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AN IMPROVED METHOD TO MORE ACCURATELY ASSESS THE JOHNSON-COOK HIGH STRAIN-RATE DEFORMATION MATERIAL MODEL PARAMETERS - PART I

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ABSTRACT

Two relevant materials found in ground vehicle underbody armor/hull designs are Aluminum 2139-T8 and RHA Steel (Class I). These are 2 very important materials that need a thorough understanding of their high-strain rate behavior. The Johnson-Cook Deformation (JC-D) model at this time is the most preferred constitutive material model to utilize for high-strain (large deformation) blast simulations. The JC-D Model contains five empirically-based input parameters which can be determined traditionally through a series of uniaxial laboratory tests where each target parameter is isolated, while the remaining parameters are held constant. There are many criticisms and problems with this approach. The objective of this two part paper is to present and adopt a more accurate approach with less criticism to the determination of these five input parameters through both a sensitivity study to determine which input parameters are the most sensitive to a particular chosen response which in return will be utilized to conduct a numerical / empirical physics-based approach known as Numerical Optimization. Part 1 will focus on the sensitivity study while part 2 will focus on the optimization study and validations to determine optimal values for the JC-D Material Model Input Parameters. In part2, these optimized material input parameters will be leveraged to run shock tube simulations after which validations with various shock-tube blast load tests under various geometrical and or loading conditions such as plate thickness, pressure loading, boundary conditions, etc. will be made.

INTRODUCTION

As part of the Near-Term Under-Body Blast (NTUBB) Program initiated in 2012 which is currently ongoing, several research activities concerning many aspects of the Under-Body Blast of ground combat vehicles were commenced. This paper is concerned with the material characterization of those parts/areas (armor/hull) of the vehicle which are exposed to blast. The two most common materials leveraged in armor/hull designs are Aluminum 2139-T8 and RHA Steel Class I. When referring to Blast Modeling and Simulation (M&S), in order to properly characterize the behavior of these materials, inherent within these key areas / components of a vehicle under blast, it is imperative that a material model that is conducive to high-strain rate material behavior is adopted. The highly used material model which captures high-strain rate behavior is historically the Johnson-Cook (JCDM) Deformation Model.

The JCDM which was developed in 1983 [1] is a Viscous-Plastic deformation Model that considers the Von-Mises Yield Stress as a function of the strain hardening, strain-rate hardening, and the thermal softening. The theoretical model consists of 5 input parameters which are empirically-based. These input parameters can be determined through a series of uniaxial tests by isolating each target parameter while the others remain constant. Through a series of tests, empirically fit test data, and stochastics, a representative value for each target parameter can be found. These methods can be found in [1-4].

There are many criticisms and problems with this approach. As a result, this paper is concerned with a more accurate approach, with less criticisms which leads to a two-part sequential approach. The first part consists of a Global Sensitivity Study [5] which focuses on the 5 JCDM input parameters. Through M&S while implementing multiple iterations or variations of certain design variables, which in this case are the 5 JCDM input parameters obtained from the traditional series of uniaxial tests as mentioned above, and comparing the influence they have on specific responses under a blast event, it can be determined which input parameters have the largest influence on the response. Those parameters which have little or no influence on the response are ignored during the part 2 of this sequential process which is referred to as Numerical Optimization (NM).

Numerical Optimization which will be presented in part 2 of this paper seeks to minimize the error between simulated results and a chosen objective function formulated from experimental test results. The objective function utilized for this current research is extracted from the Shock-Tube testing of thin and thick plates performed by Michigan State University Composite Vehicle Research Center under ARO Services Contract No. W911NF-11-D-0001.

The optimization study is carried out considering only those input parameters which are most sensitive or have the most influence upon the response under a blast event. With these optimized material input parameters in hand, validations are made between M&S with various shock-tube blast load test results under various geometrical and or loading conditions such as plate thickness, pressure loading, boundary conditions, etc.

Through validation, it will be shown that this optimization methodology provides Johnson-Cook Deformation Parameters which are more accurate and applicable to underbody blast load simulations for AL2139-T8 and RHA Steel (Class I). This approach will not only provide for more accurate/improved simulation results but will provide a proven method for determining JC-D Input Parameters for other types of isotropic metals.

