Experimental Data

Experimental data forms the baseline for comparison to the computed results. The experimental data from Johnson et al. (1999) are shown in Figure 1 and Table 1. The RCC, having a length-to-diameter ratio of one, struck the targeted fabric layup at 0° obliquity. It is seen that a V_{50} of approximately 600 m/s can be assigned to the experimental data. The V_{50} is defined within a narrow V_s range as the V_s that is bracketed by half of the projectiles in a test sampling in that narrow range not making it through the target layup ($V_r = 0$), balanced by a corresponding half number of projectiles barely penetrating the target layup ($V_r > 0$) in the same range. Once the exact "over" and "under" data points are determined, the V_{50} equals the average of the V_s values for these points. From an experimental standpoint of obtaining V_{50} for a particular penetrator and target configuration, this data set is exemplary, as the cost of determining the V_{50} is roughly proportional to the number of shots fired; the fewer the shots, the lower the cost. The V_{50} number often forms the decision point describing the acceptability of an armor configuration on a pass/fail basis when attacked by a particular penetrator. For a more rigorous explanation of how to experimentally find a V_{50}, the military standard MIL-STD-662E (Department of the Army 1992) should be studied. As the V_s increased, the fabric layup became less effective in stopping the RCC as a function of the fabric's decreasing ability to withstand dynamic loading.

* LS-DYNA Version 950d, Livermore, CA: Livermore Software Technology Corporation.

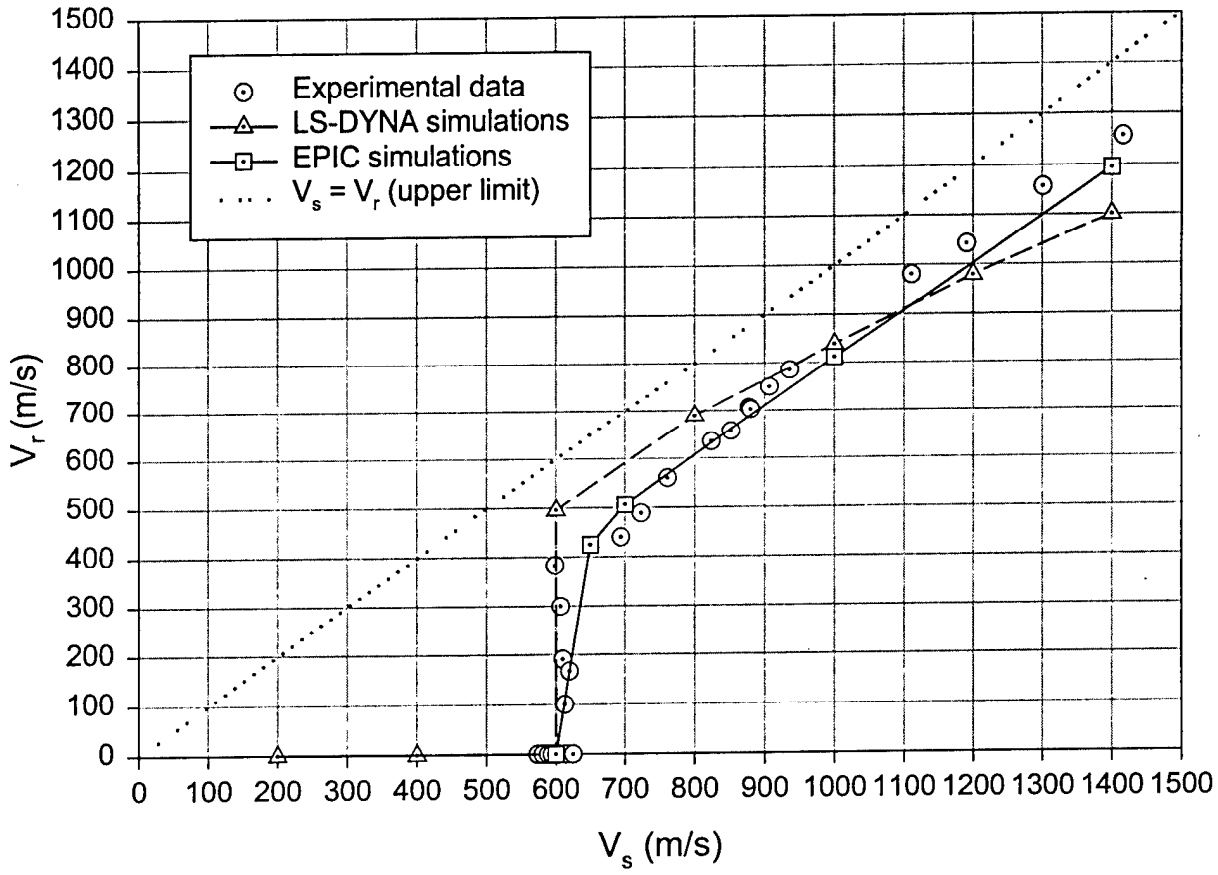

Figure 1. Comparison of simulation results with experimental V_s versus V_r data.

Table 1. V_s versus V_r values.

Experimental V_s (m/s)	Experimental V_r (m/s)	LS-DYNA V_s (m/s)	LS-DYNA V_r (m/s)	EPIC V_s (m/s)	EPIC V_r (m/s)
574	0	200	0	600	0
581	0	400	0	650	425
589	0	600	495	700	506
594	0	800	689	1000	812
599	383	1000	839	1400	1194
604	0	1200	980		
607	299	1400	1100		
610	191				
615	0				
613	100				
620	167				
625	0				
694	440				
723	488				
761	560				
824	635				
852	656				
878	706				
880	702				
907	750				
936	786				
1111	981				
1191	1042				
1301	1157				
1416	1255				

This statement is evidenced by the increase in V_r as V_s increased after the V_s value of 600 m/s had been significantly surpassed. The V_s versus V_r values starting at and including the point with the 599 m/s V_s value could reasonably be fit with a straight line that roughly parallels the $V_s = V_r$ line.

2.2 LS-DYNA Simulations

The ARL-simulated V_s versus V_r data were obtained by using LS-DYNA Version 950d and are shown in Figure 1 and Table 1. The RCC and fabric target grid generation was accomplished by running the LS-INGRID computer software package* with the ARL-designed input deck presented in Appendix A. This run gave the properly formatted (Fortran 77) node and element data that was stripped from the LS-INGRID output deck called ingrido. This stripped deck was inserted into the LS-DYNA keyword formatted deck for each LS-DYNA run, with the material property cards, among others, preformatted. A resultant typical LS-DYNA input deck used in this report, with only the extensive node and element (8-node brick) data abbreviated, is shown in Appendix B. The projectile had a total of 1331 nodes and 1000 solid elements. Each ply had 3362 nodes and 1600 solid elements, with individual element dimensions of 0.1578 × 0.5000 × 0.5000 mm. The projectile and target element sizing were comparable. Each ply was one element thick, with the ply dimensions equal to 0.1578 × 20 × 20 mm. Changes were made to the LS-DYNA input deck for each initial impact velocity, where at least each different impact velocity had to be specified, and some changes were required for the other material properties as shown in Table 2.

Table 2. Selected material properties used in LS-DYNA input deck.

Property	KM2 Ply (V_s = 200 and 400 m/s)	KM2 Ply (V_s = 600 m/s and up)	Steel
Density (g/cm^3)	1.438[a]	1.438[a]	7.87[b]
Young's Modulus (Mbar)	0.08325	0.74	2.068395[c]
Poisson's Ratio	0.2[a]	0.2[a]	0.29[d]
Yield Stress (Mbar)	–	–	0.010342[c]
Failure Strain	0.2	0.025	–

[a] Johnson et al. (1999).
[b] Lyman (1961).
[c] Flinn and Trojan (1975).
[d] Kolsky (1963).

The steel was modeled as an elastic-perfectly plastic material. Although many of the material properties in Table 2 were directly obtained from the listed references, explanations for the choice of others are required as follows.

The KM2 volumetric density in Table 2 was derived from constants found in the Johnson et al. (1999) paper and is close to the commonly quoted value of 1.44 g/cm^3, but is not that exact value. The fabric description was modified from

* LS-INGRID Version 3.5, Livermore, CA: Livermore Software Technology Corporation.

the actual weave pattern for each ply into a plate of solid elements with nominally the same material properties as the actual ply. The volumetric density for a simulated KM2 ply is dependent on the way the change from the actual weave pattern to a solid element description is interpreted. The areal density of the experimental layup was quoted as 5.22 kg/m^2 with a modeled effective thickness (not the true experimental thickness) of 3.63 mm given by Johnson et al. (1999) for the 23 plies. These constants force each ply thickness to be 0.1578 mm and the volumetric density for this thickness to be 1.438 g/cm^3. Since each actual ply was a plain weave of 850 denier yarn, this fact fixes the maximum total target thickness allowed. With 23 plies and 22 gaps between plies built in, this makes each gap 0.1391 mm wide to give a reasonable approximation of the total target thickness as 6.6896 mm, which was equal to the measured thickness of a 23-ply layup measured in the laboratory, within a small error band. It was thought that the solid elements with gaps between plies were required to minimize the effect of geometric nonproportionality on the simulated penetration process. One would encounter this effect by equating the 23 plies to some type of single-layer shell element description, for example.

