ARMY RESEARCH LABORATORY

Implementation of a Finite Strain Plasticity Model for Nylon 6/6 into DYNA3D

George A. Gazonas

ARL-RP-1

September 2000

A reprint from *Structures Under Shock and Impact VI*,
N. Jones and C. A. Brebbia, editors, WIT Press (2000), pp 523–535.

Army Research Laboratory

Aberdeen Proving Ground, MD 21005-5069

ARL-RP-1 September 2000

Implementation of a Finite Strain Plasticity Model for Nylon 6/6 into DYNA3D

George A. Gazonas

Weapons & Materials Research Directorate

A reprint from *Structures Under Shock and Impact VI*,
N. Jones and C. A. Brebbia, editors,
WIT Press (2000), pp 523–535.

Abstract

A fully three-dimensional rate and temperature dependent finite strain plasticity model for semicrystalline nylon 6/6, originally developed for finite inelastic deformation in metals, has been implemented in the explicit, Lagrangian finite element code DYNA3D. The model has been previously implemented into the implicit code NIKE2D for comparing the engagement process of nylon obturators relative to that of copper obturators. The DYNA3D material driver was used to verify model implementation for constant strain rate input histories by comparing true stress versus true strain results with predictions from Bammann's closed-form model and NIKE2D implicit finite element results. The material model is being used for modeling the interaction and erosion of the nylon 6/6 obturator band against a smoothbore gun tube during launch in 120-mm tank rounds. The adaptive slideline feature also permits modeling complex impact and penetration phenomena by calibrating the Lagrangian element erosion strains against carefully controlled penetration experiments into nylon 6/6 plates.

Relevance to the Army

Many kinetic energy projectiles rely on nylon-based materials to form an effective high-pressure seal against hot, rapidly expanding propellant gases. The seal is effected by obturator bands, which undergo high-rate pressurization, finite strain deformation, abrasion, and wear as they travel along gun tubes. A software model of the nylon material has been developed that is being used to predict the interaction and erosion of the nylon obturator band against a smoothbore gun tube during launch in 120-mm tank rounds. This software model will give designers information on tube wear that will enable them to minimize the wear on projectile systems.

This paper provides an overview of finite strain plasticity theory, describes the implementation of the model in the Lagrangian finite-element code DYNA3D, discusses model validation, and illustrates some simulation results.

Implementation of a finite strain plasticity model for Nylon 6/6 into DYNA3D

G.A. Gazonas
U.S. Army Research Laboratory
Weapons and Materials Research Directorate
Aberdeen Proving Ground, Maryland 21005, USA.

Abstract

A fully three-dimensional rate and temperature dependent finite strain plasticity model for semicrystalline nylon 6/6, originally developed for finite inelastic deformation in metals [2],[4], has been implemented in the explicit, Lagrangian finite element code DYNA3D [16]. The model has been previously implemented into the implicit code NIKE2D [10] for comparing the engagement process of nylon obturators relative to that of copper obturators [14]. The DYNA3D material driver was used to verify model implementation for constant strain rate input histories by comparing true stress versus true strain results with predictions from Bammann's closed-form model and NIKE2D implicit finite element results. The material model is being used for modeling the interaction and erosion of the nylon 6/6 obturator band against a smoothbore gun tube during launch in 120-mm tank rounds. The adaptive slideline feature also permits modeling complex impact and penetration phenomena by calibrating the Lagrangian element erosion strains against carefully controlled penetration experiments into nylon 6/6 plates.

1 Introduction

Modern kinetic energy projectiles rely upon nylon-based materials to form an effective high-pressure seal against hot, rapidly expanding propellant gases. The nylon obturator band undergoes high-rate pressurization, finite strain deformation, abrasion and wear as it travels along the gun-tube during the transient launch history lasting on the order of 10 ms. The oldest and most versatile form of nylon, Dupont Zytel® 101 or nylon 6/6, is the most commonly used nylon obturator material and is made by polymerization of hexamethylenediamine and adipic acid [7],[8], each of which contains 6 carbon atoms. Nylon 6/6 is a linear polymer consisting of monomers joined end-to-end in a line or chain, n-times,

$$\left[-HN - (CH_2)_6 - NH - \overset{O}{\overset{\|}{C}} -(CH_2)_4 - \overset{O}{\overset{\|}{C}} - \right]_n .$$

The binding energy between the chains are due to van Der Waals forces which are relatively weak, and the material easily softens as temperature is increased. Semicrystalline nylon 6/6 has excellent obturation properties by combining strength, moderate stiffness, high toughness, high resistance to impact and a relatively low coefficient of friction and abrasion resistance. In addition, nylon 6/6 is easily injection molded into a variety of shapes and sizes. The material is hygroscopic, readily absorbs moisture from the air, and equilibrates at 2.5% water at 50% relative humidity, and about 8.5% at 100% relative humidity [8]. This property can be problematic for use of nylon 6/6 in structures requiring tight tolerances such as tank rounds. This paper provides an overview of the finite strain plasticity theory, implementation of the model into DYNA3D, model validation, and illustration of some simulation results.

2 Constitutive assumptions

The finite strain plasticity model developed by Bammann [2] for characterizing the inelastic deformation of metals has been previously implemented in DYNA3D (model 38) using a set of internal state variables whose evolution is based upon micromechanical considerations. Both rate and temperature dependence is included in the constitutive description with plastic work being converted to heat which provides a mechanism for local material softening. Even though the microphenomenological deformation mechanisms in semicrystalline nylon differ considerably from that of metals, the gross deformation behavior of nylon appears "metal-like" in that nylon possesses strong rate and temperature dependence, and pressure independent yield behavior [15]. The original viscoplastic framework proposed by Bammann [2] is based upon the microphysical deformation mechanisms observed in metals, but the current nylon model is purely macrophenomenological in nature, and underscores the robustness of the general model. A full description of the large-deformation kinematics and the microscale to macroscale transition, based on dislocation dynamics, can be found in Bammann and Aifantis [3] where the deformation gradient is written as a multiplicative decomposition of elastic and plastic parts. The following kinematic/constitutive exposition essentially follows that found in [4]. The assumption of linear elasticity associated with this decomposition is given by,

$$\overset{o}{\sigma} = \lambda tr(D^e)1 + 2\mu D^e, \tag{1}$$

where λ, and μ are the Lame parameters, and the Cauchy stress σ is convected with the elastic spin W^e,

$$\overset{o}{\sigma} = \sigma - W^e\sigma + \sigma W^e. \tag{2}$$

Decomposing the velocity gradient $L = D + W$ into elastic and plastic parts, gives the elastic stretch D^e,

$$D^e = D - D^p, \tag{3}$$

and the elastic spin W^e,

$$W^e = W - W^p. \tag{4}$$

Within this framework, an additional equation is needed to describe the plastic spin W^p, which for the Jaumann stress rate (almost exclusively used in DYNA3D), implies that $W^p = 0$ (e.g., see discussion in reference [5]). Unfortunately, although the Jaumann stress rate is objective, it predicts a nonphysical oscillatory shear stress for bodies undergoing simple shear [9],[12] (Figure 1). In contrast to this behavior, the choice,

$$W^p = \frac{1}{2}R\left[\dot{U}U^{-1} - U^{-1}\dot{U}\right]R^T \tag{5}$$

recovers the objective Green-Naghdi stress rate [5] and predicts a monotonic increase in stress in bodies undergoing simple shear (Figure 2), with a minor correction to the equation in the original references [4],[5]. R and U are the rotation and right stretch tensors, respectively. The amplitude of dimensionless shear stress is nearly the same for both stress rate definitions to nearly 75% shear strain, compare e.g. Figures (1) and (2), which validates the implementation into DYNA3D.

The deviatoric flow rule is assumed to be of the form,

$$D^p = f(\theta)sinh\left[\frac{|\xi| - \kappa - Y(\theta)}{V(\theta)}\right]sgn(\xi'), \qquad \xi' = \sigma' - \alpha' \tag{6}$$

where θ is the temperature, k is a scalar hardening parameter, and ξ' is the difference between deviatoric Cauchy stress σ' and the tensor hardening variable α'. The evolution of the internal state variables α' and k are couched in a hardening minus recovery format,

$$\overset{o}{\alpha} = h(\theta)D^p - [r_d(\theta)|D^p| + r_s(\theta)|\alpha|]\,\alpha, \tag{7}$$

and,

$$\dot{\kappa} = H(\theta)|D^p| - [R_d(\theta)|D^p| + R_s(\theta)]\,\kappa^2. \tag{8}$$

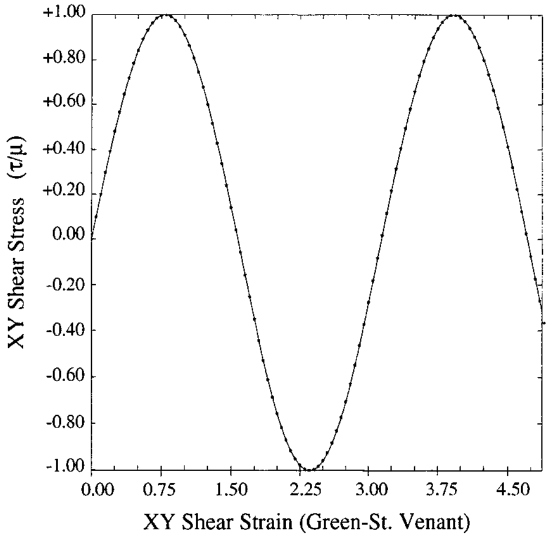

Figure 1: Dimensionless simple shear of a hypoelastic material (Jaumann stress rate); comparison of DYNA3D result ($* * *$) with closed-form result (—–) of Dienes [9].

