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Computational Ballistic Performance of Metal Panel using Different Material Constitutive Models

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Abstract: This study presents the computational-based ballistic performance of metallic panel using different constitutive material models. Finite element model of metallic panel was constructed using a commercial software package reliable for high velocity impact. Three different constitutive models were utilized in the finite element analysis: Cowper-Symonds, Johnson-Cook and Zerilli-Armstrong model. The target steel panel was subjected to projectile velocity in a range of 750 msec^{-1}- 950 msec^{-1} and the residual velocity resulting from each constitutive model was quantified and compared with data from previous experiment. Cowper-Symonds model exhibited largest percentage difference of 10.3 and Johnson-Cook model was fitted the best with the experimental data at percentage difference of 1.9. This finding will be later used for investigating the performance of various types of metallic materials under high velocity impact.

Key words: Metallic, materia, panel, softwarre, models

INTRODUCTION

Recently, there has been significant growth in utilizing computational methods to study the ballistic performance of various types of metal panels (Flores-Johnson *et al*., 2011). Computational method has decreased the needs of expensive and time consuming experimental work on ballistic. Computational methods have been used to predict the performance of ballistic resistant panels by several authors. Dey *et al*. (2004) also used simulation to predict the behaviour of double-layered steel plates impacted by ogive projectile and found that simulation result showed a good agreement with experiment. Flores-Johnson *et al*. (2011) used simulation to model the impact of 7.62 mm projectile on the double-layered steel targets and reported a good agreement between simulations and experiment observed. Hazell *et al*. (2014) also investigated the ballistic behaviour of ballistic resistant panel using simulation and experiment and concluded that simulation results showed a good agreement with experiment.

The study on behaviour of materials at high strain rates utilizing computational method requires adequate precision in material constitutive models. Constitutive material models relate the flow variables with the internal energy and the complexity level of model depends on the application (Ramesh, 2008). The materials models are frequently utilised for extrapolation of the flow stress to very high strain rates. The models generally used for high velocity impact problems are Cowper-Symonds, Johnson-Cook and Zerilli-Armstrong. Cowper-Symonds Model is the simplest model and can be obtained using high strain rate experiment without involving high temperature experiment. Johnson-Cook Model is a purely empirical model whereas Zerilli-Armstrong model is developed from dislocation theory which is the most complex and difficult to obtain among all models.

Although for simplicity and practical reason, Johnson-Cook Model has been widely used in ballistic impact study, it is necessary to study the effect of those three different constitutive models implementation on the ballistic impact of metallic plate. This is because in order to understand the evolution of deformation fields and mechanism of failure at high strain rates, precise numerical tool is required. Therefore in this study, the main objective is to find the best available constitutive material model to be utilized in studying the ballistic impact of metallic panel. A series of computational work was conducted using finite element analysis for three different constitutive material models and results from simulations were compared to experimental data from the literature. Finally, the most accurate model shall be utilized for future study.

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MATERIALS AND METHODS

Computational model: Model geometry as in Fig. 1 a was constructed using computer-aided design software and Finite Element (FE) model was built using a commercial software package suitable for high velocity impact problem. The 7.62 mm APM2 projectile was modelled as three independent parts: Brass jacket, steel core and lead filler and the target plate was modelled as a 100 mm diameter circular plate as in Fig. 1a. The plate was a 12 mm thickness High Strength Steel (HSS) according to the reference metal plate from the experiment in the literature (Borvik *et al.*, 2001) for comparison. In FE analysis, the problem was considered as axis ymmetric model taken into account that the bullet rotation does not come into consideration as in this study the main interest is the behaviour of impacted panel. A constant cell size of 0.5 mm was selected to finely resolve each problem and this resulted in a volume of approximately a million cells per problem as illustrated in the projectile was fired in the x-direction of HSS panel at initial velocity in a range of 750- 950 m sec^{-1} while the edge of target plate was fixed. The lower range was set as it is reported enough to fully penetrate the 12 mm plate while the upper range is the maximum velocity of APM2 projectile (Borvi *et al.*, 2001). Three different constitutive material models: Cowper-Symonds model Johnson-Cook Model and Zerilli-Armstrong model were applied in the computational modelling to describe behaviour of analysed material. These models were chosen based on the current implementation of constitutive models in the computational modelling involving ballistic impact (Hub, 2013).