Two quantities in Table 2 that definitely require an explanation for their origins are the Young's modulus and failure strain values. Shim et al. (2001) found, while conducting high strain-rate testing with the Split-Hopkinson Pressure Bar (SHPB), that the failure of Twaron fabric (similar to KM2 fabric) is highly strain-rate dependent with the tensile strength and modulus increasing with increasing strain rate, while the failure strain decreases with increasing strain rate. They also found that Twaron fabric failed in a more brittle manner as a function of increasing strain rate, which significantly reduced the amount of energy that could be absorbed by a particular yarn prior to its failure. This is consistent with the observed behavior described in the previous sentence. These experimental observations can be used to help describe the failure behavior of fabrics during ballistic penetration as follows. In a set of ballistic experiments, the strain rate experienced by the target material increases in some proportion to increasing projectile impact velocity, holding all other initial conditions constant. Thus, at higher impact velocities, the KM2 fabric should exhibit a higher Young's modulus and a lower strain to failure (see Table 2). Now, the Young's modulus and failure strains in Table 2 do not exactly fit the values given by Shim et al. (2001), but are extrapolated from their data. It was assumed, given the high strain rates achieved in the ballistic testing modeled in this report, that the yarns in the fabric weave could be thought to have elastic material properties to the point of failure with virtually no onset of plastic deformation. This assumption can be thought of as an elastic-perfectly brittle model. The highest modulus found for the Twaron fabric (more similar to Kevlar 29 fabric than to KM2 fabric) by Shim et al. (2001) was close to 0.74 Mbar at the highest testing strain-rate they used (495 s^{-1}). This was assumed to be a fair estimate corresponding to the strain-rate encountered on the high end of the striking velocity range of the

simulated ballistic tests with the KM2 fabric. However, KM2 fibers are somewhat tougher than Twaron or Kevlar 29 fibers, so the Shim et al. (2001) strain to failure of about 0.016 was increased to match the toughness-related increase in the ductile-to-brittle strain-to-failure criterion for the KM2 (failure strain = 0.025). Shim et al. (2001) found very low Young's moduli at the lowest end (quasi-static) of their strain-rate range (see their Figure 4). To reflect the strain-rate condition of a lower Young's modulus for a lower strain rate, a midrange-value Young's modulus was picked for the 200 and 400 m/s striking velocities as shown in Table 2. Based on the Shim et al. (2001) data values for strain-rate conditions approaching and equal to the quasi-static values for Twaron, a KM2 failure strain of 0.2 appeared to be reasonable. However, if actual SHPB data were ever obtained for KM2 fabric, the method for determining the Young's modulus and failure strain values in Table 2 would have to be readdressed.

The LS-DYNA-programmed V_s values were 200, 400, 600, 800, 1000, 1200, and 1400 m/s. The simulated penetration behavior for each V_s is visually summarized in Figures 2–9 as a product of the LS-POST software package.* For scaling purposes in these figures, it must be remembered that the projectile diameter was 5.45 mm, but this value is directly scalable only in the y-direction, as the simulations have been rotated about the y-axis to enhance the view of the deformation of the projectile and the failure of the target material. With the 200 m/s V_s, five simulated plies were penetrated and only severe deformation without failure occurred in all remaining plies. Obviously, the condition that no part of the projectile exits the last ply was met exactly for a "no perforation" condition. For the 400 m/s V_s, significantly more simulated plies (16) were penetrated than at the 200 m/s V_s, which is consistent with the fact that deeper penetration occurs experimentally as the striking velocity increases; the "no perforation" condition was still met. For V_s of 600 m/s and above, the V_r was determined by tracking, in time, the velocity of the center rear node on the back of the RCC. When the projectile's rear surface velocity converged sufficiently to a constant velocity after penetration, that velocity was picked for the V_r.

2.3 EPIC Simulations

The EPIC-simulated V_s versus V_r points from Johnson et al. (1999) are shown in Figure 1 and Table 1. Comparisons to the LS-DYNA results can be made. For example, the difference between the V_r values for the 600 m/s V_s runs is not a major disparity, since any V_r in that vicinity has been shown experimentally to be a difficult number to interpret also. Hydrocodes do not predict V_r values at or near the experimentally determined V_{50}, a meta-stable point in the true penetration process, with accuracy any better than that found experimentally. Experimental anomalies occur near the V_{50} because of subtle shot-to-shot

* LS-POST Version 1.0, Livermore, CA: Livermore Software Technology Corporation.

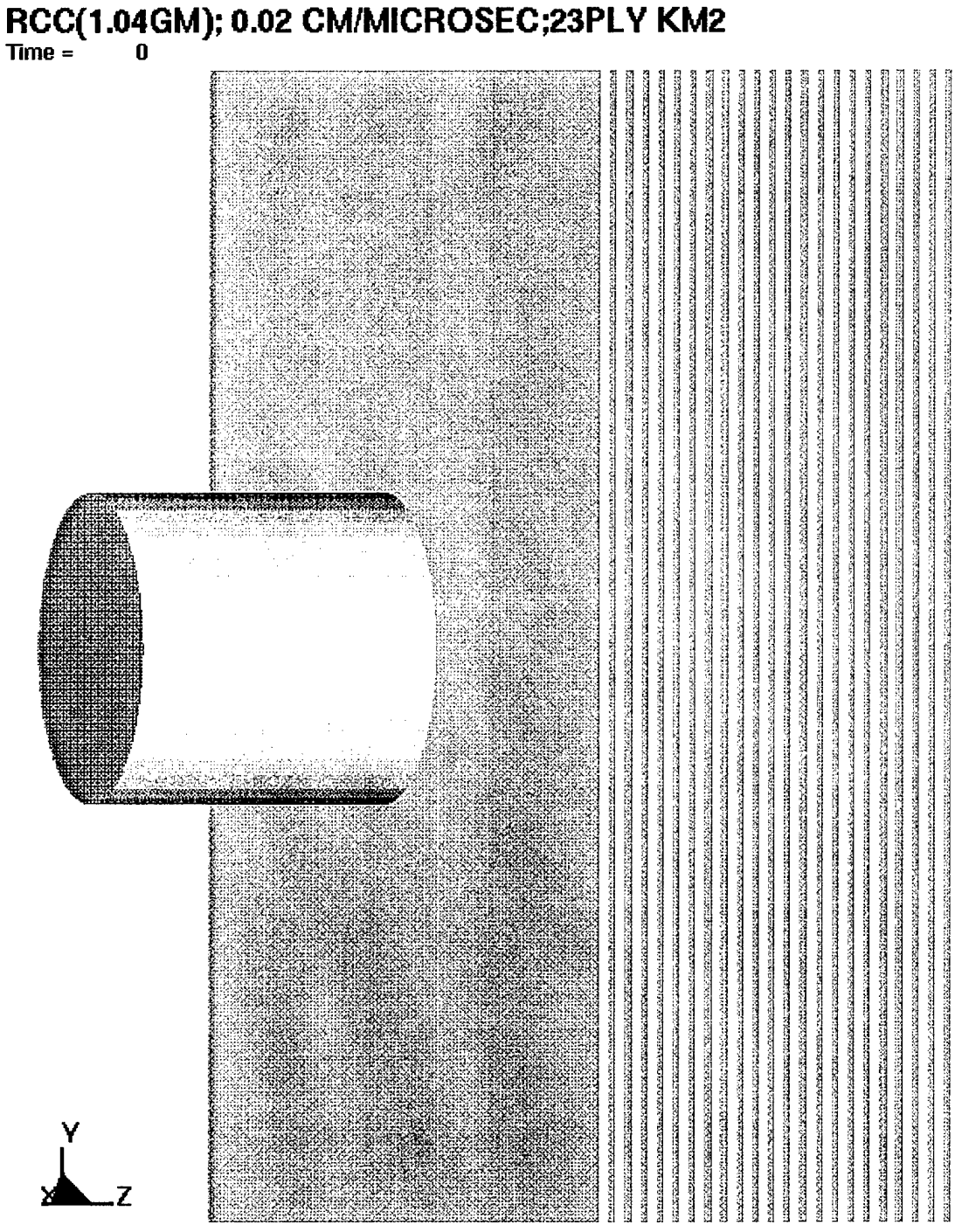

Figure 2. LS-DYNA RCC and target simulation grid prior to impact (V_s = 200 m/s).