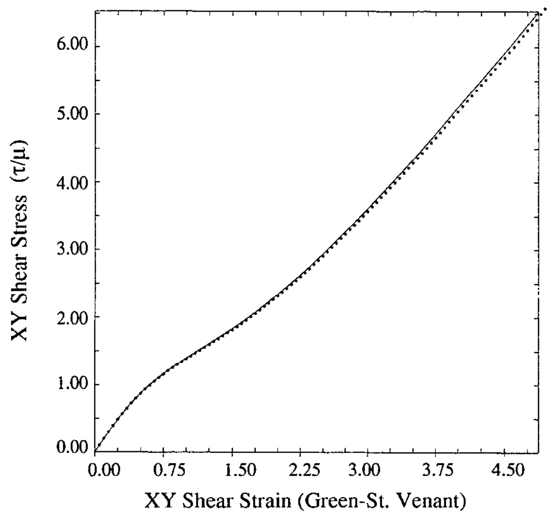

Figure 2: Dimensionless simple shear of a hypoelastic material (Green-Naghdi stress rate); comparison of **new** DYNA3D implementation ($* * *$) with closed-form result (—–) of Dienes [9].

The general theory admits nine temperature-dependent scalar exponential functions for yield $f(\theta)$, $Y(\theta)$, $V(\theta)$; hardening $h(\theta)$ and $H(\theta)$, and static/dynamic recovery $r_d(\theta)$, $r_s(\theta)$, $R_d(\theta)$, and $R_s(\theta)$. These equations are not reproduced here, but can be found in [5]. Heat flow is often neglected in simulating the physics of media undergoing rapid deformation, yet plastic work induces a local temperature increase that softens the material using the empirical expression,

$$\dot{\theta} = \frac{.9}{\rho C_v} (\sigma \cdot D^p) , \tag{9}$$

where ρ is the material density, and C_v is the specific heat.

2.1 Numerical implementation

For implementation into explicit codes such as DYNA3D (1994 version), deformation rates are used to predict stress, hence Eqn. (6) is inverted for stress. In addition, the theory is considerably simplified for application to nylon 6/6. In particular, the internal state variable evolution equations are simplified by removing the temperature dependence of the hardening functions $h(\theta) = k_1$, $H(\theta) = k_2$, by setting them equal to constant values. If all the recovery functions in (7) and (8) are set to zero, the theory predicts rate-dependent bilinear hardening behavior [4]. For application to nylon 6/6, two of the static/dynamic recovery functions $r_s(\theta) = R_d(\theta) = 0$ are set to zero. Finally, the deformation is restricted to purely kinematic hardening yield behavior. These modifications are necessary for empirically fitting experimental data obtained by Kawahara [13] to the theory outlined above. The details involving fitting the various parameters to the model are lengthy, and the interested reader is referred to the discussion in [4] for more specifics.

The numerical implementation into DYNA3D is verified using the code's material driver capability that permits evaluation of the constitutive behavior under specific user-defined load paths. For a bar in uniaxial tension under constant strain rate loading, excellent agreement is found between Bammann's closed-form result, an implicit implementation into NIKE2D, and the current explicit implementation in DYNA3D (Figure 3) at two temperatures 68 ^oF and 392 ^oF and 2% humidity. The strong temperature dependence of the flow stress seen in Figure (3) is governed principally by the temperature-dependent functions in Equation (6), rather than through those in the internal state variable evolution Equations (7) and (8).

3 Simulation results

The nylon 6/6 model is currently being used to simulate transient launch dynamics in 120 mm tank rounds. Rapid pressurization and deformation of the aft portion of a kinetic energy projectile (Figure 4) accelerates the projectile downbore, causing localized deformation, abrasion, and wear of

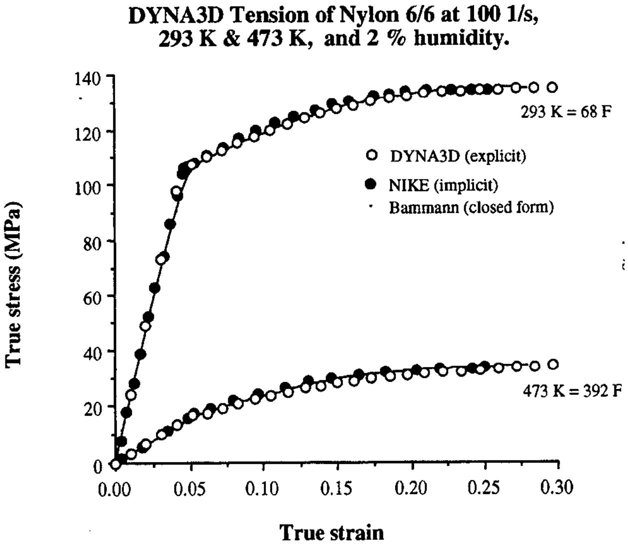

Figure 3: Validation of nylon 6/6 model implementation.

the nylon 6/6 obturator and other portions of the projectile in contact with the gun tube. Inclusion of the nylon 6/6 material model smoothes velocity transients seen within the first 4 ms of launch relative to prior models with linear elastic obturators (Figure 5). Despite this modeling improvement, a quantitative model for characterizing the erosion of the Lagrangian elements subject to abrasion in the gun tube is lacking. This information is needed for properly characterizing the frictional losses experienced by the projectile during the launch history.

An effort to improve our understanding of nylon 6/6 wear and erosion is currently underway using carefully controlled impact/penetration experiments into nylon 6/6 plates of various thickness and degree of humidity. An initial finite element model of an 8.26 g elastic steel ball, 0.5″ in diameter, V_0 = 3 km/s impacting a nylon 6/6 plate, 1 in thick, 12 x 12 in square, and weighing 2.68 kg consists of 87,374 nodes and 76,992 hexahedral elements, and costs about 1 CPU hr/10 solution μs on a Cray C90 (Figure 6). Crater topology, ballistic limit, exit velocity, exit crater topology and other impact/penetration metrics are strongly dependent upon the user-defined, equivalent plastic erosion strain $\bar{\varepsilon}^p$ level chosen in a particular simulation (Figure 7), (Figure 8), (Figure 9), hence it is imperative that carefully controlled impact/penetration tests be conducted to calibrate erosion strain. The slidesurfaces with adaptive new definitions (SAND) feature in DYNA3D was also modified to permit the penetration calculations.

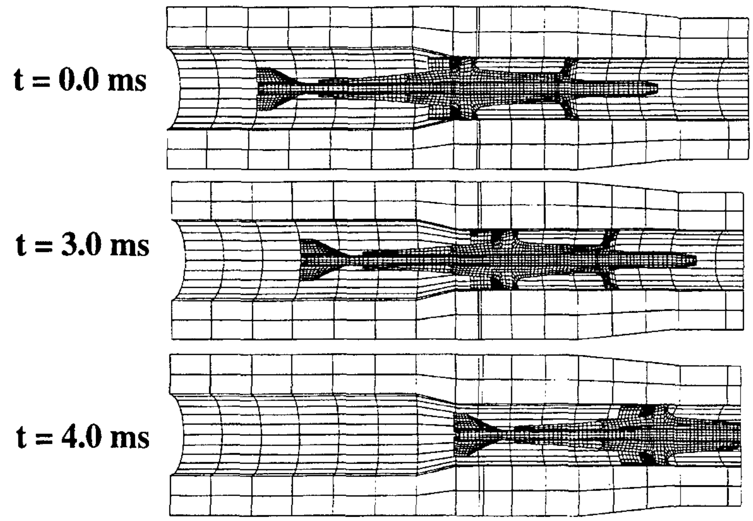

Figure 4: Kinetic energy projectile motion with nylon 6/6 obturator at $t = 0$ ms, $t = 3$ ms, and $t = 4$ ms (crossectional view).