BACKGROUND ON MATERIAL MODELS

When considering M&S, the material characterization of the components crucial to the structural integrity of a ground combat vehicle under a blast event needs to be accurately represented from both the material type selected as well as the type of material model chosen when capturing the true representative deformation/failure behavior in an actual blast event.

There are two primary material deformation models widely utilized by Subject Matter Experts (SMEs) in various fields of endeavor, when conducting M&S of a blast event. They are: (1) The Johnson-Cook Deformation Model and (2) The Piecewise Linear Isotropic Deformation Model (PLIM). In LS-DYNA, they are referred to as MAT_015 and MAT_024, respectively. Based on the experience of SMEs, the JCDM is the preferred material model chosen to characterize high strain-rate behavior of a material component. It should be noted that there is also a Johnson-Cook Failure Model available to capture failure. Due to the complexities of accurately predicting failure as well as the inaccuracies of the Johnson-Cook Failure Model, Failure is not considered and is beyond the scope of this paper. Thus research work presented in this paper is limited to the preferred Johnson-Cook Deformation Model.

Mathematically, the Johnson-Cook Deformation Model Can be expressed as:

$$\sigma_y = \left(A + B\varepsilon_p^n\right)\left(1 + C\ln\dot{\varepsilon}^*\right)\left(1 - T^{*m}\right) \qquad (1)$$

Where,

$\sigma_y \equiv$ Von Mises Yield Stress

$\varepsilon_p \equiv$ Plastic Strain

$\dot{\varepsilon}^* \equiv$ Normalized strain – Rate Term

$T^* \equiv$ Dimensionless Temperature Term Defined By,

$$T^* = \frac{T - T_r}{T_m - T_r} \qquad (2)$$

Where T is the instantaneous temperature, T_r is the reference room temperature, and T_m is the melting temperature of the material. The input parameters which are material specific are:

$A \equiv$ *Strain hardening term*
$B \equiv$ *Strain hardening coefficient*
$n \equiv$ *Strain hardening exponent*
$C \equiv$ *Strain-Rate hardening coefficient*
$m \equiv$ *Thermal softening exponent*

These properties or input parameters which are material specific are considered to be isotropic and homogeneous throughout whole test samples. The reality is much more complex than this. Usually the material properties vary within and among various test samples. Due to defects at the micro and nano scale of a material sample, a widely-varied distribution of localized and globalized property values exist. As a result, averaging techniques are utilized among many test samples and should be regarded as an approximation when listed in material specification and or property tables within the literature.

Although there are a variety of sources from which to extract material data, for a specific material and material model, these varying sources may not all be consistent with one another, in regards to the their published material property values. Reasons could result from the testing methods utilized, the averaging/stochastic methods used, and or the amount and type of micro and nano defects that were present in the material samples. Additionally, the accuracy and precision of the test equipment, as well as, any residual/pre stress present would also play a role.

Due to this variability, a need has surfaced to determine more accurate and consistent input parameters to the JCDM resulting in increased accuracy and reliability in simulating a blast event. Within this two part paper, this goal is accomplished through a two part sequential process, first with a sensitivity study followed by an optimization study.

SENSITIVITY STUDY

In 2014, Shock-Tube testing of thin and thick plates was performed by Michigan State University Composite Vehicle Research Center under ARO Services Contract No. W911NF-11-D-0001 as part of the NTUBB (Near Term Under-Body Blast) M&S Enhanced Program within the Army. This research leverages these test results to perform both a sensitivity study and an optimization study to arrive at the most optimized JCDM input parameters for those which have the most influence on the response.

Shock-Tube Testing

Below in Figure 1, is a schematic of a shock-tube apparatus.