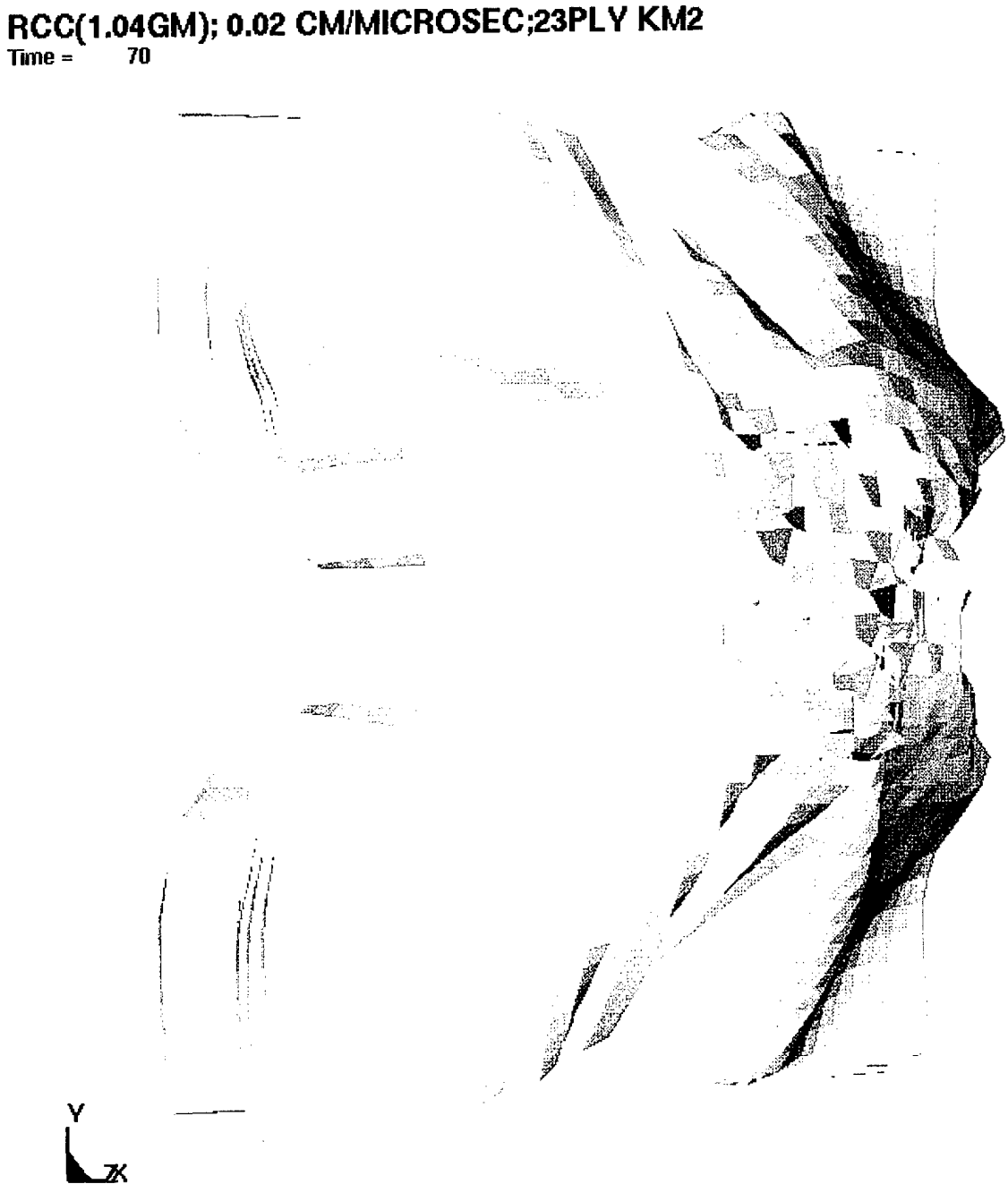

Figure 3. LS-DYNA simulation at 70 μs into run showing damage up to the fifth ply ($V_s = 200$ m/s).

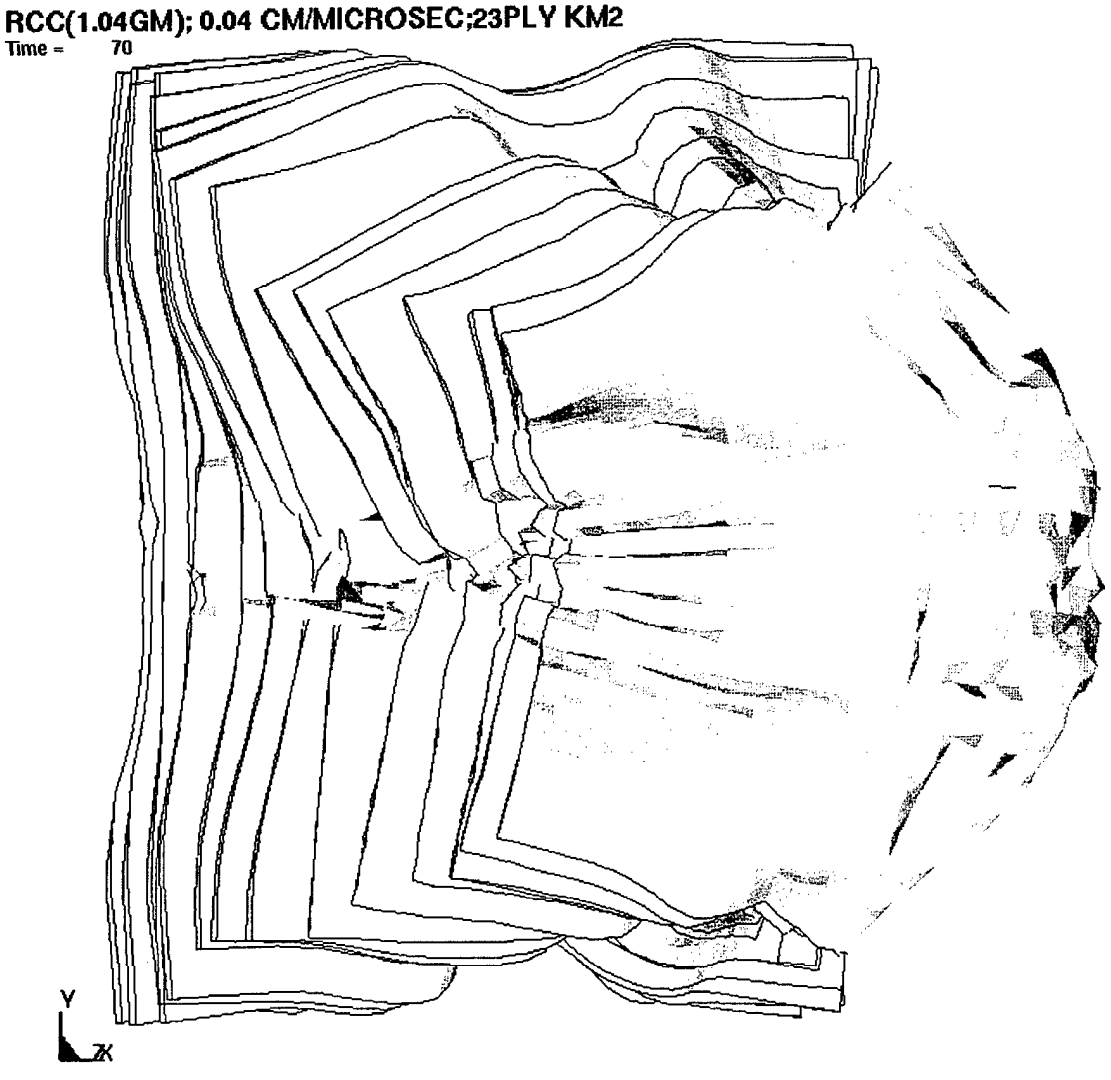

Figure 4. LS-DYNA simulation at 70 μs into run showing damage up to the sixteenth ply (V_s = 400 m/s).

