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Consistent constitutive modeling of metallic target penetration using empirical, analytical, and numerical penetration models

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Abstract

Historically, there has been little correlation between the material properties used in (1) empirical formulae, (2) analytical formulations, and (3) numerical models. The various regressions and models may each provide excellent agreement for the depth of penetration into semi-infinite targets. But the input parameters for the empirically based procedures may have little in common with either the analytical model or the numerical model. This paper builds on previous work by Riegel and Anderson (2014) to show how the Effective Flow Stress (EFS) strength model, based on empirical data, can be used as the average flow stress in the analytical Walker–Anderson Penetration model (WAPEN) (Anderson and Walker, 1991) and how the same value may be utilized as an effective von Mises yield strength in numerical hydrocode simulations to predict the depth of penetration for eroding projectiles at impact velocities in the mechanical response regime of the materials. The method has the benefit of allowing the three techniques (empirical, analytical, and numerical) to work in tandem. The empirical method can be used for many shot line calculations, but more advanced analytical or numerical models can be employed when necessary to address specific geometries such as edge effects or layering that are not treated by the simpler methods. Developing complete constitutive relationships for a material can be costly. If the only concern is depth of penetration, such a level of detail may not be required. The effective flow stress can be determined from a small set of depth of penetration experiments in many cases, especially for long penetrators such as the L/D = 10 ones considered here, making it a very practical approach. In the process of performing this effort, the authors considered numerical simulations by other researchers based on the same set of experimental data that the authors used for their empirical and analytical assessment. The goals were to establish a baseline with a full constitutive model and to determine if the EFS could be estimated from a standardized constitutive model. We were unable to accomplish this. Several papers detailing simulations using the Johnson–Cook (JC) constitutive model were located and used as a basis for comparison. The authors were somewhat surprised to find that the JC parameters employed in those studies were not actually developed for the target materials that were evaluated experimentally. More disconcerting was the fact that a number of different sets of JC parameters were published for presumably the same material. Although not intended to be a critique of the JC model, this research raises a serious concern regarding the manner in which the model has been applied to terminal ballistics problems. The details of the study are included in this paper because the authors believe it helps put the discussion of EFS into proper context.
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1. Introduction

Mathematician and physicist John Von Neumann suggested that we should not be overly impressed when a complex model appears to match a data set quite well. "With four parameters I can fit an elephant, and with five I can make him wiggle his trunk" [1]. The significance and relevance of this statement will become clear as we discuss the constitutive models used in analyzing penetration problems. Briefly, the authors found it difficult to identify an appropriate constitutive model and parameters for numerical simulation of the experiments being considered. It was discovered that many researchers have applied the widely-used Johnson–Cook (JC) constitutive model using parameters that were not developed for the armor material actually used and appeared to be willing to simply adjust the five parameters until some reasonable agreement with experiments was achieved.

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This paper builds on work recently reported by Riegel and Anderson [2], Riegel [3], and Anderson and Riegel [4]. The success of this effort hinged on examining over 8000 penetration data points and utilizing the similitude analysis procedures practiced by Wilfred Baker, Peter Westine, and Franklin Dodge [5]. It is possible to use the Effective Flow Stress (EFS) as the consistent constitutive relationship in the development of (1) empirical formulations, (2) analytical models using first principles, and (3) fully discretized numerical solutions in the form of hydrocodes. In the empirical formulation the EFS is just that, the value of target flow stress that results in the best fit to penetration data. It is not a material property but can be considered a pseudo-property. For an elastic, perfectly plastic (von Mises) material, it is the plastic flow stress value.