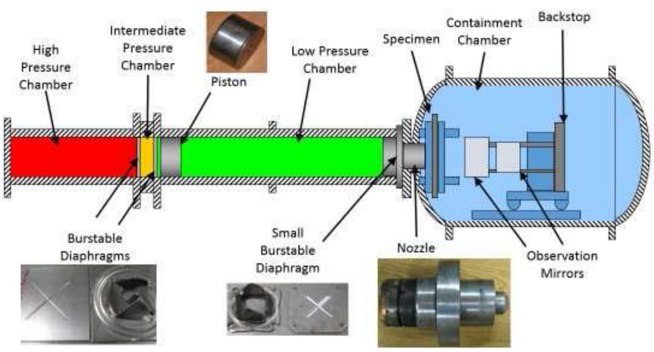

Figure 1. Schematic of a shock-tube with shock-tube components.

In brief, a shock-tube is an instrument used to replicate the effects of an actual explosion/blast with the residual effects. Basically in simplistic terms, a shock-wave is generated inside of the shock-tube, as a result of a high pressure differential between the pressure chambers, causing a diaphragm to burst resulting in a shock wave traveling down the shock-tube impacting the specimen.

As part of the experimental testing, circular plates composed of Aluminum 2139-T8 and RHA Steel Class 1were considered. Two different diameter sizes of 3in and 7in were leveraged. For each material type and testing diameter, plates with thicknesses of 0.0625in and 0.125in were loaded with various magnitudes of shock wave pressure profiles. In all, around 64 specimens were tested. Below in Figure 2, is a sketch/drawing of a 3in diameter plate specimen with a depiction of the bolt holes where the test specimen is mounted within the containment chamber. In Figure 3, below, is an actual picture/photo of a 3in diameter Aluminum 2139-T8 plate test specimen prior to testing.

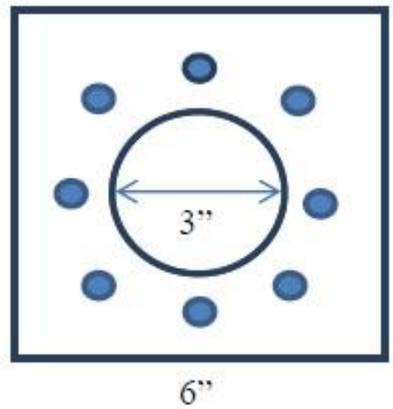

Figure 2. A drawing of a 3in diameter test specimen.

Figure 3. Photo of a 3in diameter AL 2139-T8 test specimen.

Without detailing the specifics of the testing, basically 6 different pressure profiles with various characteristics were applied to the test specimens. These characteristics are shown below in Table 1.

Pressure Profile Number	High pressure Chamber (psi)	Low Pressure Chamber (psi)	Piston Mass (kg)	Nozzle Diameter (in)	Peak Pressure (Mpa)	Total Duration (ms)	Output (kPa*s)
1	4600	450	8	1	62.7	12.38	416.4
2	4100	350	6	0.9	71.5	10.16	350.2
3	4100	300	4	0.9	90	7.68	277.6
4	4100	200	2	0.9	108.5	6.51	246.5
5	4100	100	1	0.9	123.2	3.98	146.5
6	4100	36	0.4	0.9	133.7	2.17	69.8

Table 1. Pressure profile characteristics

While the plot profiles are shown below, in Figure 4. The final results of the testing revealed that all of the aluminum specimens at 1/16in failed/ruptured due to the various pressure loadings. The 1/8in thick aluminum specimens did not fail. In contrast, none of the steel (RHA) specimens of either thickness failed with any of the pressure loadings.

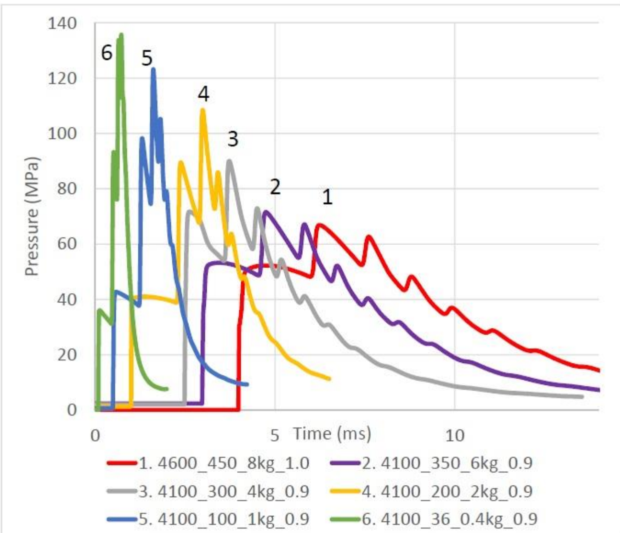

Figure 4. Pressure profiles associated with the various load cases.