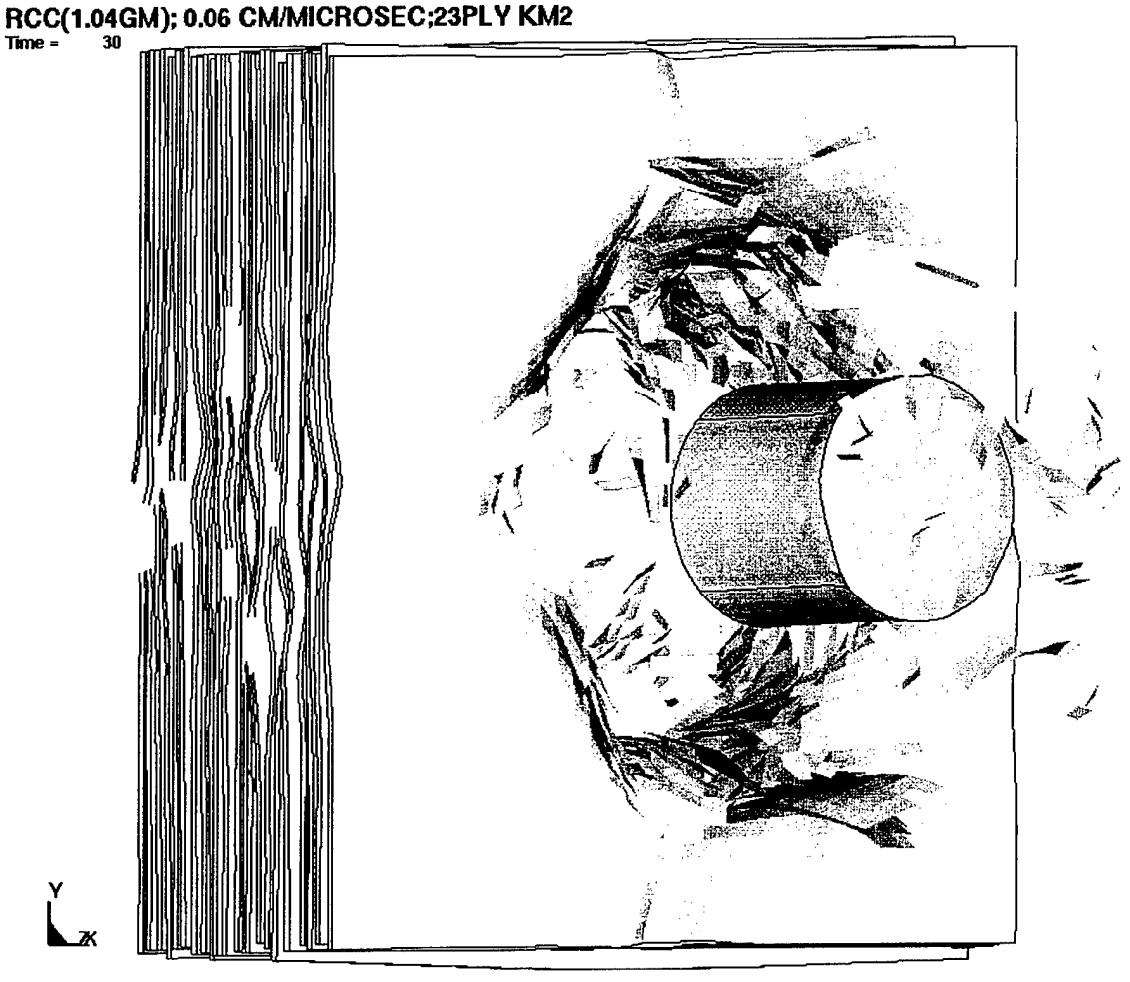

Figure 5. LS-DYNA simulation at 30 μs into run (V_s = 600 m/s).

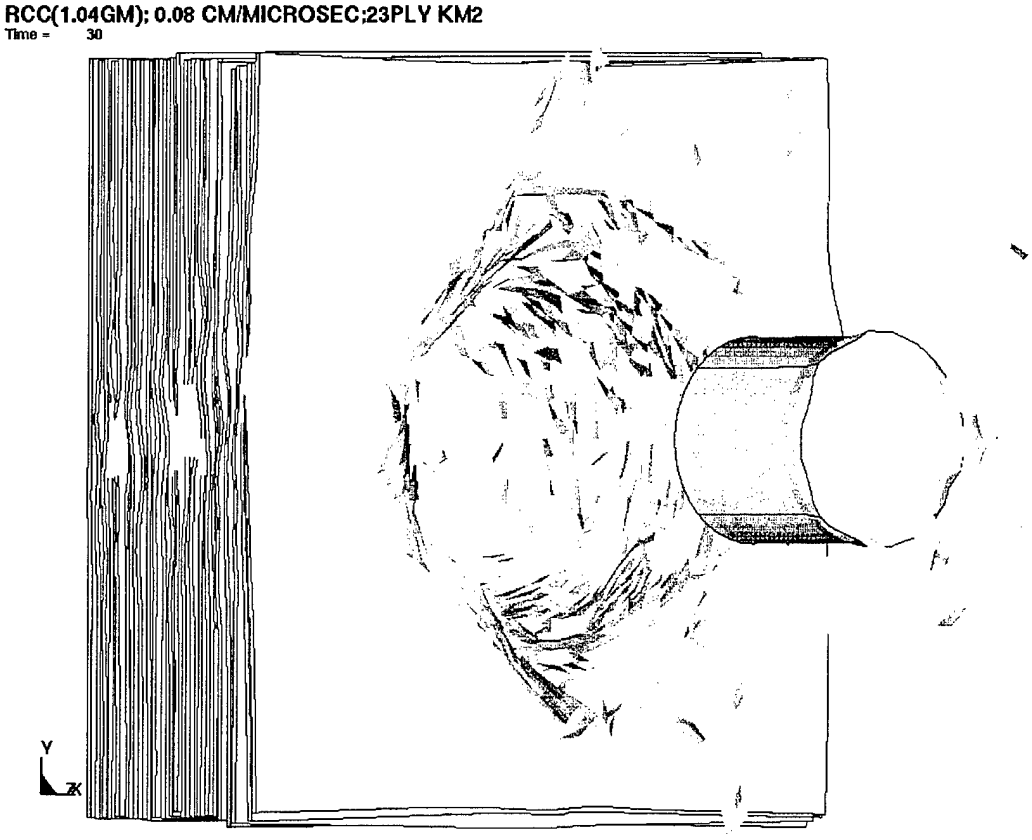

Figure 6. LS-DYNA simulation at 30 μs into run (V_s = 800 m/s).

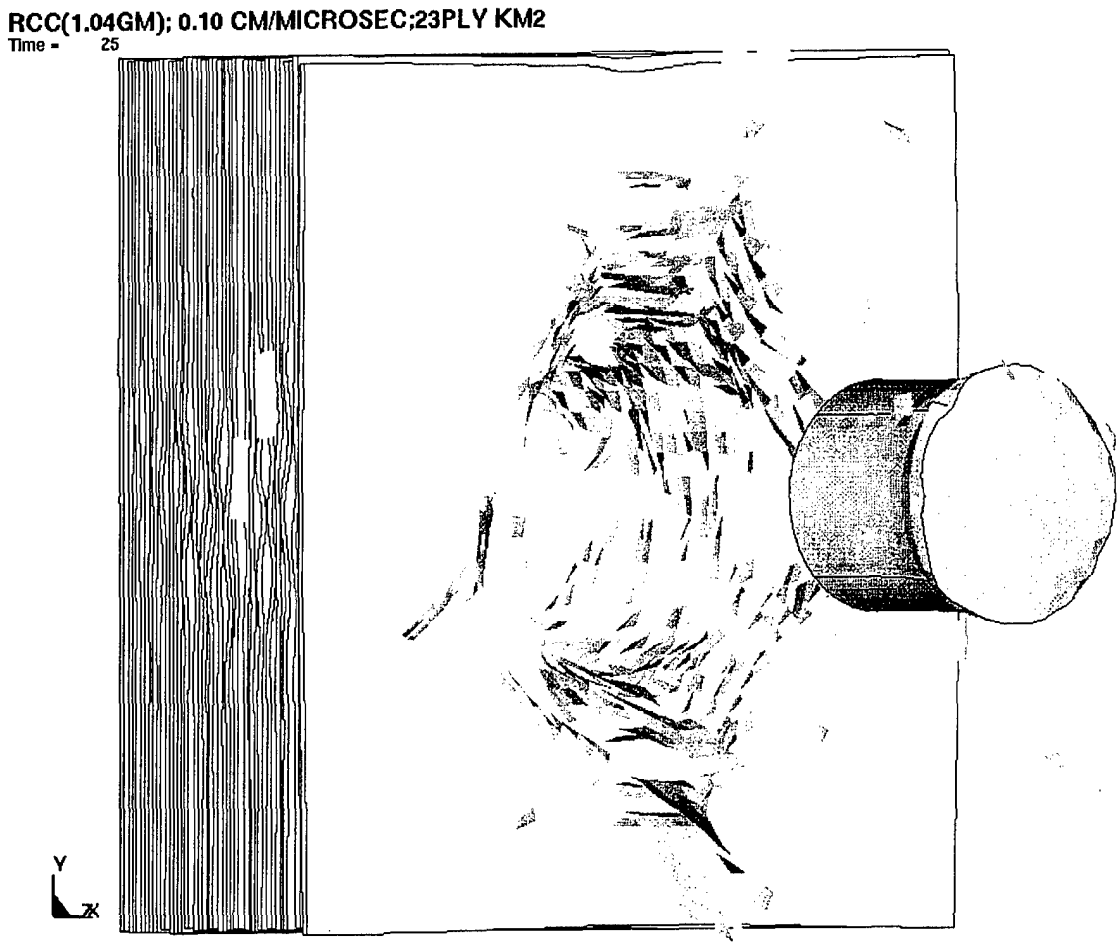

Figure 7. LS-DYNA simulation at 25 μs into run (V_s = 1000 m/s).

