Using Nonlinear Optimization Methods to Reverse Engineer Liner Material Properties from EFP Tests

M. J. Murphy
E. L. Baker

This paper was prepared for submittal to
International Symposium on Ballistics
Jerusalem, Israel
May 21-24, 1995

February 27, 1995

This is a preprint of a paper intended for publication in a journal or proceedings. Since changes may be made before publication, this preprint is made available with the understanding that it will not be cited or reproduced without the permission of the author.
DISCLAIMER

This document was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor the University of California nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or the University of California, and shall not be used for advertising or product endorsement purposes.
DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.
USING NONLINEAR OPTIMIZATION METHODS TO REVERSE ENGINEER LINER MATERIAL PROPERTIES FROM EFP TESTS

Michael J. Murphy (1)*, Ernest L. Baker (2)

(1) LLNL, P.O. Box 808, L-282, Livermore, CA USA 94550
Tel: 510-423-7049, Fax: 510-422-2382, email: mjmurphy@llnl.gov

(2) U.S. Army ARDEC, Picatinny Arsenal, NJ USA 07806-5000
Tel: 201-724-5097, Fax: 201-724-2175, email: baker@aed.pica.army.mil

The utility of variable metric nonlinear optimization methods for reverse engineering liner material constitutive modeling parameters is described. We use an effective new code created by coupling the nonlinear optimization code NLQPEB with the DYNA2D finite element hydrocode. The optimization code determines the “best” set of liner material properties by running DYNA2D in a loop, varying the liner model constitutive parameters, and minimizing the difference between the EFP profiles of the calculation and experiment. The results of four different EFP warhead tests with the same copper liner material are used to determine material parameters for the Steinberg-Guinan, Johnson-Cook, & Armstrong-Zerilli models. In a companion paper we describe the successful application of this methodology to the forward engineering of liner contours to achieve desired EFP shapes. The methodology of utilizing a coupled optimization/finite element code provides a significant improvement in warhead designs and the warhead design process.

INTRODUCTION

The successful application of variable metric nonlinear optimization methods for determining EFP liner material properties is described in this paper. We start with the projectile shapes determined from 4 tests of similar EFP warheads with different liner geometries, but the same copper liner material. These experimental projectile profiles define the projectile shapes we expect the hydrocode to calculate. The optimization code determines the “best” set of liner material properties by running DYNA2D in a loop, varying the material properties, and minimizing the difference between the experimental EFP profile and the calculated EFP profile. The results of the 4 different EFP warhead tests are used to determine the “best” set of material properties for the Steinberg-Guinan, Johnson-Cook, and Armstrong-Zerilli with 2, 3, and 4 material parameters varied respectively. Excellent agreement between the experimental and calculated results are achieved for all three material models.

1 Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.
The nonlinear optimization part of the coupled code is based on NLQPEB [1,2] which uses a Broyden, Fletcher, Golddarfb, & Shanno variable metric sequential quadratic programming methodology [3] with a modified Powell merit function [4]. In our implementation, the optimization code treats DYNA2D [5] as a cost function. It supplies DYNA2D with material property parameters and DYNA2D returns a figure of merit, or cost, which is the squared error difference between the experimental result and the calculated result. The optimization code runs DYNA2D in a loop until it finds the "best" set of material parameters by minimizing the cost. In a companion paper [6] we describe the forward engineering of EFP liner contours to achieve desired EFP projectile shapes.

WARHEAD CONFIGURATION AND TEST RESULTS

The EFP warhead used in this study, developed and tested by Alliant Techsystems[7], has an 89 mm diameter with a L/D of 0.5. It contains 300 g of LX-14 and the average mass of the 4 copper liners is 82 grams. The velocities of the EFP projectiles from the 4 liners ranges from 2470 to 2530 m/s. A description of the warhead and simulated EFP formation process is shown in Figure 1.

![Figure 1. Description of warhead geometry and EFP formation process.](image)
Liner Material

The liner material used in the warhead is fabricated using a multi-step forge/anneal/coin process. The starting OFHC copper material is machined from ASTM-B-153 half hard bar stock. A forging process transforms the 20 mm thick by 25 mm diameter "puck" of copper into an 89 mm diameter flat plate with the desired liner thickness profile. The plate is annealed, followed by a multi-step coining process to achieve the desired liner curvature. The liner grain size ranges from 15µ to 20µ and the yield strength ranges from 60 MPa to 80 MPa.