To determine which input variables to the JCDM have the largest influence on various responses, a sensitivity study is carried out utilizing LS-OPT4.2 with LS_DYNA through simulating an FE model of MSU's shock-tube test apparatus. Two different materials are considered in this sensitivity study. They are RHA Class I and Aluminum 2139-T8.

Sensitivity Study-Modeling and Simulation

To understand the influence in which the Johnson-Cook Deformation Model input parameters have on the response of a chosen FE model under a loading event which induces a highly nonlinear high rate of strain internally, a sensitivity study needs to be conducted by simulating a chosen FE model multiple times with each simulation run containing iterations or large variations (+/- 15%) of the input parameters to obtain enough data on a particular response and how the particular response may vary depending the value of the input parameters utilized. Based on the formulations/equations from sensitivity theory, LS-OPT in conjunction with LS-DYNA is the most probable tool to use.

For this study, two cases were chosen from the shock-tube testing to develop and simulate a FE model. One was the 3in diameter test specimen at 1/8in thick for the Aluminum 2139T8 case. The other was the 3in diameter test specimen for the 1/16in thick for the steel (RHA) case. The finite element model is shown below in Figure 5.

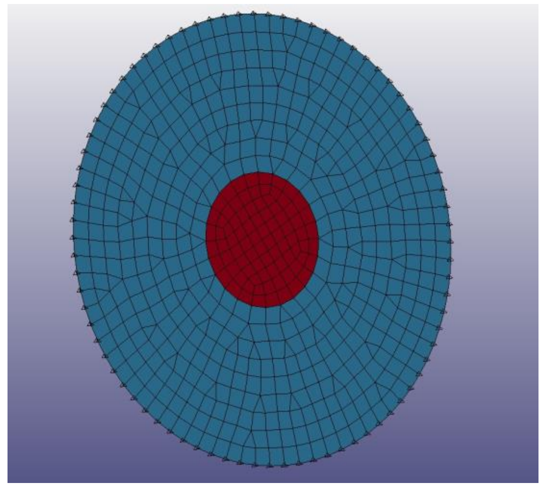

Figure 5. Shock tube finite element model.

Figure 5 shows a finite element of one of the 3in diameter test specimen. Around the outer circumference, the triangles depict the fixed boundary conditions representing the fact that the plate is bolted all around at that specific radially distance from the center of the plate. The red zone represents the 0.9in diameter section which is directly in front of the 0.9in diameter nozzle where the shock wave flows exits to impact the test specimen. The blue area is free to deform due to the shock wave impacting basically the red zone which is directly positioned in front of the nozzle. During processing of the model pressure profile 4 listed in table 1 above is applied as an external loading to both FE model cases (aluminum and RHA).

To run multiple simulations of this model for both material cases, taking into consideration the variations in the input parameters, LS-OPT4.2 is chosen as the tool to conduct the sensitivity study. LS-OPT4.2 connects with LS-DYNA to process the many simulations needed to determine the influential effects of chosen design variables on a particular response. For the two cases run multiple times, the variables chosen to determine their effect on the response were as follows:

1) AL2139-T8

   Variables: A, B, n, m

2) RHA Class 1(Steel):

Variables: A, B, n, C, m

It should be noted that the aluminum is insensitive to strain-rate hardening. The result in simplistic terms is that the parameter C=0. This is true for most aluminum materials. Therefore it is not considered for study in the case of aluminum. The upper and lower bounds for the variations of each variable were set at (+/- 15%). In all, 17 simulations were run for the aluminum 2139-T8 case; While 33 cases were run for the RHA material cases. The variations of each of the corresponding input parameters for each of the simulation runs are presented in tables 2 and 3 below.

Table 2 below provides the variations (Note: Actual numeric values are not provided) of the input parameters (design variables) for each simulation run for AL 2139-T8. Table 3. Provides the variations for RHA.