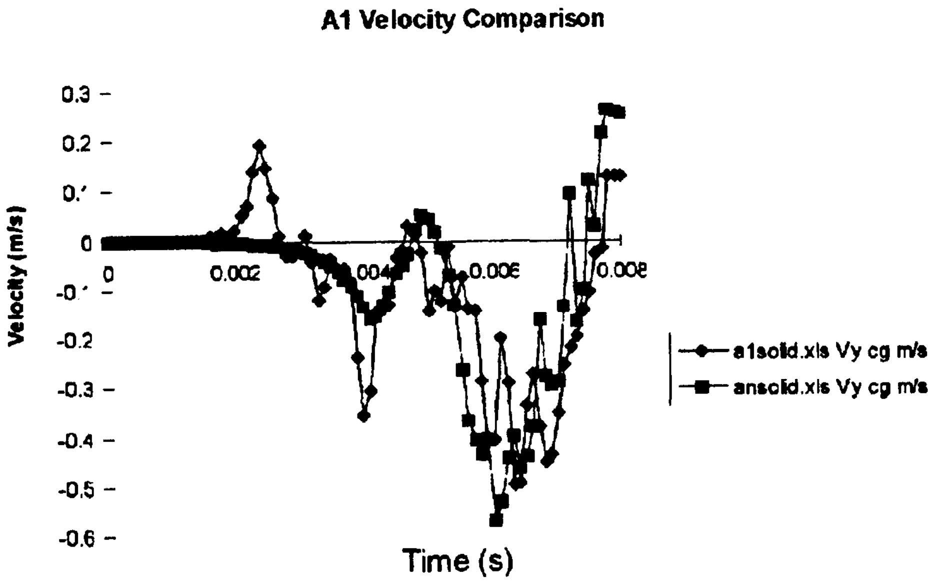

Figure 5: Vertical component of velocity history of projectile center of gravity, (cg); elastic (diamonds) vs nylon 6/6 (squares) obturator.

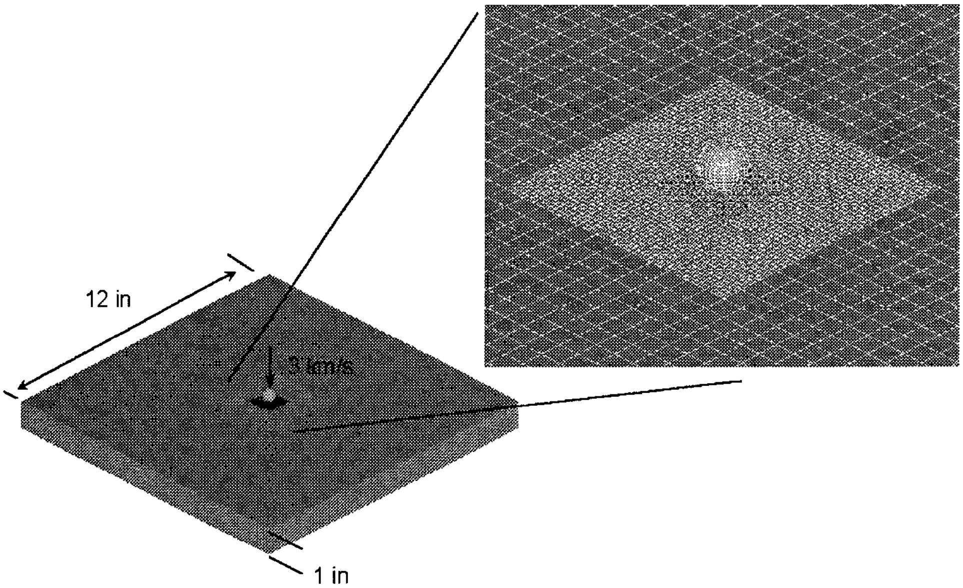

Figure 6: Steel ball penetration model in nylon 6/6 plate.

$\bar{\varepsilon}^p = 0.50$ $\bar{\varepsilon}^p = 3.00$

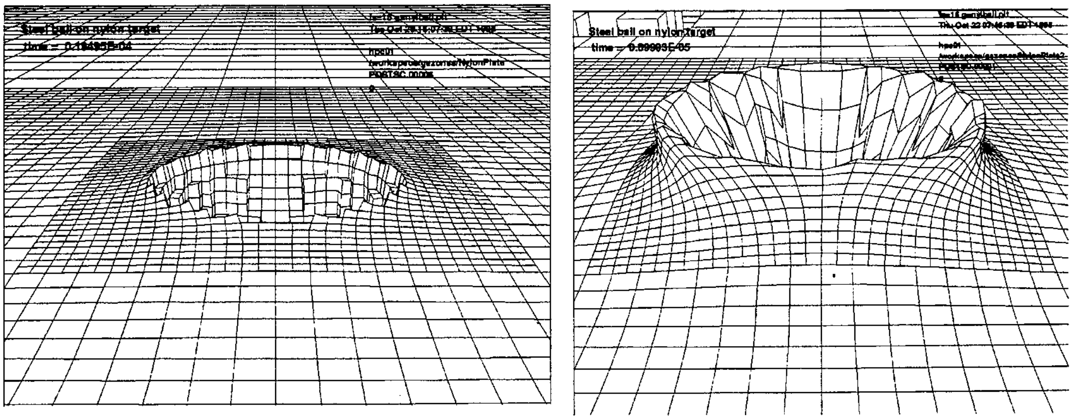

Figure 7: Influence of erosion strain $\bar{\varepsilon}^p$ level on crater formation in a nylon 6/6 plate.

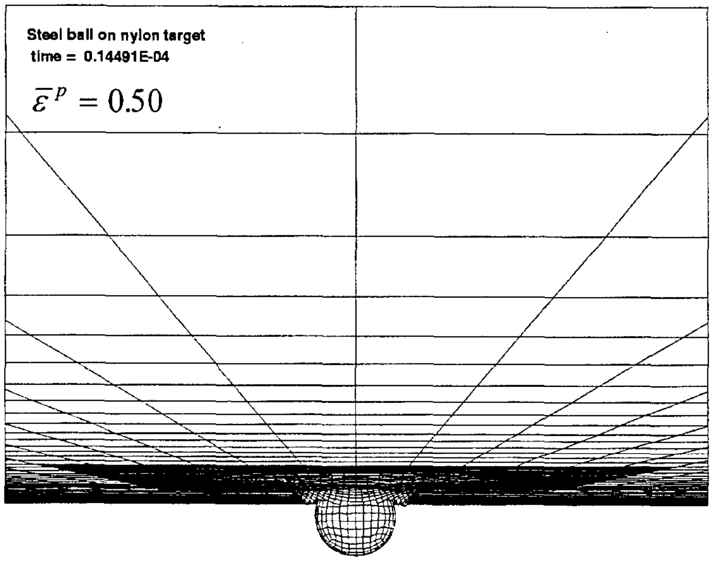

Figure 8: Steel ball exiting the bottom surface of a nylon 6/6 plate illustrating crater exit topology.

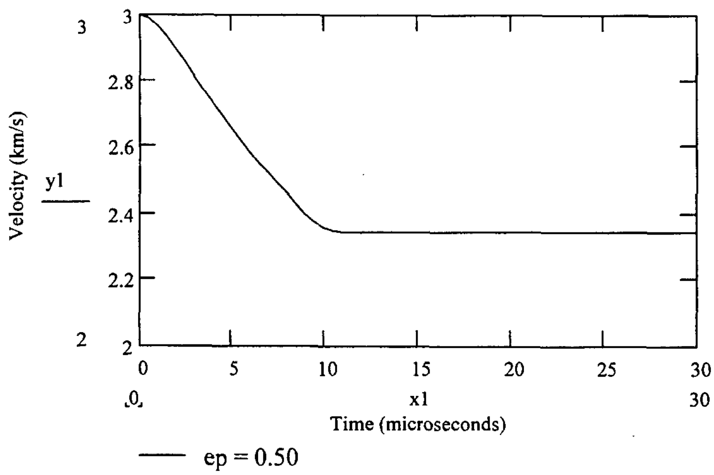

Figure 9: Velocity history of steel ball cg showing deceleration during penetration into a nylon 6/6 plate.

4 Summary

A rate and temperature dependent finite strain plasticity model for nylon 6/6 (Dupont Zytel® 101) that was originally developed for finite inelastic deformation in metals [2],[4], has been implemented in the explicit, Lagrangian finite element code DYNA3D [16]. The model has been previously implemented into the implicit code NIKE2D [10] for comparing the engagement process of nylon obturators relative to that of copper obturators [14]. Renewed interest in the mechanical behavior of nylon obturators [11] prompted this study, because of the materials' strongly hygroscopic behavior. Results were presented that demonstrated the validity of the nylon 6/6 model implementation with the closed-form results in [4], as well as implementation of a new Green-Naghdi stress rate in DYNA3D and its validation with the closed-from results in [9]. The importance of quantifying Lagrangian erosion strains were illustrated for problems involving friction, wear and penetration. The determination of proper user-defined erosion strains requires model calibration with experiments so that penetration metrics such as exit velocity and crater topology can be accurately modeled; such experiments are currently underway for nylon 6/6.

Another very important area of investigation would be the development of a microphenomenologically based internal state variable theory for the large-deformation of linear semicrystalline polymers much along the same lines as that presented by Bammann and Aifantis [3] for metals. Boyce [6] and Arruda et al [1] have made progress in this area and discuss microphysically based models for the large-deformation behavior of glassy polymers, such as PMMA. The theory is based upon both a scalar and second-order internal state variable formulation to describe polymer chain segment rotation and chain alignment, respectively, as microphysical mechanisms that contribute to plastic flow resistance in the polymer. Because the currently implemented model structure for nylon 6/6 is macrophysically based, this may pose severe limitations in the ability to extrapolate behavior in a predictive sense.