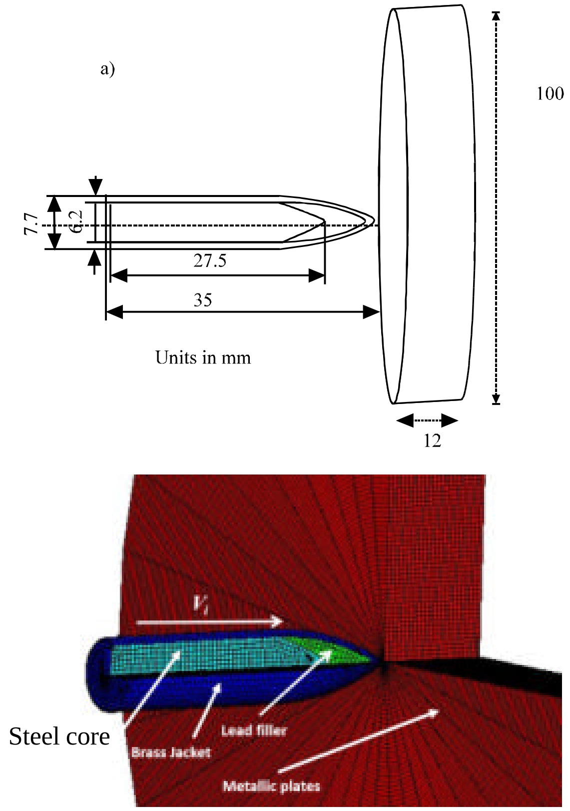

Fig. 1: a) Model geometries for 12 mm high strength steel plate and 7.62 mm APM2 projectile and b) Finite element mesh of a 7.62 mm APM2 projectile and metallic target plate

The Cowper-Symonds model is an extension of bilinear hardening model with some reinforcement in which the plasticity limit is calibrated by the coefficient determined using formula as in Eq. 1 where $\dot{\varepsilon}$ is the strain rate and C and q are the Cowper-Symonds constants (Hub, 2013).

$$1+(\varepsilon/C)^q \tag{1}$$

The Johnson-Cook model is purely empirical based model and has been utilised widely to describe the behaviour of materials subjected to large strains, high strain rate and high temperature. It is of the form as in Eq. 2 (Johnson and Cook, 1983) where $\sigma_{eq}$is the equivalent stress, ε_{eq} the equivalent plastic strain, TheA,B, n, C and m are the material constants and $\dot{\varepsilon}^* = \dot{\varepsilon}_{eq}/\dot{\varepsilon}_0$ is the dimensionless strain rate where it is a ratio of the strain rate and a user-defined strain rate. The T^{*m} represents the homologous temperature and is given by equation,T^{*m}= $(T-T_r)(T_m-T_r)$, where T_r and T_m represent the room temperature and the melting temperature, respectively.

$$s = (A+Be^n)(1+Clne)(1-T^{*m}) \tag{2}$$

The Zerilli-Armstrong model on the other hand incorporates the effect of strain hardening, thermal softening and grain size (Armstrong and Zerilli, 1988). It can be applied for face-centred cubic (fcc) and body-centred cubic (bcc) materials. Because the HSS is an bcc metal, the constitutive relation is given by Eq. 3 whereas C_0, C_1, C_3, C_4 and C_5 are the constants for dislocation-mechanics-derived constitutive relation for HSS (for bcc structure), ε is the plastic strain, $\dot{\varepsilon}$ is the dimensionless plastic strain rate and T is the temperature.

$$\sigma = C_0 + C_1 \exp(-C_3T + C_4T.\ln\varepsilon) + C_5\varepsilon^n \tag{3}$$