The analytical penetration model used in this study is the Walker–Anderson Penetration (WAPEN) model [6]. It was a key to developing the EFS concept. The WAPEN model assumes conservation of momentum along the centerline of a normally impacting penetrator. It is a first principles model that defines a target flow field that matches numerically observed flow behavior. Because the model was developed by matching the flow fields predicted by hydrocodes, it is not surprising that WAPEN predicts penetration and flow field extent that match hydrocode results. In the original formulation of WAPEN, the flow field uses the average flow stress across the field. Walker subsequently developed a methodology to utilize the Johnson–Cook constitutive (strength) model to compute the flow stress [7]. Historically, the difficulty in determining the degree to which the WAPEN model agrees with hydrocode predictions stems from the need to use an average target flow stress for WAPEN and a complete constitutive model for the hydrocode. Complete constitutive models typically require at least four parameters to describe the stress–strain relationship of a material including strain rate and temperature effects. In the standard Johnson–Cook (JC) strength model [8], five parameters are needed. In addition to the standard JC model, there are a number of modified Johnson–Cook strength models; most add at least one additional term.

In the process of examining the available experimental data points and subsequently searching the literature for papers reporting numerical simulations of some of those experiments, most using the JC constitutive model, it became clear that researchers have selected wide ranging values of the JC coefficients for materials that appear to be the same. It is quite common for the papers to indicate that the JC values chosen allowed the simulations to match experiments to within some range, typically 5–20%. In virtually every case, the values used for the constitutive model were not values obtained for the tested target material. Rather, they were values selected for "similar" materials. With four, five, or even more "knobs" to turn, we are reminded of von Neumann's admonition not to be too surprised when we can tweak a complex model to get apparent agreement with a set of data.

Riegel previously determined the best "average" flow stress for a set of Hohler–Stilp experiments by running the WAPEN model against the set of experiments. The process employed to obtain the average flow stress is described in the paper by Riegel and Anderson [2]. The same value of average flow stress was then used as the effective flow stress to develop empirical relationships. In comparison of the empirical model and the WAPEN model with experiments, it is common to find the vast majority of the computed depths of penetration agree with the experiments to better than 10%.

The hypothesis behind this effort is, "A single value of flow stress can be used in empirical, analytical, and numerical models to compute penetration." The prior work has shown that the single flow stress value used as the EFS in an empirical formulation and that used as the average in the analytical WAPEN model agree well. To address the question within numerical simulations, the authors first repeated simulations using the Johnson–Cook constitutive model, as reported by Park [9], to demonstrate that the problem was properly defined and simulated. The authors then replaced the Johnson–Cook parameters used by Park with parameters reported by other researchers and finally replaced the Johnson–Cook constitutive model with a simpler von Mises strength model (bilinear with stress proportional to strain until yield, after which the stress is constant and equal to the effective plastic flow stress), using the value of EFS as the effective plastic flow stress.

This paper will review the material properties most relevant to metal on metal semi-infinite penetration as well as the Johnson–Cook constitutive model. The results of several numerical simulations of the Hohler–Stilp experiments will be presented. There is a need for a self-consistent set of semi-infinite penetration data that more completely documents the material properties and the penetration details such as crater diameter and the extent of the plastic flow field. The availability of such data would enable the development of better survivability and vulnerability models and improve understanding of the relationship between projectile and target strength, the influence of nose shape on rigid penetration, the transition to shattered or eroding penetration, and other physical relationships. One of the authors (Riegel) reviewed more than eight thousand data points, and it is clear that no such data set exists. The best data available today were collected in the 1970s. It is time for researchers to correct the situation by filling the gaps in the existing data.

Without a methodology to tie the ballistic performance to the properties of the target, and the properties of the target to the production variables such as the chemistry and heat treatment, the designer must resort to trial and error, often in the form of V50 testing, and then use statistical techniques to establish the appropriate layer thicknesses.

A brief review of the state of analytical and empirical modeling was included in Anderson and Riegel [4]. In brief, the discussion stated that Tate [10], and independently Alekseevskii [11], modified the Bernoulli equation to account for projectile strength and target resistance. It further noted that it is often necessary to let the target resistance change with velocity [12]. The review also stated that Winter [13], after reviewing a large number of regressions and analytical models, concluded that there were insufficient data to draw definite conclusions regarding the importance of target and projectile parameters. Likewise, a study by de Rosset and D'Amico [14] noted that

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