5 Acknowlegments

The author wishes to acknowledge Dr.'s Ken J. Perano and Paul E. Nielan (Sandia National Laboratories, Livermore, CA) for providing the nylon 6/6 material constants to the ARL, as well as Dr. Mike L. Chiesa (Sandia National Laboratories, Livermore, CA) for providing some useful coding suggestions relevant to the DYNA3D implementation. Dr. James F. Newill (US Army Research Laboratory, APG, MD) provided the mesh for the KE projectile simulations/analysis seen in Figures (4) and (5).

References

[1] Arruda, E.M., Boyce, M.C. & Jayachandran, R. Effects of strain rate, temperature and thermomechanical coupling on the finite strain deformation of glassy polymers, *Mechanics of Materials*, **19**, pp. 193-212, 1995.

[2] Bammann, D.J. An internal variable model of viscoplasticity, *International Journal of Engineering Science*, **22**, pp. 1041-1053, 1984.

[3] Bammann, D.J. & Aifantis, E.C., A model for finite-deformation plasticity, *Acta Mechanica* **69**, pp. 97-117, 1987.

[4] Bammann, D.J. Modeling temperature and strain rate dependent large deformation of metals, *Applied Mechanics Reviews*, **43**, pp. 312-319, 1990.

[5] Bammann, D.J., Chiesa, M.L., McDonald, A., Kawahara, W.A., Dike, J.J., & Revelli, D. Prediction of ductile failure in metal structures, *Failure Criteria and Analysis in Dynamic Response*, ed. H.E. Lindberg. ASME AMD, Vol. 107, pp. 7-12, November 1990.

[6] Boyce, M.C. Large inelastic deformation of glassy polymers, Ph.D. Thesis, *The Massachusetts Institute of Technology*, 1986.

[7] Clark, R.L., Kander, R.G., & Sauer, B.B. Nylon 66/poly(vinyl pyrrolidone) reinforced composites: 1. Interphase microstructure and evaluation of fiber-matrix adhesion, *Composites*, **30**, pp. 27-36, 1999.

[8] Design Handbook for Dupont Engineering Plastics, Module II Zytel and Minlon, E. I. duPont de Nemours & Company, Inc., Polymer Products Department, Wilmington, Delaware, 1999.

[9] Dienes, J.K. On the analysis of rotation and stress rate in deforming bodies, *Acta Mechanica*, **32**, pp. 217-232, 1979.

[10] Hallquist, J.O., NIKE2D-A vectorized implicit, finite deformation finite element code for analyzing the static and dynamic response or two-dimensional solids with interactive rezoning and graphics. Lawrence Livermore National Laboratory Report UCID-19677 Rev. 1, December 1986.

[11] Hoppel, C.P.R., Newill, J.F., & Soencksen, K.P. Evaluation of obturator and sealing cuff properties for the M865 training projectile with comparison to ballistic testing, U.S. Army Research Laboratory, ARL-TR-2039, September 1999.

[12] Johnson, G.C. & Bammann, D.J. A discussion of stress rates in finite deformation problems, *International Journal of Solids and Structures*, **20**, pp. 725-737, 1984.

[13] Kawahara, W.A., Brandon, S.L., & Korellis, J.S. Temperature, moisture and strain rate effects on the compressive mechanical behavior of nylon 6/6 Sandia National Laboratories, Livermore, California, SAND88, January 1988.

[14] Nielan, P. Finite element modeling of nylon 6/6 band engagement, in: Minutes of February 25, 1988 DA/DOE Program Review Meeting, 1988.

[15] Smith, M.T. & Patton, E.M. Evaluation of the deformation behavior of nylon materials used in ballistic applications, U.S. Army Ballistic Research Laboratory, BRL-CR-554, June 1986.

[16] Whirley, R.G. & Engelmann, B.E. DYNA3D user's manual, a nonlinear, explicit, three-dimensional finite element code for structural mechanics, Lawrence Livermore National Laboratory Report UCRL-MA-107254 Rev. 1, November 1993.

Distribution

Admnstr
Defns Techl Info Ctr
Attn DTIC-OCP
8725 John J Kingman Rd Ste 0944
FT Belvoir VA 22060-6218

DARPA
Attn L Christodoulou
Attn M Vanfossen
Attn S Wax
2701 N Fairfax Dr
Arlington VA 22203-1714

Defns Intelligence Agency
Attn TA-5 R Crelling
Washington DC 20310

Deputy Asst Scy for R&T
Attn SARD-TT
Rm 3EA79 the Pentagon
Washington DC 20301-7100

Ofc of the Secy of Dfns Joint CCD Test Force
Attn OSD-JCCD R Williams
3909 Halls Ferry Rd
Vicksburg MS 29180-6199

SERDP Program Ofc-PM P2
Attn B Smith
Attn C Pellerin
901 N Stuart Street Ste 303
Arlington VA 22203

Defns Nuclear Agency Innovative Concepts Div
6801 Telegraph Rd
Alexandria VA 22310-3398

Commander
Attn SMCWV-QAE-Q B Vanina Bldg 44
Attn SMCWV-SPM T McCloskey Bldg 253
Watervliet Arsenal
Watervliet NY 12189-4050

US Army TACOM
Abrams Testing
Attn SFAE-CGSS-W-AB-QT T Kraskiewicz
Warren MI 48397-5000

Armor School
Attn ATZK-TD A Pomey
Attn ATZK-TD J Berg
Attn ATZK-TD R Bauen
FT Knox KY 40121

Benet Lab
Attn AMSTA-AR-CCB G Friar
Attn AMSTA-AR-CCB G Spencer
Attn AMSTA-AR-CCB H Hasenbein
Attn AMSTA-AR-CCB J Vasilakis
Attn AMSTA-AR-CCB K Miner
Attn AMSTA-AR-CCB M Scavulo
Attn AMSTA-AR-CCB P Wheeler
Attn AMSTA-AR-CCB R Fiscella
Attn AMSTA-AR-CCB-R S Sopok
Attn AMSTA-AR-CCB-T G D'Andrea
Bldg 115
Watervliet NY 12189-4050

Dept of the Army OASARDA
Attn SARD-SO
103 Army Pentagon
Washington DC 20310-0103

Directorate of Combat Dev
Attn C Kjoro
320 Engineer Loop Ste 141
FT Leonard Wood MO 65473-8929

Cmdr
Hdqtrs Dept of the Army
Attn DAMI-FIT
Nolan Bldg
Washington DC 20301-0430

Hdqtrs IOC Tank Ammunition Team
Attn AMSIO-SMT R Crawford
Attn AMSIO-SMT W Harris
Rock Island IL 61299-6000

Natl Ground Intelligence Ctr
Attn IANG-TMT
220 Seventh Street NE
Charlottesville VA 22902-5396

PM Abrams Tank Sys
Attn SFAE-ASM-AB
Warren MI 48397-5000

Distribution (cont'd)

PM AFAS
Attn SFAE-ASM-AF
Picatinny Arsenal NJ 07806-5000

PM BFV
Attn SFAE-GCSS-W-BV S Davis
Warren MI 48397-5000

PM Field Artillery Sys
Attn SFAE-FAS-PM H Goldman
Attn SFAE-FAS-PM T McWilliams
Picatinny Arsenal NJ 07806-5000

PM Fighting Vehicle Sys
Attn SFAE-ASM-BV
Warren MI 48397-5000

PM Ground Sys Integration
Attn SFAE-CGSS-W-GSI R Labatille
Warren MI 48397-5000

PM Light Tactical Vehicles
Attn AMSTA-TR-S A J Mills
MS 209
Warren MI 48397-5000

PM Manager Tank Main Armament Sys
Attn SFAE-ASM-TMA-MS R Kowalski
Bldg 171A
Picatinny Arsenal NJ 07806-5000

PM RDT&E
Attn SFAE-GCSS-W-AB J Goodell
Attn SFAE-GCSS-W-GSI-H M Ryzyi
Warren MI 48397-5000

PM SADARM
Attn SFAE-GCSS-SD B Ellis
Attn SFAE-GCSS-SD J Pritchard
Attn SFAE-GCSS-SD M Devine
Attn SFAE-GCSS-SD S Hrownak
Attn SFAE-GCSS-SD W Demassi
Picatinny Arsenal NJ 07806-5000

PM Tactical Vehicles
Attn SFAE-TVH
Attn SFAE-TVL
Attn SFAE-TVM
Warren MI 48397-5000

PM TMAS
Attn SFAE-GSSC-TMA B Patter
Attn SFAE-GSSC-TMA C Roller
Attn SFAE-GSSC-TMA D Guzowicz
Attn SFAE-GSSC-TMA E Kopacz
Attn SFAE-GSSC-TMA J McGreen
Attn SFAE-GSSC-TMA K Kimker
Attn SFAE-GSSC-TMA L D'ulisse
Attn SFAE-GSSC-TMA R Darcy
Attn SFAE-GSSC-TMA R Mcdanolds
Attn SFAE-GSSC-TMA R Morris
Attn SFAE-GSSC-TMA R Roeser
Picatinny Arsenal NJ 07806-5000