	Variables				Responses
Run	MatJCA	MatJCB	MatJCn	MatJCm	DefCntMx
1	Val 1	Val 1	Val 1	Val 1	Resp 1
2	Val 2	Val 2	Val 2	Val 2	Resp 2
3	Val 3	Val 2	Val 2	Val 2	Resp 3
4	Val 2	Val 3	Val 2	Val 2	Resp 4
5	Val 3	Val 3	Val 2	Val 2	Resp 5
6	Val 2	Val 2	Val 3	Val 2	Resp 6
7	Val 3	Val 2	Val 3	Val 2	Resp 7
8	Val 2	Val 3	Val 3	Val 2	Resp 8
9	Val 3	Val 3	Val 3	Val 2	Resp 9
10	Val 2	Val 2	Val 2	Val 3	Resp 10
11	Val 3	Val 2	Val 2	Val 3	Resp 11
12	Val 2	Val 3	Val 2	Val 3	Resp 12
13	Val 3	Val 3	Val 2	Val 3	Resp 13
14	Val 2	Val 2	Val 3	Val 3	Resp 14
15	Val 3	Val 2	Val 3	Val 3	Resp 15
16	Val 2	Val 3	Val 3	Val 3	Resp 16
17	Val 3	Val 3	Val 3	Val 3	Resp 17

Table 2. The variations in the JCDM input parameters for each simulation run for Aluminum2139-T8.

Through observation of the data in both tables it can be seen how the variations of the input parameters affect the maximum center displacements of the plate (DefCntMx).

	Variables					Responses
Run	MatJCA	MatJCB	MatJCn	MatJCm	MatJCC	DefCntMx
1	Val 1	Val 1	Val 1	Val 1	Val 1	Resp 1
2	Val 2	Val 2	Val 2	Val 2	Val 2	Resp 2
3	Val 3	Val 2	Val 2	Val 2	Val 2	Resp 3
4	Val 2	Val 3	Val 2	Val 2	Val 2	Resp 4
5	Val 3	Val 3	Val 2	Val 2	Val 2	Resp 5
6	Val 2	Val 2	Val 3	Val 2	Val 2	Resp 6
7	Val 3	Val 2	Val 3	Val 2	Val 2	Resp 7
8	Val 2	Val 3	Val 3	Val 2	Val 2	Resp 8
9	Val 3	Val 3	Val 3	Val 2	Val 2	Resp 9
10	Val 2	Val 2	Val 2	Val 3	Val 2	Resp 10
11	Val 3	Val 2	Val 2	Val 3	Val 2	Resp 11
12	Val 2	Val 3	Val 2	Val 3	Val 2	Resp 12
13	Val 3	Val 3	Val 2	Val 3	Val 2	Resp 13
14	Val 2	Val 2	Val 3	Val 3	Val 2	Resp 14
15	Val 3	Val 2	Val 3	Val 3	Val 2	Resp 15
16	Val 2	Val 3	Val 3	Val 3	Val 2	Resp 16
17	Val 3	Val 3	Val 3	Val 3	Val 2	Resp 17
18	Val 2	Val 2	Val 2	Val 2	Val 3	Resp 18
19	Val 3	Val 2	Val 2	Val 2	Val 3	Resp 19
20	Val 2	Val 3	Val 2	Val 2	Val 3	Resp 20
21	Val 3	Val 3	Val 2	Val 2	Val 3	Resp 21
22	Val 2	Val 2	Val 3	Val 2	Val 3	Resp 22
23	Val 3	Val 2	Val 3	Val 2	Val 3	Resp 23
24	Val 2	Val 3	Val 3	Val 2	Val 3	Resp 24
25	Val 3	Val 3	Val 3	Val 2	Val 3	Resp 25
26	Val 2	Val 2	Val 2	Val 3	Val 3	Resp 26
27	Val 3	Val 2	Val 2	Val 3	Val 3	Resp 27
28	Val 2	Val 3	Val 2	Val 3	Val 3	Resp 28
29	Val 3	Val 3	Val 2	Val 3	Val 3	Resp 29
30	Val 2	Val 2	Val 3	Val 3	Val 3	Resp 30
31	Val 3	Val 2	Val 3	Val 3	Val 3	Resp 31
32	Val 2	Val 3	Val 3	Val 3	Val 3	Resp 32
33	Val 3	Val 3	Val 3	Val 3	Val 3	Resp 33

Table 3. The variations in the JCDM input parameters for each simulation run for RHA Class I.