Model Calibration & Experimental Results

In a previous study [8], we calibrated $Y_0$ and $Y_m$ of the Steinberg-Guinan model by systematically changing the material parameters until the calculated shape closely matched the experimental profile of the second liner design. The warheads with the 3 other liner designs were then calculated, with the "calibrated" material model parameters, and compared to the experimental results. A graphical comparison of the experimental projectile shape and calculated shape is shown in Figure 1. A tabulated comparison of the experimental projectile velocity and length to these "hand calibrated" calculated results is given in Table 1.

![Figure 2. Calculated and experimental EFP geometry's for 4 different liner designs.](image-url)
Table 1. Comparison of analysis and experimental results for the 4 EFP designs.

<table>
<thead>
<tr>
<th></th>
<th>design 1</th>
<th>design 2</th>
<th>design 3</th>
<th>design 4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>analysis</td>
<td>test</td>
<td>analysis</td>
<td>test</td>
</tr>
<tr>
<td>velocity (m/s)</td>
<td>2545</td>
<td>n/a</td>
<td>2544</td>
<td>2520</td>
</tr>
<tr>
<td>length (mm)</td>
<td>51</td>
<td>48</td>
<td>58</td>
<td>60</td>
</tr>
</tbody>
</table>

OPTIMIZATION CODE ANALYSIS

In order to demonstrate and evaluate the utility of the coupled optimization code/finite element code, we used it to re-determine the "best" set of material constitutive properties for the copper liners. As discussed above, we had previously calibrated $Y_0$ & $Y_m$ of the Steinberg-Guinan model and determined a set of parameters that matched the experiments. However, in that "hand" calibration study, only one of the four designs (# 2) was used to determine the liner material properties. We are now using the experimental results of all four of the liner designs to determine an "optimized" set of material parameters.

Material Models

The optimization code determined the "best" set of material parameters, for each of the material models, by matching the experimental and calculated shapes for all four of the liner designs. The optimization procedure was conducted three separate times to get the "best" set of material properties for the Steinberg-Guinan, Johnson-Cook, and Zerilli-Armstrong material models with 2, 3, & 4 material parameters varied respectively. We did not allow the code to vary all of the constitutive parameters for each material model. We calibrated a subset of the parameters that addressed strain hardening, strain rate hardening, and thermal softening.

The initial yield strength ($Y_0$) and maximum flow stress ($Y_m$) coefficients were the only parameters varied for the Steinberg-Guinan model. The initial yield ($A$), strain hardening ($B$), and strain rate hardening ($C$) coefficients were the only parameters varied for the Johnson-Cook model. For the Zerilli-Armstrong model, we allowed the optimization code to vary the yield ($C_0$), strain hardening ($C_2$), strain rate hardening ($C_4$), and thermal softening ($C_3$) coefficients. The portions of the 3 flow stress model equations that were used in the optimization process are given in equations 1, 2, & 3.

\[
Y = Y_0[1 + b \cdot (\varepsilon p)]^n \leq Y_m \quad \text{Steinberg-Guinan} \quad (1)
\]

\[
Y = [A + B \cdot (\varepsilon p)^n][1 + C \cdot \ln(\dot{\varepsilon})][1 - Tm] \quad \text{Johnson-Cook} \quad (2)
\]

\[
Y = C_0 + C_2 \sqrt{\varepsilon p} \cdot (\varepsilon)\left[ -C_3 T + C_4 T \cdot \ln(\dot{\varepsilon}) \right] + k \sqrt{\dot{\varepsilon}} \quad \text{Zerilli-Armstrong} \quad (3)
\]
Optimization Results

The optimization code varied the constitutive properties for each material model until the cost (difference between the calculated and experimental result) was minimized and a "best" set of properties was found. A comparison of the number of parameters varied, number of cycles required to complete the optimization (4 DYNA2D runs per cycle), initial cost value using the published baseline material properties, and the final minimized cost value obtained with the optimized parameters is shown in Table 2. The SG* material model, shown at the bottom of the table, is the cost value for the original set of material parameters we had previously determined without the optimization code. Each series of optimizations was conducted overnight on a SGI workstation. The hand calibrated SG* optimization took about 2 weeks.