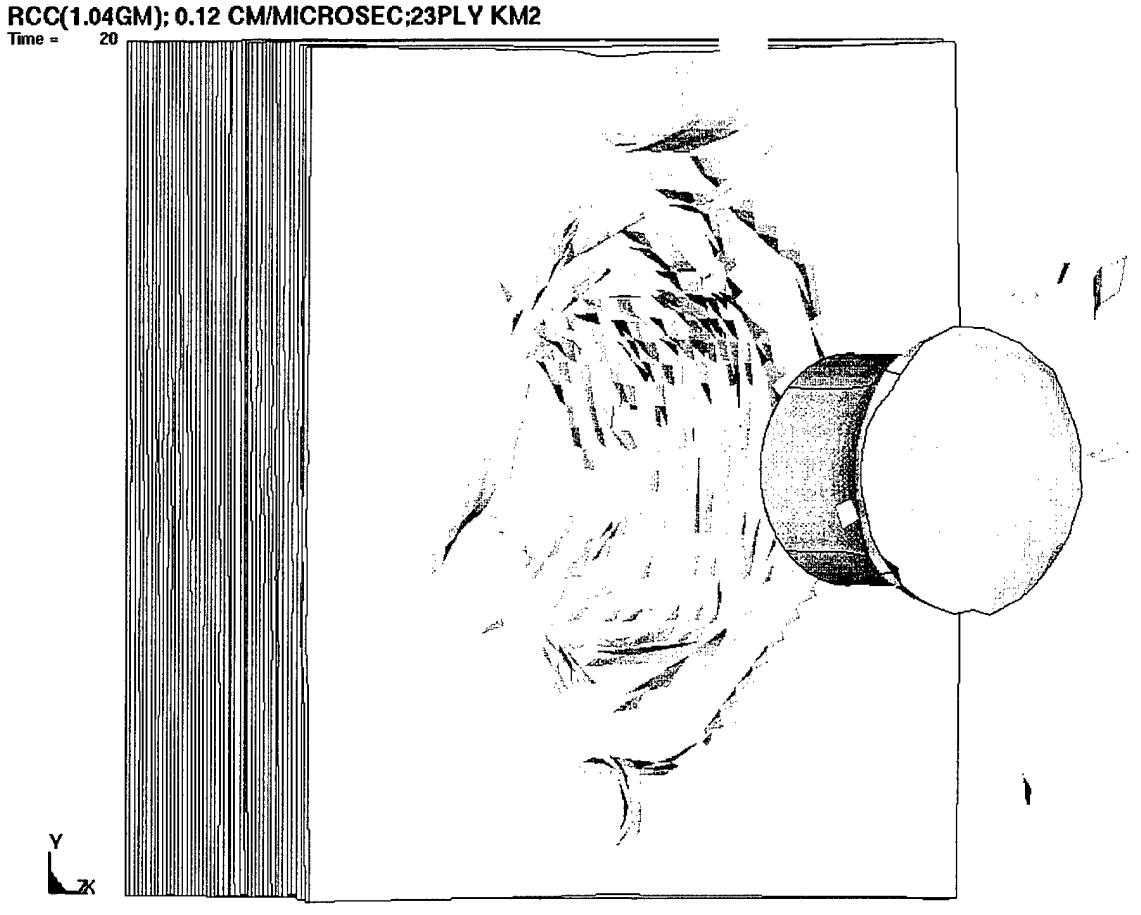

Figure 8. LS-DYNA simulation at 20 μs into run (V_s = 1200 m/s).

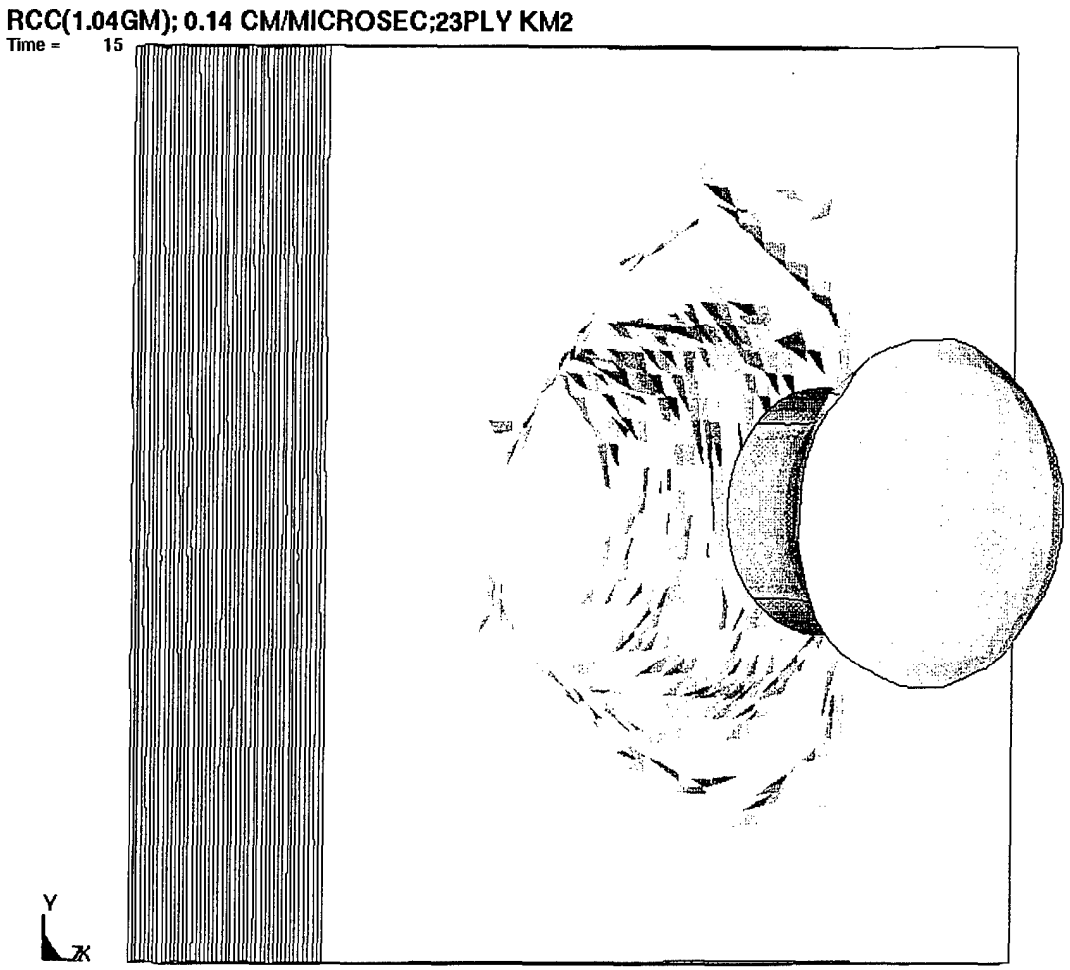

Figure 9. LS-DYNA simulation at 15 μs into run (V_s = 1400 m/s).

variations in the way real fabrics tear in the final penetration process. This effect leads to some penetrators being just caught by the last fabric ply or just making it through that ply with little velocity to spare, given the same V_s. The LS-DYNA computations are flexible, as they allow for the uncertainty of such behavior by letting key input material properties change as required, specifically the Young's modulus and failure strain in Table 2 in this case, accounting for this behavior. Actually, EPIC picked a V_r value that can be thought of as a V_0 value. V_0 is defined as the V_s at which no residual velocity can be obtained. Although EPIC predicted a V_0 in this case, V_0 is not usually obtained experimentally with exacting precision, so its determination to an overly precise number for comparison purposes should not be a computational goal.

3. Summary

The work here forms a baseline for the simulation of fabric penetration by fragment and bullet threats. Future plans include extending the LS-DYNA simulation techniques reported here to a study of 9-mm bullet impact on similar fabric layups. Also, more SHPB testing needs to be sponsored to assist in the process of defining increasingly accurate values for the Young's modulus and failure strain (as functions of strain rate) of KM2 and other ballistic fabrics of interest. This could lead to the development of analytical expressions describing Young's modulus and failure strain as functions of strain rate rather than the first-order discontinuous step model used in the present study. This report demonstrates a technique for reasonably describing the ballistic response of KM2 fabric using the LS-DYNA Lagrangian hydrocode. Using this technique, simulations can be performed to gain additional insight into understanding how the fabric components of armored vests resist ballistic penetration.

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4. References

Department of the Army. *V_{50} Ballistic Test for Armor.* MIL-STD-662E, Washington, DC, 27 May 1992.

Flinn, R. A., and P. K. Trojan. *Engineering Materials and Their Applications.* Boston: Houghton Mifflin, pp. 61 and 72, 1975.

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Lyman, T. (editor). *Metals Handbook – 8th Edition, Volume 1: Properties and Selection of Materials.* Metals Park, OH: American Society for Metals, p. 798, 1961.

Shim, V. P. W., C. T. Lim, and K. J. Foo. "Dynamic Mechanical Properties of Fabric Armour." *International Journal of Impact Engineering,* vol. 25, p. 1–15, 2001.

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Appendix A. LS-Ingrid Input Deck for RCC and 23-Ply Target

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```
GRID 1.0 GM RCC AND 23 PLIES KM2
dn3d kw93
c Definition of Parts
start
c ijk notation (Part 1 - Impactor)
1 11;1 11;1 11;
c geometry
0.0545 -0.0545 0.0545 -0.0545 0.000 0.545
a 1 1 1 2 2 2 3 0.2725
C Assign a part number.
mate 1
end
start
c ijk notation (Part 2 - Ply 1)
1 41;1 41;1 2;
c geometry
1.0 -1.0 1.0 -1.0 0.58500 0.60078
c Assign a part number.
mate 2
end
start
c ijk notation (Part 3 - Ply 2)
1 41;1 41;1 2;
1.0 -1.0 1.0 -1.0 0.61469 0.63047
mate 3
end
start
c ijk notation (Part 4 - Ply 3)
1 41;1 41;1 2;
1.0 -1.0 1.0 -1.0 0.64438 0.66016
mate 4
end
start
c ijk notation (Part 5 - Ply 4)
1 41;1 41;1 2;
1.0 -1.0 1.0 -1.0 0.67407 0.68985
mate 5
end
start
c ijk notation (Part 6 - Ply 5)
1 41;1 41;1 2;
1.0 -1.0 1.0 -1.0 0.70376 0.71954
mate 6
end
start
c ijk notation (Part 7 - Ply 6)
1 41;1 41;1 2;
1.0 -1.0 1.0 -1.0 0.73345 0.74923
mate 7
end
start
c ijk notation (Part 8 - Ply 7)
1 41;1 41;1 2;
1.0 -1.0 1.0 -1.0 0.76314 0.77892
```