The target plate has density of 7800 kg m^{-3}, elastic modulus of 210 GPa and Poisson's ratio of 0.25. For

Table 1: Johnson-Cook constitutive material model constants for HSS plate (Borvike *et al*., 2001)

A (MPa)	B (MPa)	n	c	m	Tm (K)
819	362	1	0.0108	1	1800

Table 2: Zerilli-Armstrong constitutive material model constants for HSS plate (Johnson and Cook, 1983)

C_0 (MPa)	C_1 (MPa)	C_3	C_4	C_5(MPa)	T (K)
1470	20.3	0.00668	0.00246	702	1800

Table 3: Material properties and modified Johnson-Cook model parameters (Borvike *et al*., 2001)

Material Properties	Steel core	Lead cap	Brass jacket
Density, p (kg/m3)	7850	10600	8520
Young's modulus E (GPa)	210	1	115
Poisson's ratio,i	0.33	0.42	0.31
Yield strength, A (MPa)	1200	24	206
Strain hardening, B (MPa)	1200	24	206
Strain hardening exponent,(n)	50000	300	505
Strain rate constant, (c)	0	0.1	0.1
Thermal softening constant, (m)	1	1	1.68
Melting temperature, Tm (K)	1811	760	1189

Cowper-Symonds material model constants, the value of C and q were set at 300 and 5, respectively (Hub, 2013). The constitutive material model constants for Johnson-Cook model and Zerilli-Armstrong model were tabulated in Table 1 and 2, respectively. Meanwhile, the 7.62 mm APM2 projectile materials were represented by Johnson-Cook constitutive material models as tabulated in Table 3, throughout the simulation works. Data collected from the simulation was the residual velocity for each initial projectile velocity.

RESULTS AND DISCUSSION

Figure 2a-c show the perforation process resulted from three different constitutive material models occurred at time 70 ìs for an initial velocity of 750 m sec^{-1}. The perforated length of metallic plate using Cowper-Symonds model in Fig. 3a is seen the longest compared to others. This is because Cowper-Symonds model had over alculated the stress on the plate after it achieved the yield strength of the material (Zamani and Etemadi, 2011). Figure 3a-c illustrates the perforation process for an initial velocity of 950 msec^{-1} captured at 70 μs. Marginal difference in travelled length of projectile can be seen when these three constitutive models were applied for higher velocity.

Figure 4 presents the residual velocity resulting from different initial projectile velocity for each constitutive material model. Zerilli-Armstrong model has given the lowest residual velocity, 667 m sec^{-1} and Cowper-Symonds model gives the highest residual velocity of 720 m s^{-1}. Johnson-Cook model produced result in terms of residual velocity, 687 relatively close to the experimental result of 664 msec^{-1}. The residual velocity denotes that Johnson-Cook model gives the output equivalent to the experiment data from the literature for a range of initial velocity from 750 msec^{-1}-950 msec^{-1}. However, at initial velocity of 850 msec^{-1}-950 msec^{-1}, Zerilli-Armstrong model gave more accurate results for a percentage difference of 0.68%-2.41%. At high velocity, during the deformation process, the dislocations interaction becomes intense and large amount of energy rises up, generating the strain hardening effect as the mechanical response (Lin and Chen, 2010) Cowper-Symonds Model does not include the strain hardening effect resulting in large amount of stress flow to penetratethe plate faster. Johnson-Cook Model