PM US TACOM
Attn AMCPM-ABSM T Dean
Warren MI 48092-2498

TRADOC Sys Mgr Ags
Attn ATZK-TS S Jaburg
Attn ATZK-TS W Meinshausesen
FT Knox KY 40121-5000

US Army ARDEC
Attn AMSTA-AR-CCF-D J Gehbauer
Attn AMSTA-AR-CCH-A P Donadio
Bldg 65 S
Attn AMSTA-AR-CCL L Puzycki Bldg 65
Attn AMSTA-AR-AE-WW E Baker
Attn AMSTA-AR-AE-WW J Pearson
Attn AMSTA-AR-CC C Baulieu
Attn AMSTA-AR-CC G Payne
Attn AMSTA-AR-CC H Opat
Attn AMSTA-AR-CCH M Luciano
Attn AMSTA-AR-CCH P J Lutz
Attn AMSTA-AR-CCH R Carr
Attn AMSTA-AR-CCH-A E Logsden
Attn AMSTA-AR-CCH-A S Musali Bldg 65S
Attn AMSTA-AR-CCH-A T Louzeiro
Attn AMSTA-AR-CCH-A W Andrews
Attn AMSTA-AR-CCH-B C Knutson
Attn AMSTA-AR-CCH-B F Chang Bldg 65
Attn AMSTA-AR-CCH-B F Donlon
Attn AMSTA-AR-CCH-B G Eustice Bldg 65
Attn AMSTA-AR-CCH-B G Wagnecz
Attn AMSTA-AR-CCH-B P Valenti
Attn AMSTA-AR-CCH-B R Sayer Bldg 65
Attn AMSTA-AR-CCH-B S Patel

Distribution (cont'd)

US Army ARDEC (cont'd)
Attn AMSTA-AR-CCH-C H Chanin
Attn AMSTA-AR-CCH-C S Chico
Attn AMSTA-AR-CCL D Conway
Attn AMSTA-AR-CCL E Jaroszewski
Attn AMSTA-AR-CCL M Clune
Attn AMSTA-AR-CCL R Mchugh
Attn AMSTA-AR-CCL R Schlenner
Attn AMSTA-AR-FSA A Warnash
Attn AMSTA-AR-FSA B Machak
Attn AMSTA-AR-FSA M Chiefa
Attn AMSTA-AR-FSB-G D Carlucci
Attn AMSTA-AR-FSB-G M Schiksnis
Attn AMSTA-AR-FSE T Gora
Attn AMSTA-AR-M D Demella
Attn AMSTA-AR-M F Diorio
Attn AMSTA-AR-PSF T C Livecchia
Attn AMSTA-AR-QAC T D Rigoglioso
Bldg 354 M829E3 IPT
Attn AMSTA-AR-QACT/C C Patel
Attn AMSTA-AR-SRE D Yee
Attn SMCAR-ASF
Picatinny NJ 07806-5000

US Army ARDEC Industrial Ecology Ctr
Attn AMSTA-AR-WET T Sachar
Bldg 172
Picatinny NJ 07806-5000

US Army ARDEC Intelligence Specialist
Attn AMSTA-AR-WELL-F M Guerriere
Picatinny NJ 07806-5000

US Army ARDEC Production Base Modern Acty
Attn AMSMC-PBM-K
Picatinny NJ 07806-5000

US Army Armament RDE Ctr
Attn AMSTA-AR-FSP-I P Kisatsky
Picatinny NJ 07806-5000

US Army ATCOM Aviation Applied Tech Dir
Attn J Schuck
FT Eustis VA 23604

US Army Avn & Mis Cmnd Comanche Program Mgmt Ofc
Attn SFAE-RAH-TV D Caldwell
Bldg 5681
Redstone Arsenal AL 35898

US Army CECOM Night Vsn & Elec Sensors Directorate
Attn AMSEL-RD-NV-CM-CCD A Yingst
Attn AMSEL-RD-NV-CM-CCD R Adams
Attn AMSEL-RD-NV-CM-CCD R McLean
Attn AMSEL-RD-NV-VISP E Jacobs
10221 Burbeck Rd
FT Belvoir VA 22060-5806

US Army CERL
Attn R Lampo
2902 Newmark Dr
Champaign IL 61822

US Army Cold Regions Rsrch & Engr Ctr
Attn P Dutta
72 Lyme Rd
Hanover NH 03755

US Army Corp of Engrg
Attn CERD-C T Liu
Attn CERD-ET T Tan
20 Mass Ave NW
Washington DC 20314

US Army Field Artillery School
Attn ATFS-CD LTC Bumgarner
FT Sill OK 73503-5600

US Army Materiel Cmnd
Attn AMXMI-INT
5001 Eisenhower Ave
Alexandria VA 22333-0001

US Army Materiel Sys Analysis
Attn AMXSY-TD P Dietz
392 Hopkins Rd
Aberdeen Proving Ground MD 21005-5071

US Army Natl Ground Intel Ctr
Attn D Leiter
Attn H C Ardleigh
Attn J Crider
Attn J Gaston

US Army Natl Ground Intel Ctr (cont'd)
Attn M Holtus
Attn M Wolfe
Attn R Warner
Attn S Eitelman
Attn S Mingledorf
Attn W Gstattenbauer
220 Seventh Street NE
Charlottesville VA 22091

US Army SBCCOM
Attn Ballistics Team J Ward
Attn Bus Area Advocacy Team W Haskell
Attn Marine Corps Team J Mackiewicz
Attn SSCNC-WST S Beaudoin
Attn SSCNC-WST T Merrill
Attn SSCNC-WST W Nykvist
Kansas Street
Natick MA 01760-5019

US Army Sys Manager Abrams
Attn ATZK-TS LTC J H Nunn
Bldg 1002 Rm 110
FT Knox KY 40121

US Army TACOM
Attn AMSTA-JSK J Florence
Attn AMSTA-CS-SF H Hutchenson
Attn AMSTA-JSK J Thomson
Attn AMSTA-SF
Attn AMSTA-CS-SF F Schwarz
Attn AMSTA-JSK K Iyer
Attn AMSTA-TR-D B Raju
Attn AMSTA-TR-D D Ostberg
Attn AMSTA-TR-D L Hinojosa
Attn AMSTA-TR-R D Thomas
Attn AMSTA-TR-R (MS 202) R McClelland
Attn AMSTA-JSK S Goodman
Attn AMSTA-TR D Hansen
Attn AMSTA-TR J Chapin
Attn AMSTA-TR-R J Bennett MS263
Attn AMSTA-ZDB D Cochran
Warren MI 48397-5000

USAIC
Attn ATZB-COM LIC T J Cummings
FT Benning GA 31905-5800

Waterways Experiment
Attn D Scott
3909 Halls Ferry Rd SC-C
Vicksburg MS 39180

David Taylor Rsrch Ctr
Attn R Rockwell
Attn W Phyillaier
Bethesda MD 20054-5000

David Taylor Rsrch Ctr Ship Structures & Protectors Dept
Attn Code 1702 J Corrado
Bethesda MD 20084

Expeditionary Warfare Div
Attn N85 F Shoup
2000 Navy Pentagon
Washington DC 20350-2000

Nav Air Sys Cmnd
Attn J Thompson
48142 Shaw Rd Unit 5
Patuxent River MD 20670

Nav Rsrch Lab
Attn Code 63404 L Gause
Washington DC 20375

Nav Rsrch Lab
Attn Code 63404 R Badaliance
Attn Code 6383 I Wolock
Washington DC 20375-5000

Nav Surface Warfare Ctr
Attn CD 6551 C Williams
Attn U Sorathia
9500 Macarthur Blvd
West Bethesda MD 20817

Nav Surface Warfare Ctr
Attn Code 323 Tech Lib
Attn Code B02 M E Lacy
Attn Code G30 J H Francis
Attn Code G32 D Wilson
Attn Code G32 R D Cooper
Attn Code G33 E Rowe
Attn Code G33 J Fraysse
Attn Code G33 L De Simone
Attn Code G33 T Duran

Distribution (cont'd)

Nav Surface Warfare Ctr (cont'd)
Attn Dahlgren Div Code G06
Attn R Hubbard Code G33 C
17320 Dahlgren Rd
Dahlgren VA 22448

Nav Surface Warfare Ctr Carderock Div
Attn Code 1730 M Critchfield
Attn Code 2020 R Peterson
Bethesda MD 20084

Nav Surface Warfare Ctr Carderock Div
Attn Code 2802 R Crane
Attn Code 6553 C Williams
3A Leggett Cir
Annapolis MD 21402

Nav Surface Warfare Ctr Crane Div
Attn Code 20H4 M Johnson
Louisville KY 40214-5245

NAVSEA
Attn Code 91W2311 D Liese
Attn G Camponeschi
2531 Jefferson Davis Hwy
Arlington VA 22242-5160

Ofc of Nav Rsrch
Attn J Kelly
800 N Quincy Street
Arlington VA 22217-5000

Ofc of Nav Rsrch
Attn Code 315 D Siegel
800 N Quincy Street
Arlington VA 22217-5660