```
mate 8
end
start
c ijk notation (Part 9 - Ply 8)
1 41;1 41;1 2;
1.0 -1.0 1.0 -1.0 0.79283 0.80861
mate 9
end
start
c ijk notation (Part 10 - Ply 9)
1 41;1 41;1 2;
1.0 -1.0 1.0 -1.0 0.82252 0.83830
mate 10
end
start
c ijk notation (Part 11- Ply 10)
1 41;1 41;1 2;
1.0 -1.0 1.0 -1.0 0.85221 0.86799
mate 11
end
start
c ijk notation (Part 12 - Ply 11)
1 41;1 41;1 2;
1.0 -1.0 1.0 -1.0 0.88190 0.89768
mate 12
end
start
c ijk notation (Part 13 - Ply 12)
1 41;1 41;1 2;
1.0 -1.0 1.0 -1.0 0.91159 0.92737
mate 13
end
start
c ijk notation (Part 14 - Ply 13)
1 41;1 41;1 2;
1.0 -1.0 1.0 -1.0 0.94128 0.95706
mate 14
end
start
c ijk notation (Part 15 - Ply 14)
1 41;1 41;1 2;
1.0 -1.0 1.0 -1.0 0.97097 0.98675
mate 15
end
start
c ijk notation (Part 16 - Ply 15)
1 41;1 41;1 2;
1.0 -1.0 1.0 -1.0 1.00066 1.01644
mate 16
end
start
c ijk notation (Part 17 - Ply 16)
1 41;1 41;1 2;
1.0 -1.0 1.0 -1.0 1.03035 1.04613
```