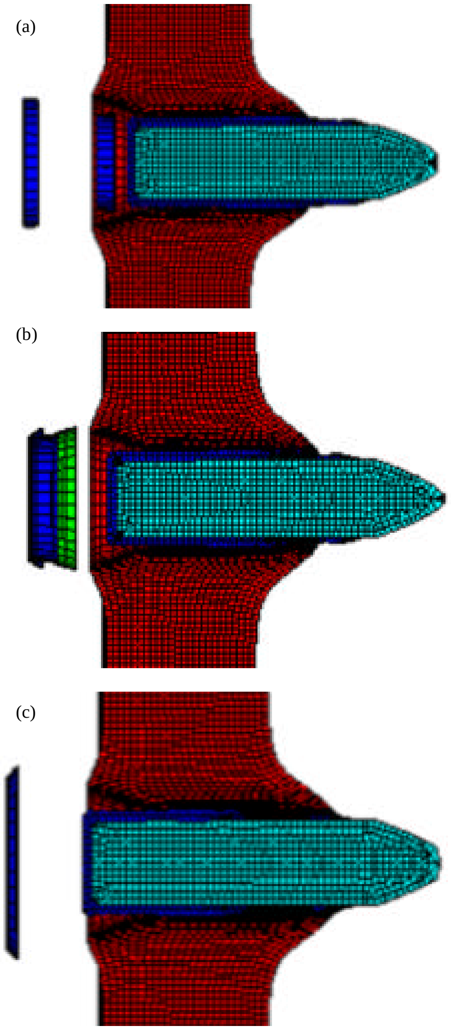

Fig. 2: Perforation process for initial projectile velocity of 750 m sec^{-1} at time 70 μs for: a) Cowper-Symonds Model; b) Johnson-Cook Model and c) Zerilli-Armstrong model

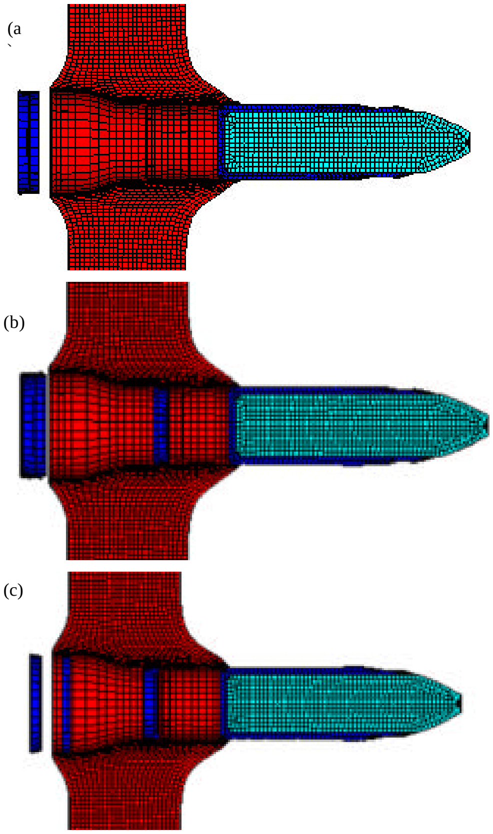

Fig. 3: Perforation process for initial projectile velocity of 950 m sec^{-1} at time 70 μs for: a) Cowper-Symonds model; b) Johnson-Cook model and c) Zerilli-Armstrong model

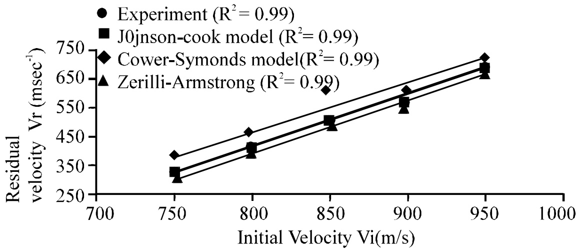

Fig. 4: Comparison between residual velocity from experiment data (Borvik *et al.*, 2001) and simulation using different constitutive material models

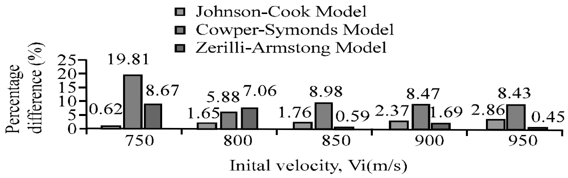

Fig. 5: Percentage difference of residual velocity between simulation results with three constitutive models application and experiment (Borvik *et al.*, 2001) at different initial velocity.