AFRL/MLBC
2941 P Street Rm 136
Wright Patterson AFB OH 45433-7718

AFRL/MLS-OL
Attn L Coulter
7278 4th Street Bldg 100 Bay D
Hill AFB UT 84056-5205

AFRL/MLSS
Attn R Thomson
2179 12th Street RM 122
Wright Patterson AFB OH 45433-7718

Wright Patterson AFB
Attn WL-MLBM F Abrams
Attn WL-MLBM J Brown
2977 P Street Ste 6
Dayton OH 45433

Marine Corps Intelligence Acty
Attn D Kositzke
3300 Russell Rd Ste 250
Quantico VA 22134-5011

US Dept of Energy Ofc of Environ
Management
Attn P Ritzcovan
19901 Germantown Rd
Germantown MD 20874-1928

Lawrence Livermore Natl Lab
Attn R Christensen
Attn S Deteresa
PO Box 808
Livermore CA 94550

Lawrence Livermore Natl Lab
Attn L 355 F Magness
Attn L 355 M Finger
Livermore CA 94550-0622

Lawrence Livermore Natl Lab
Attn L282 M Murphy
Livermore CA 94551-5554

Los Alamos Natl Lab
Attn MS B216 F Addessio
PO Box 1633
Los Alamos NM 87545

Oak Ridge Natl Lab
Attn MS 8048 C Eberle
Attn C D Warren MS 8039
PO Box 2009
Oak Ridge TN 37922

Oak Ridge Natl Lab
Attn R M Davis
PO Box 2008
Oak Ridge TN 37831-6195

Distribution (cont'd)

Sandia Natl Lab Applied Mechanics Dept
Attn Div 9042 J Handrock
Attn Div 9042 J Lauffer
Attn Div 9042 Y-R Kan
PO Box 969
Livermore CA 94550-0096

Central Intelligence Agency
Attn OTI/WDAG/GT W L Waltman
PO Box 1925
Washington DC 20505

FAA
Attn MIL-HDBK-17 CHAIR L Ilcewicz
1601 Lind Ave SW ANM-115N
Renton WA 98055

FAA Tech Ctr
Attn AAR 431 D Oplinger
Attn AAR 431 P Shyprykevich
Atlantic City NJ 08405

FHWA
Attn E Munley
6300 Georgetown Pike
McLean VA 22101

NASA Langley Rsrch Ctr
Attn T Gates MS 188E
Hampton VA 23661-3400

NIST Polymers Div
Attn D Duthinh MS 8611
Attn D Hunston MS 8543
Attn J Chin MS 8621
Attn J Dunkers
Attn J Martin MS 8621
Attn M Vanlandingham MS 8621
Attn R Parnas
Gaithersburg MD 20899

US DOT Fed Railroad
Attn RDV-31 M Fateh
Washington DC 20590

US DOT-FHWA
Attn J Scalzi
400 Seventh Street SW 3203 HNG-32
Washington DC 20590

Drexel Univ
Attn ASD Wang
32nd and Chestnut Streets
Philadelphia PA 19104

GA Inst of Techgy GA Techgy Rsrch Inst
Attn P Friederich
Atlanta GA 30392

Michigan State Univ
Attn R Averill
3515 EB MSM Dept
East Lansing MI 48824-1226

MIT
Attn P Lagace
77 Mass Ave
Cambridge MA 01887

North Carolina State Univ Civil Engrg Dept
Attn W Rasdorf
PO Box 7908
Raleigh NC 27696-7908

Pennsylvania State Univ
Attn R McNitt
Attn C Bakis
227 Hammond Bldg
University Park PA 16801

Pennsylvania State Univ
Attn R S Engel
245 Hammond Bldg
University Park PA 16802

Purdue Univ School of Aero & Astro
Attn C T Sun
W Lafayette IN 47907-1282

Royal Military College of Sci Shrivenham
Attn B Lawton
Attn D Bulman
Swindon Wilts SN6 8LA
United Kingdom

Southwest Rsrch Inst
Attn J P Riegel
6220 Culebra Rd
San Antonio TX 78228-0510

Distribution (cont'd)

Stanford Univ Dept of Aeronautics & Aeroballistics
Attn S Tsai
Durant Bldg
Stanford CA 94305

The Univ of Texas at Austin
J J Pickle Rsrch Campus
Attn Mail Code R7000 A Walls
Attn J Kitzmiller
Attn J Price
Center for Electromechanics
Austin TX 78712

UCLA Mane Dept Engr IV
Attn H T Hahn
Los Angeles CA 90024-1597

Univ of Austin Texas Inst for Advanced Techlgy
Attn T M Kiehne
Attn I Mcnab
Attn W Reinecke
Attn H Fair
Attn P Sullivan
4030 2 W Braker Lane
Austin TX 78759-5329

Univ of Dayton
Attn J M Whitney
College Park Av
Dayton OH 45469-0240

Univ of Dayton Rsrch Institute
Attn A K Roy
Attn R Y Kim
300 College Park Ave
Dayton OH 45469-0168

Univ of Delaware Ctr for Composite Materials
Attn D Heider
Attn D Kukich
Attn G Palmese
Attn J Gillespie
Attn M Santare
Attn S Advani
Attn S Yarlagadda
201 Spencer Lab
Newark DE 19716

Univ of IL at Urbana Champaign Natl Ctr for Composite Materials Rsrch
Attn J Economy
104 S Wright Street 216 Talbot Lab
Urbana IL 61801

Univ of Kentucky
Attn L Penn
763 Anderson Hall
Lexington KY 40506-0046

Univ of Maryland Dept of Aerospace Engrg
Attn A J Vizzini
College Park MD 20742

Univ of Utah Dept of Mech & Industrial Engrg
Attn S Swanson
Salt Lake City UT 84112

Univ of Wyoming
Attn D Adams
PO Box 3295
Laramie WY 82071

VA Polytechnical Institute & State Univ
Attn M W Hyer
Attn R Jones
Attn R Reifsnider
Dept of ESM
Blacksburg VA 24061-0219

AAI Corp
Attn T G Stastny
PO Box 126

Advanced Composite Materials Corp
Attn J Rhodes
Attn P Hood
1525 S Buncombe Rd
Greer SC 29651-9208

Advanced Glass Fiber Yarns
Attn T Collins
281 Spring Run Ln Ste A
Downington PA 19335

Aerospace Corp
Attn G Hawkins M4/945
2350 E El Segundo Blvd
El Segundo CA 90245

Distribution (cont'd)

Aerospatiale A/BTE/CC/RTE MD132
Attn S Andre
316 Route de Bayonne
Toulouse 31060
France

Alliant Techsystems Inc
Attn E Lynam
Attn J Condon
Attn J Gerhard
WV01 16 State RT 956 PO Box 210
Rocket Center WV 26726-0210

Alliant Techsystems Inc
Attn B See
Attn C Aakhus
Attn D Fisher
Attn M Hissong
Attn MN11-1428 C Candland
Attn R Becker
Attn R Copenhafer
Attn R Dohrn
Attn S Haglund
Attn V Vlahakus
Attn W Worrell
Attn D Kamdar
600 2nd Street NE
Hopkins MN 55343-8367

AMOCO Performance Products Inc
Attn M Michno Jr
4500 McGinnis Ferry Rd
Alpharetta GA 30202-3944

Amoco Polymers
Attn J Banisaukas
4500 McGinnis Ferry Rd
Alpharetta GA 30005

Applied Composites
Attn W Grisch
333 North Sixth Street
ST Charles IL 60174

Armtec Defns Prod
Attn S Dyer
PO Box 848
85 901 Ave 53
Coachella CA 92236

Arrow Tech Asso
1233 Shelburne Rd Ste D8
South Burlington VT 05403-7700

Battelle
Attn C R Hargreaves
505 Knight Ave
Columbus OH 43201-2681

Battelle Natick Ops
Attn B Halpin
Attn J Connors
209 W Central Street Ste 302
Natick MA 01760

Battelle NW DOE PNNL
Attn T Hall MS K231
Battle Blvd
Rickland WA 993652

Boeing
Attn R Bohlmann
PO Box 516 MC 5021322
ST Louis MO 63166-0516

Boeing Defns & Spc Grp
Attn S 4X55 J Russell
Attn S 4X55 W Hammond
PO Box 3707
Seattle WA 98124-2207

Boeing Douglas Products Div
Attn L J Hart-Smith
3855 Lakewood Blvd D800-0019
Long Beach CA 90846-0001

Boeing Rotorcraft
Attn P Handel
Attn P Mingurt
800 B Putnam Blvd
Wallingford PA 19086

Briggs Co
Attn J Backofen
2668 Peterborough St
Herndon VA 22071-2443

Distribution (cont'd)

Civil Aviation Administration
Attn T Gottesman
PO Box 8
Ben Gurion Intern'l Airport LOD 70150
Israel

Civil Engrg Rsrch Foundation
Attn H Bernstein
Attn R Belle
1015 15th Street NW Ste 600
Washington DC 20005

Composite Materials Inc
Attn R Holland
11 Jewel Court
Orinda CA 94563

Composite Materials Inc
Attn D Shortt
19105 63 Ave NE PO Box 25
Arlington WA 98223