<table>
<thead>
<tr>
<th>material model</th>
<th># of parameters</th>
<th># of cycles</th>
<th>baseline cost</th>
<th>minimized cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>SG</td>
<td>2</td>
<td>25</td>
<td>8.38</td>
<td>0.27</td>
</tr>
<tr>
<td>JC</td>
<td>3</td>
<td>46</td>
<td>0.68</td>
<td>0.35</td>
</tr>
<tr>
<td>ZA</td>
<td>4</td>
<td>56</td>
<td>3.99</td>
<td>0.24</td>
</tr>
<tr>
<td>SG*</td>
<td>2</td>
<td>-</td>
<td>8.38</td>
<td>0.40</td>
</tr>
</tbody>
</table>

Table 2. Comparison of the number of parameters varied, number of cycles required for optimization, baseline cost, and the final cost value for optimizing the three material models. The SG* values are for the previous hand calibration.

These results clearly indicate the utility of the optimization code for determining material model parameters. Our companion paper also demonstrates the viability of optimal EFP design using modern nonlinear optimization technology. Several additional observations can be made from the results presented in Table 2. The cost was reduced from the baseline cost for all materials, thus, providing a better analysis/experiment correlation. All of the new sets of parameters did better than the original hand calibrated SG set. The number of cycles goes up with the number of parameters varied. The Zerilli-Armstrong material model correlated best with the experiment. The baseline Johnson-Cook parameters were better than all of the other models. The baseline Steinberg-Guinan parameters are for half hard OFHC copper which is why its initial cost is so high. It is not clear why the Zerilli-Armstrong baseline cost is much higher than the Johnson-Cook baseline cost since both baseline sets of material properties are based on the same data.

A comparison of the final calculated EFP shapes and fringes of effective plastic strain for the 4 warhead designs using the 3 sets of optimized material parameters is given in Figure 3. When calibrated, all three of these material models are suitable for simulating the EFP formation and stretching process. The final EFP shapes and plastic strain contours are practically indistinguishable between the 3 models. A tabular comparison of the calculated EFP length and tail diameter for the different models with test results is given in Table 3. Again the SG* value is for the original set of matched parameters.
Figure 3. Comparison of the final calculated EFP shapes and fringes of effective plastic strain for the four 89 mm warhead designs using the optimized parameters for the SG, JC, & ZA material models.
Table 3. Comparison of the test results with the calculated EFP length and tail diameter using the optimized properties for the different material models.

<table>
<thead>
<tr>
<th>material model</th>
<th>design 1 (cm)</th>
<th>design 2 (cm)</th>
<th>design 3 (cm)</th>
<th>design 4 (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>length</td>
<td>48.0</td>
<td>60.0</td>
<td>59.0</td>
<td>67.5</td>
</tr>
<tr>
<td>diameter</td>
<td>28.0</td>
<td>24.0</td>
<td>23.4</td>
<td>23.0</td>
</tr>
<tr>
<td>TEST</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SG</td>
<td>51.4</td>
<td>59.5</td>
<td>60.3</td>
<td>65.6</td>
</tr>
<tr>
<td>diameter</td>
<td>32.4</td>
<td>26.2</td>
<td>26.8</td>
<td>25.6</td>
</tr>
<tr>
<td>JC</td>
<td>51.8</td>
<td>61.0</td>
<td>61.7</td>
<td>68.0</td>
</tr>
<tr>
<td>diameter</td>
<td>32.6</td>
<td>26.2</td>
<td>27.0</td>
<td>25.4</td>
</tr>
<tr>
<td>ZA</td>
<td>50.8</td>
<td>59.6</td>
<td>61.4</td>
<td>66.9</td>
</tr>
<tr>
<td>diameter</td>
<td>33.0</td>
<td>26.0</td>
<td>26.0</td>
<td>25.6</td>
</tr>
<tr>
<td>SG*</td>
<td>51.1</td>
<td>58.2</td>
<td>59.4</td>
<td>64.7</td>
</tr>
<tr>
<td>diameter</td>
<td>33.6</td>
<td>27.6</td>
<td>27.6</td>
<td>27.0</td>
</tr>
</tbody>
</table>

CONCLUSIONS

The utility of variable metric nonlinear optimization methods for reverse engineering liner material constitutive modeling parameters has been demonstrated. The new code created by coupling the nonlinear optimization code NLQPEB with DYNA2D is very effective and powerful. We applied the code to the reverse engineering of EFP liner material properties and obtained excellent correlation with experimental results using the Steinberg-Guinan, Johnson-Cook, & Armstrong-Zerilli models. We expect this methodology, utilizing a coupled optimization/finite element code, will significantly improve future warhead designs as well as the warhead design process.

REFERENCES


