UNIFIED CONSTITUTIVE MODELS FOR DEFORMATION OF THIN-WALLED STRUCTURES

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To my beloved father and mother

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ABSTRACT

Sheet metals are widely used as body panels and trims in automotive body structures. In the event of a crash, these panels will likely to experience impact loads in the range where the strain rate effect is significant. The behaviour of sheet metals differs as the strain rate increases. Thus, Abaqus FE software was employed as an aid to predict the behaviour of the sheet metals. The Johnson–Cook (JC) model was used in the FE simulation. Low carbon steel (SGACD, SPCC and SHS) and high strength steel (DP600) were employed to study the effect of loading rate onto sheet metals. Metallurgical study was carried out to identify the element composition and orientation of the microstructure since the materials had undergone several processes during manufacturing. Tension tests were conducted at strain rate 0.001/s to 0.1/s to study the stress-strain relation of the material. Parameters of the JC model *(A, B, C, m* and *n)* were extracted using results from the tension tests. These parameters were incorporated into the JC model and used in FE simulation. FE simulation of tension test was performed in order to validate the JC model parameters. Experiment and FE simulation of axial compression test on thin-walled tube and drop weight impact test on steel plate were conducted. Results from the experiment were compared with FE simulation for validation where the large deviation of the compressive load-displacement curve occurred in the axial compression test. Whereas, in the drop weight impact test, the dynamic acceleration and deceleration were accurately predicted by FE model and served to validate the model.

ABSTRAK

Kepingan besi digunakan secara meluas pada bahagian badan kereta. Ketika berlakunya pelanggaran antara badan kereta, bahagian badan kereta akan menerima hentaman beban yang tinggi di mana kesan kadar terikan menjadi ketara. Kelakuan pada kepingan besi berubah-ubah apabila kadar terikan meningkat. Oleh itu, perisian simulasi Abaqus FE digunakan sebagai salah satu cara untuk meramal keadaan sesebuah kepingan besi itu. Model Johnson–Cook (JC) juga digunakan di dalam simulasi FE tersebut. Dalam projek ini, keluli karbon rendah (SGACD, SPCC dan SHS) dan keluli kekuatan tinggi (DP600) digunakan untuk mengkaji kesan kadar bebanan ke atas kepingan besi itu. Kajian metarlugi dijalankan untuk mengenalpasti kandungan kimia dan orientasi mikrostruktur besi itu memandangkan ia telah menjalani beberapa proses pembuatan di kilang. Kemudian ujian tegangan dijalankan pada kadar terikan dari 0.001/s hingga 0.1/s untuk mengkaji hubungan antara tegasan dan terikan bahan itu. Parameter model JC *(A, B, C, m, dan n)* juga disari dengan menggunakan keputusan yang diperolehi daripada ujian tegangan tadi . Simulasi bagi ujian tegangan dilakukan untuk mengesahkan parameters untuk model JC itu. Pada masa yang sama, eksperimen pada ujian tekanan pada keluli berongga dan ujian impak pada kepingan besi dijalankan. Keputusan daripada eksperimen tersebut dibandingkan dengan simulasi untuk pengesahan dimana ada perbezaan besar di antara keputusan eksperimen dan juga simulasi di dalam graf beban tekanan kepada perubahan panjang. Manakala, untuk keputusan ujian impak pada kepingan besi, pecutan dan nyahpecutan dinamik memberikan keputusan yang tepat dan telah mengesahkan model tersebut.

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LIST OF ABBREVIATIONS

FE	-	Finite Element
FEM	-	Finite Element Method
NVI	-	Normal Velocity Interferometer
TDI	-	Transverse Displacement interferometer
RD	-	Rolling direction
TD	-	Transverse direction
ND	-	Normal direction
FCC	-	Face centre cubic
BCC	-	Body centre cubic
HCP	-	Hexagonal close packed
RO	-	Ramberg-Osgood
CS	-	Cowper-Symonds
HSLA350	-	High strength low alloy 350
RK	-	Rusinek-Klepaczko
HSLA65	-	High strength low alloy 65
JC	-	Johnson-Cook
SGACD	-	Hot-Dip Galvanized Steel Sheet
SPCC	-	Cold Rolled Steel Sheet
DP600	-	Dual Phase 600
SHS	-	Square Hollow Section
ERW	-	Form-Square Weld-Square
GDS	-	Glow Discharge Spectrometer
AES	-	Atomic Emission Spectroscopy
ASTM	-	American Society for Testing and Materials
ETOTAL	-	Total Energy