```
mate 17
end
start
c ijk notation (Part 18 - Ply 17)
1 41;1 41;1 2;
1.0 -1.0 1.0 -1.0 1.06004 1.07582
mate 18
end
start
c ijk notation (Part 19 - Ply 18)
1 41;1 41;1 2;
1.0 -1.0 1.0 -1.0 1.08973 1.10551
mate 19
end
start
c ijk notation (Part 20 - Ply 19)
1 41;1 41;1 2;
1.0 -1.0 1.0 -1.0 1.11942 1.13520
mate 20
end
start
c ijk notation (Part 21 - Ply 20)
1 41;1 41;1 2;
1.0 -1.0 1.0 -1.0 1.14911 1.16489
mate 21
end
start
c ijk notation (Part 22 - Ply 21)
1 41;1 41;1 2;
1.0 -1.0 1.0 -1.0 1.17880 1.19458
mate 22
end
start
c ijk notation (Part 23 - Ply 22)
1 41;1 41;1 2;
1.0 -1.0 1.0 -1.0 1.20849 1.22427
mate 23
end
start
c ijk notation (Part 24 - Ply 23)
1 41;1 41;1 2;
1.0 -1.0 1.0 -1.0 1.23818 1.25396
mate 24
end
end
```

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Appendix B. Abbreviated LS-DYNA Input Deck for RCC Impacting 23-Ply Target (V_s = 200 m/s)

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```
*KEYWORD
*TITLE
RCC(1.04gm); 0.02 cm/microsec;23ply KM2
$        mass, length,      time,    force, pressure & modulus & stress,      energy
$ Unit=   gm,       cm, microsec, 1e+07 N,                              Mbar, 1e+07 N-cm
$
$---+----1----+----2----+----3----+----4----+----5----+----6----+----7----+----8
$
*CONTROL_TIMESTEP
$  dtinit    tssfac
   0.0000    0.7000
*CONTROL_TERMINATION
$  endtime
     70.0
*CONTROL_CONTACT
$   slsfac
      1.0
$   usrstr
        0
*CONTROL_ENERGY
$     hgen       rwen
        2          2
*CONTROL_OUTPUT
$    npopt     neecho
        0          0
$
*DATABASE_EXTENT_BINARY
$    neiph      neips     maxint     strflg     sigflg     epsflg     rltflg     engflg
        0          0          0          1          0          0          0          0
$
$   cmpflg     ieverp     beamip      dcomp       shge      stssz     n3thdt
        0          0          0          0          0          0          0
$
*DATABASE_BINARY_D3PLOT
$  dt/cycl
      5.0
*DATABASE_BINARY_D3THDT
$  dt/cycl
      5.0
*DATABASE_MATSUM
$  dt/cycl
      1.0
*DATABASE_HISTORY_NODE
$ node id1       id2        id3        id4        id5        id6        id7        id8
        1         61
*DATABASE_NODOUT
$  dt/cycl
      1.0
*DATABASE_ELOUT
$  dt/cycl
      1.0
*DATABASE_NODFOR
$  dt/cycl
      1.0
*DATABASE_GLSTAT
$  dt/cycl
      1.0
*DATABASE_TRHIST
$  dt/cycl
      1.0
*DATABASE_TRACER
$start  dt L(0)/E(1)          x          y          z
      0.0          0        0.0        0.0        0.0
$
$slave impactor to all plies $$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$
*CONTACT_ERODING_SURFACE_TO_SURFACE
$     ssid       msid      sstyp      mstyp
```

```
         1         2         3         3
$     fric
       0.0
$      sfs
       1.0
$     isym    erosop
         1         1
$
*CONTACT_ERODING_SURFACE_TO_SURFACE
$     ssid      msid     sstyp     mstyp
         1         3         3         3
$     fric
       0.0
$      sfs
       1.0
$     isym    erosop
         1         1
$
*CONTACT_ERODING_SURFACE_TO_SURFACE
$     ssid      msid     sstyp     mstyp
         1         4         3         3
$     fric
       0.0
$      sfs
       1.0
$     isym    erosop
         1         1
$
*CONTACT_ERODING_SURFACE_TO_SURFACE
$     ssid      msid     sstyp     mstyp
         1         5         3         3
$     fric
       0.0
$      sfs
       1.0
$     isym    erosop
         1         1
$
*CONTACT_ERODING_SURFACE_TO_SURFACE
$     ssid      msid     sstyp     mstyp
         1         6         3         3
$     fric
       0.0
$      sfs
       1.0
$     isym    erosop
         1         1
$
*CONTACT_ERODING_SURFACE_TO_SURFACE
$     ssid      msid     sstyp     mstyp
         1         7         3         3
$     fric
       0.0
$      sfs
       1.0
$     isym    erosop
         1         1
$
*CONTACT_ERODING_SURFACE_TO_SURFACE
$     ssid      msid     sstyp     mstyp
         1         8         3         3
$     fric
       0.0
$      sfs
       1.0
$     isym    erosop
         1         1
$
```

```
*CONTACT_ERODING_SURFACE_TO_SURFACE
$      ssid      msid     sstyp     mstyp
          1         9         3         3
$      fric
        0.0
$       sfs
        1.0
$      isym    erosop
          1         1
$
*CONTACT_ERODING_SURFACE_TO_SURFACE
$      ssid      msid     sstyp     mstyp
          1        10         3         3
$      fric
        0.0
$       sfs
        1.0
$      isym    erosop
          1         1
$
*CONTACT_ERODING_SURFACE_TO_SURFACE
$      ssid      msid     sstyp     mstyp
          1        11         3         3
$      fric
        0.0
$       sfs
        1.0
$      isym    erosop
          1         1
$
*CONTACT_ERODING_SURFACE_TO_SURFACE
$      ssid      msid     sstyp     mstyp
          1        12         3         3
$      fric
        0.0
$       sfs
        1.0
$      isym    erosop
          1         1
$
*CONTACT_ERODING_SURFACE_TO_SURFACE
$      ssid      msid     sstyp     mstyp
          1        13         3         3
$      fric
        0.0
$       sfs
        1.0
$      isym    erosop
          1         1
$
*CONTACT_ERODING_SURFACE_TO_SURFACE
$      ssid      msid     sstyp     mstyp
          1        14         3         3
$      fric
        0.0
$       sfs
        1.0
$      isym    erosop
          1         1
$
*CONTACT_ERODING_SURFACE_TO_SURFACE
$      ssid      msid     sstyp     mstyp
          1        15         3         3
$      fric
        0.0
$       sfs
        1.0
$      isym    erosop
```

```
         1         1
$
*CONTACT_ERODING_SURFACE_TO_SURFACE
$     ssid      msid     sstyp     mstyp
         1        16         3         3
$     fric
       0.0
$      sfs
       1.0
$     isym    erosop
         1         1
$
*CONTACT_ERODING_SURFACE_TO_SURFACE
$     ssid      msid     sstyp     mstyp
         1        17         3         3
$     fric
       0.0
$      sfs
       1.0
$     isym    erosop
         1         1
$
*CONTACT_ERODING_SURFACE_TO_SURFACE
$     ssid      msid     sstyp     mstyp
         1        18         3         3
$     fric
       0.0
$      sfs
       1.0
$     isym    erosop
         1         1
$
*CONTACT_ERODING_SURFACE_TO_SURFACE
$     ssid      msid     sstyp     mstyp
         1        19         3         3
$     fric
       0.0
$      sfs
       1.0
$     isym    erosop
         1         1
$
*CONTACT_ERODING_SURFACE_TO_SURFACE
$     ssid      msid     sstyp     mstyp
         1        20         3         3
$     fric
       0.0
$      sfs
       1.0
$     isym    erosop
         1         1
$
*CONTACT_ERODING_SURFACE_TO_SURFACE
$     ssid      msid     sstyp     mstyp
         1        21         3         3
$     fric
       0.0
$      sfs
       1.0
$     isym    erosop
         1         1
$
*CONTACT_ERODING_SURFACE_TO_SURFACE
$     ssid      msid     sstyp     mstyp
         1        22         3         3
$     fric
       0.0
$      sfs
```

```
       1.0
$     isym    erosop
         1         1
$
*CONTACT_ERODING_SURFACE_TO_SURFACE
$     ssid      msid     sstyp     mstyp
         1        23         3         3
$     fric
       0.0
$      sfs
       1.0
$     isym    erosop
         1         1
$
*CONTACT_ERODING_SURFACE_TO_SURFACE
$     ssid      msid     sstyp     mstyp
         1        24         3         3
$     fric
       0.0
$      sfs
       1.0
$     isym    erosop
         1         1
$
$initiate master-slave routine for each ply $$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$
*CONTACT_ERODING_SURFACE_TO_SURFACE
$     ssid      msid     sstyp     mstyp
         2         3         3         3
$     fric
       0.0
$      sfs
       1.0
$     isym    erosop
         1         1
$
*CONTACT_ERODING_SURFACE_TO_SURFACE
$     ssid      msid     sstyp     mstyp
         2         4         3         3
$     fric
       0.0
$      sfs
       1.0
$     isym    erosop
         1         1
$
*CONTACT_ERODING_SURFACE_TO_SURFACE
$     ssid      msid     sstyp     mstyp
         3         4         3         3
$     fric
       0.0
$      sfs
       1.0
$     isym    erosop
         1         1
$
*CONTACT_ERODING_SURFACE_TO_SURFACE
$     ssid      msid     sstyp     mstyp
         3         5         3         3
$     fric
       0.0
$      sfs
       1.0
$     isym    erosop
         1         1
$
*CONTACT_ERODING_SURFACE_TO_SURFACE
$     ssid      msid     sstyp     mstyp
```

```
         4         5         3         3
$     fric
       0.0
$      sfs
       1.0
$     isym    erosop
         1         1
$
*CONTACT_ERODING_SURFACE_TO_SURFACE
$     ssid      msid     sstyp     mstyp
         4         6         3         3
$     fric
       0.0
$      sfs
       1.0
$     isym    erosop
         1         1
$
*CONTACT_ERODING_SURFACE_TO_SURFACE
$     ssid      msid     sstyp     mstyp
         5         6         3         3
$     fric
       0.0
$      sfs
       1.0
$     isym    erosop
         1         1
$
*CONTACT_ERODING_SURFACE_TO_SURFACE
$     ssid      msid     sstyp     mstyp
         5         7         3         3
$     fric
       0.0
$      sfs
       1.0
$     isym    erosop
         1         1
$
*CONTACT_ERODING_SURFACE_TO_SURFACE
$     ssid      msid     sstyp     mstyp
         6         7         3         3
$     fric
       0.0
$      sfs
       1.0
$     isym    erosop
         1         1
$
*CONTACT_ERODING_SURFACE_TO_SURFACE
$     ssid      msid     sstyp     mstyp
         6         8         3         3
$     fric
       0.0
$      sfs
       1.0
$     isym    erosop
         1         1
$
*CONTACT_ERODING_SURFACE_TO_SURFACE
$     ssid      msid     sstyp     mstyp
         7         8         3         3
$     fric
       0.0
$      sfs
       1.0
$     isym    erosop
         1         1
$
```

```
*CONTACT_ERODING_SURFACE_TO_SURFACE
$     ssid      msid     sstyp     mstyp
         7         9         3         3
$     fric
       0.0
$      sfs
       1.0
$     isym    erosop
         1         1
$
*CONTACT_ERODING_SURFACE_TO_SURFACE
$     ssid      msid     sstyp     mstyp
         8         9         3         3
$     fric
       0.0
$      sfs
       1.0
$     isym    erosop
         1         1
$
*CONTACT_ERODING_SURFACE_TO_SURFACE
$     ssid      msid     sstyp     mstyp
         8        10         3         3
$     fric
       0.0
$      sfs
       1.0
$     isym    erosop
         1         1
$
*CONTACT_ERODING_SURFACE_TO_SURFACE
$     ssid      msid     sstyp     mstyp
         9        10         3         3
$     fric
       0.0
$      sfs
       1.0
$     isym    erosop
         1         1
$
*CONTACT_ERODING_SURFACE_TO_SURFACE
$     ssid      msid     sstyp     mstyp
         9        11         3         3
$     fric
       0.0
$      sfs
       1.0
$     isym    erosop
         1         1
$
*CONTACT_ERODING_SURFACE_TO_SURFACE
$     ssid      msid     sstyp     mstyp
        10        11         3         3
$     fric
       0.0
$      sfs
       1.0
$     isym    erosop
         1         1
$
*CONTACT_ERODING_SURFACE_TO_SURFACE
$     ssid      msid     sstyp     mstyp
        10        12         3         3
$     fric
       0.0
$      sfs
       1.0
$     isym    erosop
```

```
         1         1
$
*CONTACT_ERODING_SURFACE_TO_SURFACE
$     ssid      msid     sstyp     mstyp
        11        12         3         3
$     fric
       0.0
$      sfs
       1.0
$     isym    erosop
         1         1
$
*CONTACT_ERODING_SURFACE_TO_SURFACE
$     ssid      msid     sstyp     mstyp
        11        13         3         3
$     fric
       0.0
$      sfs
       1.0
$     isym    erosop
         1         1
$
*CONTACT_ERODING_SURFACE_TO_SURFACE
$     ssid      msid     sstyp     mstyp
        12        13         3         3
$     fric
       0.0
$      sfs
       1.0
$     isym    erosop
         1         1
*CONTACT_ERODING_SURFACE_TO_SURFACE
$     ssid      msid     sstyp     mstyp
        12        14         3         3
$     fric
       0.0
$      sfs
       1.0
$     isym    erosop
         1         1
$
*CONTACT_ERODING_SURFACE_TO_SURFACE