Composix
Attn D Blake
Attn L Dixon
120 O'Neil Dr
Hebrun OH 43025

Conneaught Industries Inc
Attn J Santos
PO Box 1425
Coventry RI 02816

Custom Analytical Engrg Sys Inc
Attn A Alexander
13000 Tensor Lane NE
Flintstone MD 21530

Cytec
Attn M Lin
Attn W Web
1440 N Kraemer Blvd
Anaheim CA 92806

Cytec-Fiberite
Attn D Kohli
Attn M Gillio
Attn R Dunne

Cytec-Fiberite (cont'd)
Attn R Mayhew
1300 Revolution Street
Havre De Grace MD 21078

Daimler-Benz Aerospace
Attn J Bauer
Munchen Munich D-81663
Germany

Def Res Establishment Valcartier
Attn A Dupuis
2459 Blvd Pie XI North PO Box 8800
Courcelette Quebec GOA 1R0
Canada

Defense Research Estab
Attn F Lesage
PO Box 8800
Courcelette Quebec GOA 1R0
Canada

Defns Tech & Proc Agency Ground
Attn I Crewther
General Herzog Haus 3602 Thun
Switzerland

Deutsche Aerospace AG Dynamics Sys
Attn M Held
PO Box 1340
Schrobenhausen D 86523
Germany

DRA Fort Halstead
Attn D Scott
Attn M Hinton
Attn P N Jones
Sevenoaks Kent TN14 7BP
United Kingdom

DSTO Materials Rsrch Lab Nav Platform Vulnerability Ship Structures & Materials Div
Attn N Burman
PO Box 50
Ascot Vale Victoria 3032
Australia

Distribution (cont'd)

Dynamec Rsrch AB
Attn A Persson
Paradisgrnd 7 Sodertalje S 151 36
Sweden

Ecole Polytech
Attn J Manson
Lausanne DMX-LTC
Switzerland

Ecole Royal Militaire
Attn E Celens
Ave de la Renaissance
30 Bruxelle 1040
Belgique

Eichelberger Consultant
Attn R Eichelberger
409 W Catherine St
Bel Air MD 21014-3613

Ernst Mach Institut EMI
Attn A Stilp
Eckerstrasse 4 Freiburg 7800
Germany

Dir Ernst Mach Institut EMI
Hauptstrasse 18 Weil Am Rhein 79576
Germany

FOA Natl Defns Rsrch Estab
Attn B Janzon
Attn R Holmlin
Dir Dept of Weapons & Protection
Stockholm S 172 90
Sweden

Foster-Miller
Attn J J Gassner
Attn M Roylance
Attn W Zukas
195 Bear Hill Rd
Waltham MA 02354-1196

Gen Corp Aerojet
Attn C Flynn
Attn D Pillasch
Attn D Rubarezul
Attn M Greiner

Gen Corp Aerojet (cont'd)
Attn T Coulter
1100 West Hollyvale Street
Azusa CA 91702-0296

General Dynamics Amphibious Sys
Attn Survivability Lead G Walker
991 Annapolis Way
Woodbridge VA 22191

General Dynamics Land Sys Div
Attn D Bartle
PO Box 1901
Warren MI 48090

General Dynamics Land Sys Muskegon Ops
Attn W Sommers Jr
76 Getty Street
Muskegon MI 49442

General Synamics Land Sys
Attn D Rees
Attn M Pasik
PO Box 2074
Warren MI 48090-2074

GKN Aerospace
Attn D Olds
15 Sterling Dr
Wallingford CT 06492

GLCC Inc
Attn J Ray
Attn M Bradley
103 Trade Zone Drive Ste 26C
West Columbia SC 29170

Graphite Masters Inc
Attn J Willis
3815 Medford Street
Los Angeles CA 19335

Hercules Inc
Hercules Plaza
Wilmington DE 19894

Hexcel
Attn F Policelli
Attn J Poesch

Hexcel (cont'd)
Attn R Boe
PO Box 98
Magna UT 84044

Hexcel
Attn T Bitzer
11711 Dublin Blvd
Dublin CA 94568

IIT Rsrch Ctr
Attn D Rose
201 Mill Street
Rome NY 13440-6916

Institut Franco Allemand de Recherches de Saint Louis
Attn D M Giraud
5 Rue du General Cassagnou
Boite Postale 34 Saint Louis Cedex F68301
France

Israel Institute of Technology Faculty of Mechanical Engrg
Attn S Bodner
Haifa 3200
Israel

JPS Glass
Attn L Carter
PO Box 260 Slater Rd
Slater SC 29683

Lockheed Martin
Attn D/73-62, MZ 0648 S Reeve
8650 Cobb Dr
Marietta GA 30063-0648

Lockheed Martin
Attn R Fields
1195 Irwin CT
Winter Springs FL 32708

Lockheed-Martin Skunk Works
Attn D Fortney
1011 Lockheed Way
Palmdale CA 93599-2502

Loral Vought Sys
Attn G Jackson

Loral Vought Sys (cont'd)
Attn K Cook
1701 W Marshall Dr
Grand Prairie TX 75051

Materials Sciences Corp
Attn B W Rosen
500 Office Center Dr Ste 250
FT Washington PA 19034

MERL Ltd
Attn R Martin
Tamworth Rd
Hertford SG13 7DG
United Kingdom

Milliken Rsrch Corp
Attn H Kuhn
Attn M Macleod
PO Box 1926
Spartanburg SC 29303

Ministry of Defence Rafael
Attn M Mayseless
PO Box 2250
Armament Development Auth Haifa 31021
Israel

Northrop Grumman Environ Programs
Attn A Yen
Attn R Osterman
8900 E Washington Blvd
Pico Rivera CA 90660

Northrup Grumman Corp Elec Sensors & Sys Div
Attn E Schoch
1745A W Nursey Rd Mailstop V-16
Linthicum MD 21090

O'Gara-Hess & Eisenhardt
Attn M Gillespie
9113 Lesaint Dr
Fairfield OH 45014

Olin Corp
Attn L Whitmore
10101 9th Street North
ST Petersburg FL 33702

Distribution (cont'd)

Olin Corp Flinchbaugh Div
Attn B Stewart
Attn E Steiner
PO Box 127
Red Lion PA 17356

Pacific Northwest Lab
Attn M Smith
Attn G Van Arsdale
Attn K8-41 R Shippell
PO Box 999
Richland WA 99352

Pratt & Whitney
Attn D Hambrick
400 Main Street MS 114-37
East Hartford CT 06108

Projectile Technology Inc
515 Giles St
Havre De Grace MD 21078

Protection Materials Inc
Attn F Crilley
Attn M Miller
14000 NW 58 Ct
Miami Lakes FL 33014

PW Lay SMC Scotland
Attn D Rosyth
Rosyth Royal Dockyard
Dunfermline Fife KY11 2XR
United Kingdom

ROM Dev Corp
Attn R O'Meara
136 Swinburne Row Brick Market Place
Newport RI 02840

SAIC
Attn G Chryssomallis
3800 W 80th Street Ste 1090
Bloomington MN 55431

SAIC
Attn M Palmer
2109 Air Park Rd S E
Albuquerque NM 87106

Sikorsky
Attn B Kay
Attn G Jacaruso
Attn J Adelmann
Attn S Garbo
Attn T Carstensan
6900 Main Street PO Box 9729
Stratford CT 06601-1381

Simula
Attn J Coltman
Attn R Huylett
10016 S 51st Street
Phoenix AZ 85044

Sioux Mfg
Attn B Kriel
PO Box 400
FT Totten MD 58335

Swiss Federal Armaments Wks
Attn W Lanz
3602 Thun Allmendstrasse 86
Switzerland

Textron Sys
Attn M Treasure
Attn T Foltz
201 Lowell Street
Wilmington MA 08870-2941

TNO Defense Rsrch
Attn I H Pasman
Postbus 6006 JA Delft 2600
The Netherlands

TNO Prins Maurits Lab
Attn R Ijsselstein
PO Box 45
Lang Kleiweg 137 Rijswijk 2280 AA
The Netherlands

United Defns Limited Partners
Attn R Brynsvold
Attn MS170 P Janke
Attn MS236 T Giovanetti
Attn MS389 B Van Wyk
4800 East River Rd
Minneapolis MN 55421-1498

Distribution (cont'd)

United Defns Limited Partners
Attn PO Box 359 D Martin
Attn PO Box 58123 G Thomas
Santa Clara CA 95052-0359

United Defns Limited Partners
Attn A Lee Mail Drop N11
Attn M MacLean Mail Drop N06
Attn M Pedrazzi Mail Drop N09
1205 Coleman Ave
Santa Clara CA 95052-0359

United Defns Limited Partners
Attn R Barrett
Attn V Horvatich
328 W Brokaw Rd Mail Drop M53
Santa Clara CA 95052-0359

Zernow Techl Services
Attn L Zernow
425 W Bonita Ave Ste 208
San Dimas CA 91773

NASA Langley Rsrch Ctr Vehicle Techlgy Ctr
Attn AMSRL-VT F Bartlett Jr
Attn AMSRL-VT G Farley
Attn AMSRL-VT W Elber
Hampton VA 23681-0001