ALLIE	-	Internal Energy
ALLPD	-	Plastic Dissipation Energy
ALLKE	-	Kinetic Energy
PEEQ	-	Equivalent Plastic Strains

LIST OF SYMBOLS

E	-	Young's modulus
σ_{eng}	-	Engineering stress
ε_{eng}	-	Engineering strain
σ_y	-	Yield stress
σ_{true}	-	True stress
ε_{true}	-	True strain
P	-	Load
A	-	Current cross-sectional area
A_o	-	Original cross-sectional area
L	-	Current length
L_o	-	Original length
Δ	-	Elongation
$d\varepsilon_t$	-	Logarithmic strain
dL	-	Change in displacement
dV	-	Change in volume
σ_x	-	Normal stress in *x*-direction
σ_y	-	Normal stress in *y*-direction
σ_z	-	Normal stress in *z*-direction
σ_{xy}	-	Shear stresses in *x*-*y* plane
σ_{zx}	-	Shear stresses in *x*-*z* plane
σ_{yz}	-	Shear stresses in *y*-*z* plane
τ_{xy}	-	Shear stresses in *x*-*y* plane
τ_{zx}	-	Shear stresses in *x*-*z* plane
τ_{yz}	-	Shear stresses in *y*-*z* plane

ε_x	-	Normal strain in *x*-direction
ε_y	-	Normal strain in *y*-direction
ε_z	-	Normal strain in *z*-direction
ε_{xy}	-	Shear strain in *x*-*y* plane
ε_{xz}	-	Shear strain in *x*-*z* plane
ε_{yz}	-	Shear strain in *y*-*z* plane
γ_{xy}	-	Shear strain in *x*-*y* plane
γ_{xz}	-	Shear strain in *x*-*z* plane
γ_{yz}	-	Shear strain in *y*-*z* plane
G	-	Shear modulus
υ	-	Poisson's ratio
P_C	-	Euler load or critical buckling load
A	-	Ferrite
Γ	-	Austenite
K	-	Ramberg-Osgood strength coefficient
N	-	Ramberg-Osgood strain hardening coefficient
$\dot{\varepsilon}$	-	Strain rate
D	-	Cowper-Symond material constant
q	-	Cowper-Symond material constant
σ_μ	-	Internal stress
σ^*	-	Effective stress
θ^*	-	Rusinek-Klepaczko homologous temperature
n_o	-	Rusinek-Klepaczko strain hardening
T	-	Temperature
T_m	-	Melting temperature
D_1	-	Rusinek-Klepaczko material constant
D_2	-	Rusinek-Klepaczko material constant
$\dot{\varepsilon}_{max}$	-	Maximum strain rates
$\dot{\varepsilon}_{min}$	-	Minimum strain rates
B_o	-	Rusinek-Klepaczko plasticity modulus
ν	-	Rusinek-Klepaczko temperature sensitivity
m^*	-	Rusinek-Klepaczko coefficient temperature and strain rate

		effect
σ_o^*	-	Rusinek-Klepaczko effective stress
A	-	Johnson-Cook material constant
B	-	Johnson-Cook material constant
N	-	Johnson-Cook strain hardening
C	-	Johnson-Cook strain rate sensitivity
M	-	Johnson-Cook temperature sensitivity
$\dot{\varepsilon}^*$	-	Johnson-Cook dimensionless strain rate
$\dot{\varepsilon}_0$	-	Johnson-Cook nominal strain rate
T^*	-	Johnson-Cook homologous temperature
T_r	-	Johnson-Cook reference temperature

CHAPTER 1

INTRODUCTION

1.1 Background of Study

Automotive industries have concerns on the reliability of the automobile structures in terms of product design, product specification and others. The basic safety features installed in the vehicle including energy absorbing structures, air bags, seat belts and other devices to improve crashworthiness. One of the major aspects that need to be addressed is energy absorbing features of a car structures. Energy absorbing features called front and rear longitudinal and fenders are located at the front, rear and side of a car's structure. Since crashworthiness deals with impact such as frontal impact and side impact during the crash events, thus the car will expose to high strain rate loading [1, 2].