$     ssid      msid     sstyp     mstyp
        13        14         3         3
$     fric
       0.0
$      sfs
       1.0
$     isym    erosop
         1         1
$
*CONTACT_ERODING_SURFACE_TO_SURFACE
$     ssid      msid     sstyp     mstyp
        13        15         3         3
$     fric
       0.0
$      sfs
       1.0
$     isym    erosop
         1         1
$
*CONTACT_ERODING_SURFACE_TO_SURFACE
$     ssid      msid     sstyp     mstyp
        14        15         3         3
$     fric
       0.0
$      sfs
       1.0
```

```
$      isym     erosop
          1          1
$
*CONTACT_ERODING_SURFACE_TO_SURFACE
$      ssid       msid      sstyp      mstyp
        14         16          3          3
$      fric
        0.0
$       sfs
        1.0
$      isym     erosop
          1          1
$
*CONTACT_ERODING_SURFACE_TO_SURFACE
$      ssid       msid      sstyp      mstyp
        15         16          3          3
$      fric
        0.0
$       sfs
        1.0
$      isym     erosop
          1          1
$
*CONTACT_ERODING_SURFACE_TO_SURFACE
$      ssid       msid      sstyp      mstyp
        15         17          3          3
$      fric
        0.0
$       sfs
        1.0
$      isym     erosop
          1          1
$
*CONTACT_ERODING_SURFACE_TO_SURFACE
$      ssid       msid      sstyp      mstyp
        16         17          3          3
$      fric
        0.0
$       sfs
        1.0
$      isym     erosop
          1          1
*CONTACT_ERODING_SURFACE_TO_SURFACE
$      ssid       msid      sstyp      mstyp
        16         18          3          3
$      fric
        0.0
$       sfs
        1.0
$      isym     erosop
          1          1
$
*CONTACT_ERODING_SURFACE_TO_SURFACE
$      ssid       msid      sstyp      mstyp
        17         18          3          3
$      fric
        0.0
$       sfs
        1.0
$      isym     erosop
          1          1
$
*CONTACT_ERODING_SURFACE_TO_SURFACE
$      ssid       msid      sstyp      mstyp
        17         19          3          3
$      fric
        0.0
$       sfs
```

```
       1.0
$     isym    erosop
         1         1
$
*CONTACT_ERODING_SURFACE_TO_SURFACE
$     ssid      msid     sstyp     mstyp
        18        19         3         3
$     fric
       0.0
$      sfs
       1.0
$     isym    erosop
         1         1
$
*CONTACT_ERODING_SURFACE_TO_SURFACE
$     ssid      msid     sstyp     mstyp
        18        20         3         3
$     fric
       0.0
$      sfs
       1.0
$     isym    erosop
         1         1
$
*CONTACT_ERODING_SURFACE_TO_SURFACE
$     ssid      msid     sstyp     mstyp
        19        20         3         3
$     fric
       0.0
$      sfs
       1.0
$     isym    erosop
         1         1
$
*CONTACT_ERODING_SURFACE_TO_SURFACE
$     ssid      msid     sstyp     mstyp
        19        21         3         3
$     fric
       0.0
$      sfs
       1.0
$     isym    erosop
         1         1
$
*CONTACT_ERODING_SURFACE_TO_SURFACE
$     ssid      msid     sstyp     mstyp
        20        21         3         3
$     fric
       0.0
$      sfs
       1.0
$     isym    erosop
         1         1
$
*CONTACT_ERODING_SURFACE_TO_SURFACE
$     ssid      msid     sstyp     mstyp
        20        22         3         3
$     fric
       0.0
$      sfs
       1.0
$     isym    erosop
         1         1
$
*CONTACT_ERODING_SURFACE_TO_SURFACE
$     ssid      msid     sstyp     mstyp
        21        22         3         3
$     fric
```

```
       0.0
$      sfs
       1.0
$     isym    erosop
         1         1
$
*CONTACT_ERODING_SURFACE_TO_SURFACE
$     ssid      msid     sstyp     mstyp
        21        23         3         3
$     fric
       0.0
$      sfs
       1.0
$     isym    erosop
         1         1
$
*CONTACT_ERODING_SURFACE_TO_SURFACE
$     ssid      msid     sstyp     mstyp
        22        23         3         3
$     fric
       0.0
$      sfs
       1.0
$     isym    erosop
         1         1
$
*CONTACT_ERODING_SURFACE_TO_SURFACE
$     ssid      msid     sstyp     mstyp
        22        24         3         3
$     fric
       0.0
$      sfs
       1.0
$     isym    erosop
         1         1
$
*CONTACT_ERODING_SURFACE_TO_SURFACE
$     ssid      msid     sstyp     mstyp
        23        24         3         3
$     fric
       0.0
$      sfs
       1.0
$     isym    erosop
         1         1
$
*INITIAL_VELOCITY_GENERATION
$      sid      styp     omega        vx        vy        vz
         1         1                                     0.02
$       xc        yc        zc

$
*SET_PART
$    setid
         1
$     pid1
         1
$
*PART
$      pid       sid       mid
16 gr RCC
         1         1         1
 1st ply of KM2
         2         1         2
 2nd ply of KM2
         3         1         2
 3rd ply of KM2
         4         1         2
```

```
 4th ply of KM2
        5         1         2
 5th ply of KM2
        6         1         2
 6th ply of KM2
        7         1         2
 7th ply of KM2
        8         1         2
 8th ply of KM2
        9         1         2
 9th ply of KM2
       10         1         2
10th ply of KM2
       11         1         2
11th ply of KM2
       12         1         2
12th ply of KM2
       13         1         2
13th ply of KM2
       14         1         2
14th ply of KM2
       15         1         2
15th ply of KM2
       16         1         2
16th ply of KM2
       17         1         2
17th ply of KM2
       18         1         2
18th ply of KM2
       19         1         2
19th ply of KM2
       20         1         2
20th ply of KM2
       21         1         2
21st ply of KM2
       22         1         2
22nd ply of KM2
       23         1         2
23rd ply of KM2
       24         1         2
$
$Type 3 - Steel Impactor $$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
*MAT_PLASTIC_KINEMATIC
$      mid       rho         e        pr      sigy      etan      beta
         1      7.87  2.068395      0.29  0.010342       0.0       0.0
$      src       srp        fs
                        9999.0
$Type 1 - Fabric $$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
*MAT_ELASTIC
$      mid       rho         e        pr        da        db         k
         2     1.438   0.08325       0.2
$
$EROSION FOR FABRIC - TYPE1 $$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
*MAT_ADD_EROSION
$      mid      excl
         2    9999.0
$    pfail     sigp1     sigvm     epsp1     epssh     sigth   impulse
      99.0      99.0      99.0     0.200      99.0      99.0      99.0
$
*SECTION_SOLID
$      sid    elform
         1         1
$
$---+----1----+----2----+----3----+----4----+----5----+----6----+----7----+----8
$
*NODE
$node id               x               y               z      tc      rc
       1 1.926866323E-01 1.926866323E-01 0.000000000E+00       0       0
```

```
       2 1.601715088E-01 2.204571813E-01 0.000000000E+00       0       0
       3 1.237124354E-01 2.427993417E-01 0.000000000E+00       0       0
       4 8.420714736E-02 2.591629624E-01 0.000000000E+00       0       0
       5 4.262839630E-02 2.691451609E-01 0.000000000E+00       0       0
       6-1.056444709E-08 2.725000679E-01 0.000000000E+00       0       0
       7-4.262841865E-02 2.691451609E-01 0.000000000E+00       0       0
       8-8.420717716E-02 2.591629922E-01 0.000000000E+00       0       0
       9-1.237124726E-01 2.427993566E-01 0.000000000E+00       0       0
      10-1.601715535E-01 2.204572111E-01 0.000000000E+00       0       0
      11-1.926866323E-01 1.926866323E-01 0.000000000E+00       0       0
      12 2.204571813E-01 1.601715088E-01 0.000000000E+00       0       0
NOTE: THE MISSING NODES IN THIS ABBREVIATED DECK ARE HERE IN THE ACTUAL RUN
   78646-4.499999881E-01-1.000000000E+00 1.253960252E+00       0       0
   78647-5.000000000E-01-1.000000000E+00 1.253960252E+00       0       0
   78648-5.500000119E-01-1.000000000E+00 1.253960252E+00       0       0
   78649-6.000000238E-01-1.000000000E+00 1.253960252E+00       0       0
   78650-6.499999762E-01-1.000000000E+00 1.253960252E+00       0       0
   78651-6.999999881E-01-1.000000000E+00 1.253960252E+00       0       0
   78652-7.500000000E-01-1.000000000E+00 1.253960252E+00       0       0
   78653-8.000000119E-01-1.000000000E+00 1.253960252E+00       0       0
   78654-8.500000238E-01-1.000000000E+00 1.253960252E+00       0       0
   78655-8.999999762E-01-1.000000000E+00 1.253960252E+00       0       0
   78656-9.499999881E-01-1.000000000E+00 1.253960252E+00       0       0
   78657-1.000000000E+00-1.000000000E+00 1.253960252E+00       0       0
*ELEMENT_SOLID
       1       1       1       2      13      12     122     123     134     133
       2       1       2       3      14      13     123     124     135     134
       3       1       3       4      15      14     124     125     136     135
       4       1       4       5      16      15     125     126     137     136
       5       1       5       6      17      16     126     127     138     137
       6       1       6       7      18      17     127     128     139     138
       7       1       7       8      19      18     128     129     140     139
       8       1       8       9      20      19     129     130     141     140
       9       1       9      10      21      20     130     131     142     141
      10       1      10      11      22      21     131     132     143     142
      11       1      12      13      24      23     133     134     145     144
      12       1      13      14      25      24     134     135     146     145
NOTE: THE MISSING SOLID ELEMENTS IN THIS ABBREVIATED DECK ARE HERE IN THE ACTUAL RUN
   37789      24   76923   76924   76965   76964   78604   78605   78646   78645
   37790      24   76924   76925   76966   76965   78605   78606   78647   78646
   37791      24   76925   76926   76967   76966   78606   78607   78648   78647
   37792      24   76926   76927   76968   76967   78607   78608   78649   78648
   37793      24   76927   76928   76969   76968   78608   78609   78650   78649
   37794      24   76928   76929   76970   76969   78609   78610   78651   78650
   37795      24   76929   76930   76971   76970   78610   78611   78652   78651
   37796      24   76930   76931   76972   76971   78611   78612   78653   78652
   37797      24   76931   76932   76973   76972   78612   78613   78654   78653
   37798      24   76932   76933   76974   76973   78613   78614   78655   78654
   37799      24   76933   76934   76975   76974   78614   78615   78656   78655
   37800      24   76934   76935   76976   76975   78615   78616   78657   78656
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A Study of a Steel Right Circular Cylinder (RCC) Striking 23 Plies of KM2 Fabric Using the LS-DYNA Lagrangian Hydrocode

5. FUNDING NUMBERS
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6. AUTHOR(S)
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12a. DISTRIBUTION/AVAILABILITY STATEMENT
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12b. DISTRIBUTION CODE

13. ABSTRACT*(Maximum 200 words)*

A study was conducted to examine the terminal effects of a 1.0-g steel RCC impacting 23 plies of KM2 fabric using the LS-DYNA Lagrangian hydrocode. The simulated impact velocities were 200, 400, 600, 800, 1000, 1200, and 1400 m/s. The fabric was a plain weave of 850 denier yarn. The LS-DYNA-simulated V_s versus V_r data points generated at the U.S. Army Research Laboratory (ARL) were compared to both experimental data and EPIC-generated data. Also, the LS-POST software package was used to view the simulated physical descriptions of the penetrator and target at various stages of the penetration process.

14. SUBJECT TERMS
steel, right circular cylinder, RCC, KM2, fabric, LS-DYNA, Lagrangian hydrocode, striking velocity, residual velocity, simulation, impact, fragment, penetration

15. NUMBER OF PAGES
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