US Army Rsrch Lab
Attn AMSRL-CI
Attn AMSRL-CI-S A Mark
Attn AMSRL-CI-CB R C Kaste
Attn AMSRL-CI-HA W Sturek
Attn AMSRL-CS-IO-FI M Adamson
Attn AMSRL-SL-BL R Henry
Attn AMSRL-WM-BA F Brandon
Attn AMSRL-WM-BC D Lyon
Attn AMSRL-WM-BC J Newill
Attn AMSRL-WM-BC P Plostins
Attn AMSRL-WM-BD B Rice
Attn AMSRL-WM-BD R Fifer
Attn AMSRL-WM-BD R Pesce-Rodriguez
Attn AMSRL-WM-BD S Wilkerson
Attn AMSRL-WM-BE C Leveritt
Attn AMSRL-WM-BE D Kooker
Attn AMSRL-WM-M B Tanner
Attn AMSRL-WM-M D Viechnicki
Attn AMSRL-WM-M G Hagnauer

US Army Rsrch Lab (cont'd)
Attn AMSRL-WM-MA A Teets
Attn AMSRL-WM-MA D Flanagan
Attn AMSRL-WM-MA D Harris
Attn AMSRL-WM-MA G Rodriguez
Attn AMSRL-WM-MA L Ghiorse
Attn AMSRL-WM-MA N Beck-Tan
Attn AMSRL-WM-MA P Moy
Attn AMSRL-WM-MA P Patterson
Attn AMSRL-WM-MA P Touchet
Attn AMSRL-WM-MA R Shuford
Attn AMSRL-WM-MA R Yin
Attn AMSRL-WM-MA S McKnight
Attn AMSRL-WM-MA S Nguyen
Attn AMSRL-WM-MB B Fink
Attn AMSRL-WM-MB C Hoppel
Attn AMSRL-WM-MB D Granville
Attn AMSRL-WM-MB D Henry
Attn AMSRL-WM-MB D Hopkins
Attn AMSRL-WM-MB D Spagnuolo
Attn AMSRL-WM-MB E Wetzel
Attn AMSRL-WM-MB G Gazonas
Attn AMSRL-WM-MB J Bender
Attn AMSRL-WM-MB J Sands
Attn AMSRL-WM-MB J Tzeng
Attn AMSRL-WM-MB K Boyd
Attn AMSRL-WM-MB L Burton
Attn AMSRL-WM-MB M Klusewitz
Attn AMSRL-WM-MB M Leadore
Attn AMSRL-WM-MB P Dehmer
Attn AMSRL-WM-MB R Bossoli
Attn AMSRL-WM-MB R Dooley
Attn AMSRL-WM-MB R Lieb
Attn AMSRL-WM-MB R Rigas
Attn AMSRL-WM-MB S Cornelison
Attn AMSRL-WM-MB S Ghiorse
Attn AMSRL-WM-MB T Blanas
Attn AMSRL-WM-MB T Bogetti
Attn AMSRL-WM-MB W Drysdale
Attn AMSRL-WM-MB W Spurgeon
Attn AMSRL-WM-MC A Wereczcak
Attn AMSRL-WM-MC E Chin
Attn AMSRL-WM-MC J Beatty
Attn AMSRL-WM-MC J Lasalvia
Attn AMSRL-WM-MC J Montgomery
Attn AMSRL-WM-MC J Swab

US Army Rsrch Lab (cont'd)
Attn AMSRL-WM-MC J Wells
Attn AMSRL-WM-MD S Walsh
Attn AMSRL-WM-MD W Roy
Attn AMSRL-WM-T B Burns
Attn AMSRL-WM-T D Dietrich
Attn AMSRL-WM-TA B Gooch
Attn AMSRL-WM-TA E Horwath
Attn AMSRL-WM-TA J Runyeon
Attn AMSRL-WM-TA M Burkins
Attn AMSRL-WM-TA T Havel
Attn AMSRL-WM-TA W Bruchey
Attn AMSRL-WM-TA W Gillich
Attn AMSRL-WM-TC R Coates
Attn AMSRL-WM-TD A D Gupta
Attn AMSRL-WM-TD A Rajendran
Attn AMSRL-WM-TD M Boteler
Attn AMSRL-WM-TD M Raftenberg
Attn AMSRL-WM-TD T Haduch
Attn AMSRL-WM-TD T Moynihan
Attn AMSRL-WM-TD T Weerasooriya
Attn AMSRL-WM-TE J Powell
Attn AMSRL-WM-B A Horst
Attn AMSRL-WM-B E Schmidt
Attn AMSRL-WM-BC A Zielinski
Aberdeen Proving Ground MD 21005

US Army Rsrch Lab
Attn AMSRL-WM-TD F Gregory
Attn AMSRL-WM-BA W D'Amico
Attn AMSRL-WM-BD B Forch
Attn AMSRL-WM-BE G Wren
Attn AMSRL-WM-BF A Niiler
Attn AMSRL-WM-BR J A Bornstein
Aberdeen Proving Ground MD 21005-5066

US Army Rsrch Lab
Attn AMSRL-WM-BR C Shoemaker
Aberdeen Proving Ground MD 21005-5067

US Army Rsrch Lab
Attn AMSRL-SL-BA
Attn AMSRL-SL-B J Smith
Attn AMSRL-SL-BG A Young
Aberdeen Proving Ground MD 21005-5068

US Army Rsrch Lab
Attn AMSRL-SL-I
Attn AMSRL-WM-M J McCauley
Attn AMSRL-WM-TD D Dandekar
Aberdeen Proving Ground MD 21005-5069

Director
US Army Rsrch Ofc
Attn AMSRL-RO-D JCI Chang
Attn AMSRL-RO-P H Everitt
Attn AMSRL-RO-P A Crowson
Attn AMSRL-RO-P D Kisrow
Attn AMSRL-RO-P D Stepp
Attn AMSRL-RO-PM J Prater
Attn AMSRL-RO-E R E Singleton
Attn AMSRL-RO-EN G Anderson
PO Box 12211
Research Triangle Park NC 27709

US Army Rsrch Lab
Attn AMSRL-DD J M Miller
Attn AMSRL-CI-AI-R Mail & Records Mgmt
Attn AMSRL-CI-AP Techl Pub (3 copies)
Attn AMSRL-CI-LL Techl Lib (3 copies)
Attn AMSRL-IS J Chandra
Attn AMSRL-SE-DE R Reyzer
Attn AMSRL-SE-DS R Atkinson
Attn AMSRL-SE-L D Snyder
Attn AMSRL-SE-L D Woodbury
Attn AMSRL-SE-L J Desmond
Attn AMSRL-SE-L R Weinraub
Attn AMSRL-SE-R B Wallace
Attn AMSRL-SE-RE R Chase
Attn AMSRL-WM-MB A Abrahamian
Attn AMSRL-WM-MB A Frydman
Attn AMSRL-WM-MB E Szymanski
Attn AMSRL-WM-MB M Berman
Attn AMSRL-WM-MB T Li
Attn AMSRL-WM-MB W McIntosh
Adelphi MD 20783-1197

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE September 2000

3. REPORT TYPE AND DATES COVERED Reprint, Oct 1999 to Jul 2000

4. TITLE AND SUBTITLE Implementation of a Finite Strain Plasticity Model for Nylon 6/6 into DYNA3D

5. FUNDING NUMBERS
DA PR: AH80
PE: 622618

6. AUTHOR(S) George A. Gazonas

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Research Laboratory
Attn: AMSRL-WM-MB email: gazonas@arl.army.mil
Aberdeen Proving Ground, MD 21005-5069

8. PERFORMING ORGANIZATION REPORT NUMBER ARL-RP-1

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Research Laboratory
Aberdeen Proving Ground, MD 21005-5069

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
ARL PR:
AMS code: 622618H8011
A reprint from *Structures Under Shock and Impact VI*, N. Jones and C. A. Brebbia, editors, WIT Press (2000), pp 523–535.

12a. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

A fully three-dimensional rate and temperature dependent finite strain plasticity model for semicrystalline nylon 6/6, originally developed for finite inelastic deformation in metals, has been implemented in the explicit, Lagrangian finite element code DYNA3D. The model has been previously implemented into the implicit code NIKE2D for comparing the engagement process of nylon obturators relative to that of copper obturators. The DYNA3D material driver was used to verify model implementation for constant strain rate input histories by comparing true stress versus true strain results with predictions from Bammann's closed-form model and NIKE2D implicit finite element results. The material model is being used for modeling the interaction and erosion of the nylon 6/6 obturator band against a smoothbore gun tube during launch in 120-mm tank rounds. The adaptive slideline feature also permits modeling complex impact and penetration phenomena by calibrating the Lagrangian element erosion strains against carefully controlled penetration experiments into nylon 6/6 plates.

14. SUBJECT TERMS nylon 6/6, computational finite elements, finite deformation viscoplasticity, polymers, DYNA3D, impact, penetration, Green-Naghdi stress rate, Jaumann stress rate

15. NUMBER OF PAGES 32

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102