and Zerilli-Armstrong model on the other hand include the strain hardening effect on the equation models and efficiently handle the dislocation effects. The percentage of difference for each constitutive model is illustrated as bar chart in Fig. 5. All constitutive material models studied have overestimated the ballistic residual velocity for metallic plate studied. The lowest overestimation occurred for Johnson-Cook Model at percentage error ranging from 0.62-2.86% for initial velocity of 750-50 m sec^{-1}. Johnson-Cook has given the closest value compared to others. At velocity 750 m sec^{-1} m , Cowper-Symonds model exhibits the largest percentage difference of 19.81%. This phenomenon happened because the model does not include the temperature and strain hardening effects. Each phenomenon represents the condition of flow stresses during high impact velocity. Zerilli-Armstrong model has defined correctly the thermal softening of the material in adiabatic condition which causes the plastic instabilities taking place during high velocity impact of 850- 950 m sec^{-1} (Lin and Chen, 2010) while Johnson-Cook model treats the strain hardening as constant power law (Johnson and Cook, 1983) makes it less effective in calculating flow stress at high velocity than the Zerilli-Armstrong Model.

CONCLUSION

This study facilitates the choice making of constitutive material model for ballistic impact simulation. Material models chosen are limited to ballistic impact application for metallic panel. Johnson-Cook constitutive material model gives the best fit of experimental results for an average difference between simulation and experimental data from the literature of 1.9%. Based on overall results, depending on the high level of accuracy needed in the study related to safety and defence issues, Johnson-Cook constitutive material model seems to be the best model representing metallic plate for a ballistic testing considering of wide range of impact velocity.

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REFERENCES

Armstrong, R.W. and F.J. Zerilli, 1988. Dislocation mechanics based analysis of material dynamics behaviour. Journal de Physique, 49: 529-534.

Borvik, T., M. Langseth, O.S. Hopperstad and K.A. Malo, 2002. Perforation of 12 mm thick steel plates by 20 mm diameter projectiles with flat, hemispherical and conical noses: Part I: Experimental study. Int. J. Impact Eng., 27: 19-35.

Dey, S., T. Borvik, O.S. Hopperstad, J.R. Leinum and M. Langseth, 2004. The effect of target strength on the perforation of steel plates using three different projectile nose shapes. Int. J. Impact Eng., 30: 1005-1038.

Flores-Johnson, E.A., M. Saleh and L. Edwards, 2011. Ballistic performance of multi-layered metallic plates impacted by a 7.62-mm APM2 projectile. Int. J. Impact Eng., 38: 1022-1032.

Hazell, P.J., G.J. Appleby-Thomas and S. Toone, 2014. Ballistic compaction of a confined ceramic powder by a non-deforming projectile: Experiments and simulations. Mater. Des., 56: 943-952.

Hub, J., 2013. Numerical estimation of ballistic resistance of armour materials against the bullet 7.62x54R. Proceedings of the International Conference on Military Technology, May 22-23, 2013, University of Defense, Brno, Czech Republic, pp: 817-824.

Johnson, G.R. and W.H. Cook, 1983. A constitutive model and data for metals subjected to large strains, high strain rates and high temperatures. Proceedings of the 7th International Symposium on Ballistics, April 19-21, 1983, The Hague, Netherlands, pp: 541-547.

Lin, Y.C. and X.M. Chen, 2010. A combined Johnson-Cook and Zerilli-Armstrong model for hot compressed typical high-strength alloy steel. Comput. Mater. Sci., 49: 628-633.

Ramesh, K.T., 2008. High Rates and Impact Experiments. In: Springer Handbook of Experimental Solid Mechanics, Sharpe, Jr. W.N. (Ed.). Chapter 33, Springer, Berlin, Germany, ISBN: 978-0-387-26883-5, pp: 929-960.

Zamani, J. and E. Etemadi, 2011. Constitutive equations for metallic crystals under very high strain rates loadings. Proceedings of the International Conference on Advanced Materials Engineering, November 22-24, 2011, Shenyang, Liaoning, China -.