The particular response chosen as benchmark from which to measure against was the center node displacement at the center of the plate (DefCntMx in table 2 and 3). There are several analysis methods available for a sensitivity study. The focus in this paper, due to the simplicity, will be directed toward Sobol's indices method. Sobol's computational method is based on what is known as Meta models. Meta models provide an approximation of the response based on the variables used. From [5], based on the evaluation of the Meta model, the Sobol's indice, S_i of variable υ_i is computed from (Also see [6-8])

$$S_i = \frac{\text{variance caused by } \upsilon_\text{i}}{\text{total variance of response}}. \qquad (3)$$

As a check, the sum of all of the Sobol's indices in regards to one response is equal to 1. This can be expressed mathematically as,

$$\sum_{i=1}^{n} S_i = 1 \qquad (4)$$

Where n is equal to the number of variables. Through the use of Sobol's indices. In LS-OPT, Sobol's indices are represented as horizontal bars. There are 2 numbers or percentages preceding the horizontal bars. The first number is the Sobol's indice; while the second number represents the cumulative Sobol's indice. The cumulative indices of all of the variables should add up to 1.

Post-Processing of the results for the aluminum revealed that the strain hardening term, *A* had the largest influence on the response or the center displacement of the plate at 72.4% followed by the strain hardening coefficient, *B* at 18.1%, the strain hardening exponent, *n* at 8.1%, and finally the thermal softening exponent, *m* at 1.4%. With the thermal softening exponent only having a 1.4% influence, it can be regarded as having little influence. Therefore, it can be concluded that the influential players on the response for Aluminum 2139-T8 are the parameters *A*, *B*, *n*. The Global Sensitivities Plot depicting these results are shown below, in figure 6.

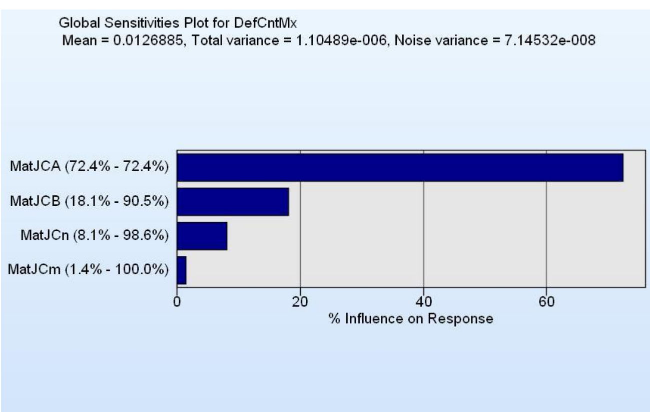

Figure 6. Global Sensitivity Plot depicting the influence of each parameter on the response for Aluminum2139-T8.

This information can be represented in a transpose /composite form as shown in Figure 7.

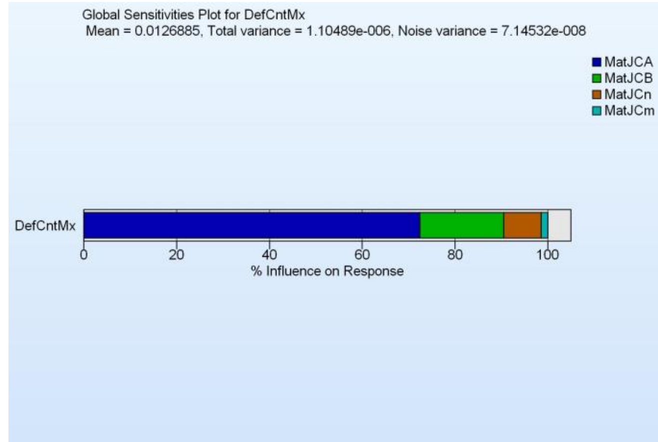

Figure 7. Counterpart to Figure 6 in transpose form.