During high strain rate loading, the velocity of a car can reach more than 200 km/h. Impacts at that speed can cause severe injuries, or in a worst case, death. Therefore, continuous improvement of these features is highly recommended to reduce crash fatalities. Numerous enhancements to car safety have been made which focus on the car structure such as reducing the length of the front longitudinal structures and utilizing lighter reinforcement structures. Lighter materials can be obtained when sheet metals are used to manufacture car components so that the weight of a car is reduced in order to optimize car fuel efficiency without reducing the crashworthiness requisition [2].

The aim of the research is to examine the behaviour of sheet metal at high strain rates. The mechanical behaviour of sheet metal is demonstrated using finite element method (FEM). The analyses capitalize on previous researches regarding the determination of the parameters for high strain rate material models. Those extracted parameters are used in the material models and implemented in the FEM. The current study is the continuation of research on the determination of material model parameters and the construction of a methodology to predict the behaviour of sheet metal at higher loading rates. All the tests including static and dynamic tests are performed using low carbon steel sheet materials.

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1.2 Problem Definition

Crash is considered a complex problem lure category since it involves numerous types of loading such as axial compression, bending torsion and under static and dynamic condition. Deformation of a car structure during a crash event is one of the crash failure characteristic. Therefore, it is important to understand the deformation behaviour and its mechanism on sheet metals. Sheet metal appears to expose different strength at different loading rate. It shows that the strength increases as the strain rate increases. However, when the car structure is subjected to high loading strain rate during impact, the absorbing structures of a car might be unable to withstand the external forces as the car structure incapable to absorb the impact energy during crash. Large localized stresses occur at the impact zone of the car structures due to the relative motion of its body. Therefore, the inelastic strain from localized stresses tends to give rise to large deformation of the structures.

Large deformation of the car structures depends on the local strain rate. As the localized strain rates become higher, it tends to increase the possibility of failure of the car structures. Thus, the use of a material model is recommended to demonstrate the deformation of the sheet metal under high loading rate. The Johnson-Cook (J-C) model can be used to model the deformation failure of the sheet metal. The research is focused on the deformation behaviour of low carbon sheet metal under quasi static and impact loading.

The research is intended to fill in the gap of the previous studies that is to develop a structured procedure to predict the behaviour of the sheet metals. The structured procedures include the selection of the type of the sheet metals, metallurgical study and tests on sheet metals. Then the results of the model will be validate with FE simulation and experimental data.

1.3 Objectives

The objectives of the project are:

1. To evaluate Johnson-Cook constitutive model for the behaviour of sheet metals at various strain rates.
2. To examine the Johnson-Cook model using FE simulation of sheet metal structures in the application of:
   i. Axial compression on thin-walled tube
   ii. Drop weight impact on sheet plate

1.4 Scope of Study

The scope of the study comprises:

1. Johnson-Cook unified constitutive model evaluated for steel sheets.
2. Research materials consist of low carbon steel and dual phase steel sheet specimen.
3. Series of tension tests conducted of extracting Johnson-Cook parameter extraction.
4. Abaqus FE software is employed for the simulation
5. Selected sample applications consist of axial compression test of thin-walled tube and drop weight impact test on clamped steel plate.

1.5 Significance of the Finding

This study addresses the method to predict the behaviour of sheet metal when it is subjected to impact loading. J-C material model comprises important aspects including strain hardening, strain rate sensitivity and temperature sensitivity that will be explained in Chapter 2. Strain hardening, strain rate sensitivity and temperature sensitivity acknowledge the capability of J-C model parameters to predict sheet metals behaviour. The J-C model is expected to provide better prediction as it represents the methodology for prediction sheet metals behaviour.

In this research, sheet metals with thickness 7 mm and 12 mm have been used. Sheet metal is an excellent components used in the automotive industries since it have high absorption of energy and can improve the safety features of a car. The types of sheet metals used are low carbon steel and high strength steel. In the selection of sheet metals, the optimum hardness value is required to obtain adequate results. A high range of strain rate is required so that the sheet metal behaviour can be compared and verified by using J-C model as a means to predict the behavior in the FE simulation.

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