The entire influence of each parameter is depicted on one horizontal bar which is color coded according to the percent influence of each variable.

For the case of RHA Class 1 (Steel) the order of influence is *n*, *B*, *C*, *A* with *m* neglected due to its negligible influence on the response. This is shown in the Global Sensitivities Plot, in Figure 8.

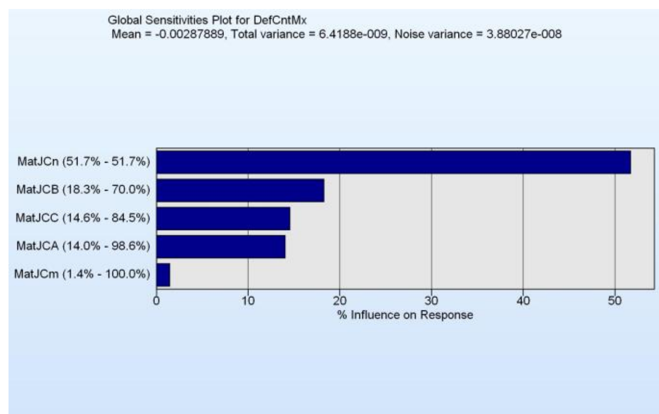

Figure 8. Global Sensitivity Plot depicting the influence of each parameter on the response for RHA Class 1.

The transpose form of Figure 8 is depicted in Figure 9 where again the percent influence of each variable is color coded on one horizontal bar. In addition to the plots providing the influence each variable has on the chosen response, it is also evident, that for each of the two materials, the order and percentage of influence with regards to each variable can differ depending on the material type and most likely the response under concern.

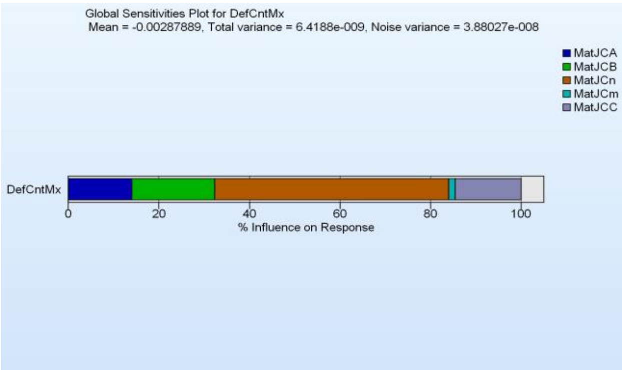

Figure 9. Counterpart of Fig. 8 in transpose form.

OPTIMIZATION STUDY-PART II

Part 2 will be the subject of another paper to follow which will utilize the results from this paper (Part I) to conduct an comprehensive optimization study utilizing these shock tube FE models only seeking to optimize those variables which have influence on the response, for each of the two material cases (Aluminum and RHA). For the Aluminum case, only the three variables *A*, *B*, *n* need to be optimized because of their sensitive nature of influence. For the case of RHA, only the four variables *n*, *B*, *C*, *A* need to be included. For those variables which showed little or no influence, the standard values found in the literature will be used.

Following a comprehensive optimization study, validation and verification studies will also be performed in part 2 where various simulation runs, utilizing the optimized input parameters, will be compared to the test results. The validations will take into account enough variations in the geometrical aspects of the plate specimens to obtain a more accurate analysis of the validations.

SUMMARY

In this paper, a comprehensive analysis has been presented regarding a sensitivity study to determine which variables within the Johnson-Cook Deformation Model have the most influence on the response. The background information on the material model, the parameters under study, a description of the process, the underlying theory, as well as the computational results of a sensitivity study have been presented.

The goals and purpose of each step in the process have been explained. The results for the Aluminum 2139-T8 revealed that only 3 of the five variables have a measureable effect on the response; while the results for the RHA showed 4 of the variables had influence on the response. Also, the order of their influence between both material cases differed.

Part 2 will be continuation of this paper leading into the optimization study followed by validations, and a final analysis of the results.

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