

UNIFIED CONSTITUTIVE MODELS FOR DEFORMATION OF  
THIN-WALLED STRUCTURES

SITI SYALEIZA BINTI ARSAD

A thesis submitted in fulfilment of the  
requirements for the award of the degree of  
Master of Engineering (Mechanical)

Faculty of Mechanical Engineering  
Universiti Teknologi Malaysia

FEBRUARY 2014

To my beloved father and mother

## ACKNOWLEDGEMENT

First and foremost, I would like to express my heart felt appreciation to my respectful supervisors, Assoc. Prof. Dr. Amran Ayob and Prof. Dr. Mohd. Nasir Tamin for providing me with an opportunity to pursue my studies here in the Computational Solid Mechanics Laboratory (CSMLab), Faculty of Mechanical Engineering, Universiti Teknologi Malaysia.

I would like to extend my gratitude to all my CSMLab members especially who have provided me with valuable suggestions and recommendations. To all CSMLab members, thank you for providing assistance at various occasions throughout my study. Their views and tips are useful indeed. Unfortunately, it is not possible to list all of their names in this limited space.

Last but not least, I wouldlike to extend my sincere appreciation to my beloved family for their continuous support and encouragement throughout these years. I am greatly indebted to them for their infinite love and confidence towards me.

## 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.

## TABLE OF CONTENTS

CHAPTER	TITLE	PAGE
	<b>DECLARATION</b>	<b>ii</b>
	<b>DEDICATION</b>	<b>iii</b>
	<b>ACKNOWLEDGEMENTS</b>	<b>iv</b>
	<b>ABSTRACT</b>	<b>v</b>
	<b>ABSTRAK</b>	<b>vi</b>
	<b>TABLE OF CONTENTS</b>	<b>vii</b>
	<b>LIST OF TABLES</b>	<b>x</b>
	<b>LIST OF FIGURES</b>	<b>xi</b>
	<b>LIST OF ABBREVIATIONS</b>	<b>xv</b>
	<b>LIST OF SYMBOLS</b>	<b>xvii</b>
<b>1</b>	<b>INTRODUCTION</b>	<b>1</b>
	1.1 Background of the Study	1
	1.2 Problem Definition	3
	1.3 Objectives	4
	1.4 Scope of Study	4
	1.5 Significance of Finding	5
<b>2</b>	<b>LITERATURE REVIEW</b>	<b>6</b>
	2.1 Stress-strain Behaviour for Sheet Metal	6
	2.1.1 Plane Stress and Plane Strain	11
	2.1.2 High Strain Rates Response	15
	2.1.3 Compression Behaviour of Thin-walled	19

	Structure	
	2.1.4 Anisotropy of Sheet Metal due to Cold Rolling	21
	2.1.5 Metallurgy of Steel	23
2.2	Reviews on Constitutive Material Models for Steel Sheets	28
	2.2.1 Classical Constitutive Material Model	32
	2.2.1.1 Ramberg-Osgood Material Model	32
	2.2.2 Unified Constitutive Material Models	34
	2.2.2.1 Cowper-Symond Material Model	34
	2.2.2.2 Rusinek-Klepaczko Material Model	37
	2.2.2.3 Johnson-Cook Material Model	42
<b>3</b>	<b>RESEARCH METHODOLOGY</b>	<b>53</b>
3.1	Operational Framework	53
3.2	Materials and Metallurgical Characterization	55
3.3	Tension Test	57
3.4	Johnson-Cook Model Parameters	58
3.5	Validation Experiment	62
	3.5.1 Axial Compression Test on Thin-walled Tube	62
	3.5.2 Drop Weight Impact Test on Sheet Plate	63
3.6	FE Simulation	64
	3.6.1 Mesh Convergence Study	64
	3.6.2 Tension Test	66
	3.6.3 Axial Compression Test on Thin-walled Tube	67
	3.6.4 Drop Weight Impact Test on Sheet Plate	68
<b>4</b>	<b>RESULTS AND DISCUSSION</b>	<b>70</b>
4.1	Introduction	70
4.2	Materials and Metallurgical Characteristic	70
4.3	Stress-strain Diagrams	75
4.4	Tensile Fracture Features	79
4.5	Johnson-Cook Model Parameters	81

4.6	Validation Test Data	83
4.6.1	Mesh Convergence Results	83
4.6.2	Stress-strain Diagram	85
4.6.3	Axial Compression Behaviour of Thin-walled Tube	89
4.6.4	Drop Weight Impact Response on Sheet Plate	91
<b>5</b>	<b>CONCLUSIONS &amp; RECOMMENDATIONS</b>	<b>95</b>
7.1	Conclusions	95
7.2	Recommendations	97
	<b>REFERENCES</b>	<b>98</b>

Appendix A



## LIST OF TABLES

<b>TABLE NO.</b>	<b>TITLE</b>	<b>PAGE</b>
2.1	Dynamic aspects of mechanical testing and its application	17
2.2	Reviewed on high strain rate testing	18
2.3	Microstructure of 0.046% Fe and 0.36% C by weight percent during hot-rolled process	26
2.4	RO model parameters for 7075-T6	33
2.5	CS parameters of various types of metallic alloys	36
2.6	RK model parameters for HSLA-65	43
2.7	Chemical composition for high strength alloy steel	48
2.8	JC model parameters for 4340 steel	51
3.1	Test samples preparation	57
3.2	Material parameters used for Johnson-Cook model	66
4.1	Chemical composition of sheet metals	71
4.2	Microstructure of sheet metals	72
4.3	Materials properties for sheet metals	78
4.4	Average and standard deviation of the materials properties	79
4.5	Parameter values for JC model of sheet metals	82
4.6	Mesh size dimension	83
4.7	Yield stress for different size of mesh element	85

## LIST OF FIGURES

FIGURE NO.	TITLE	PAGE
2.1	Engineering stress-strain curve of low carbon steel	9
2.2	Initial portion of engineering stress -strain curve of low carbon steel	9
2.3	Comparison between engineering stress-strain curve and true stress-strain curve of low carbon steel	11
2.4	Plane stress and plane strain	15
2.5	Load-displacement curves for (a) a perfect column and (b) a thin plate	20
2.6	Buckling modes of thin-walled structures	21
2.7	Orthotropy axes of the rolled sheet metals	22
2.8	Engineering stress-strain curve at $0^\circ$ , $45^\circ$ and $90^\circ$ for AA7003	23
2.9	Atomic arrangements in metallic crystal structure	24
2.10	Iron-Carbon diagram	25
2.11	Ductile fracture	27
2.12	Brittle fracture of mild steel	28
2.13	The von Mises yield surface	30
2.14	Yield locus of isotropic and kinematic hardening	31
2.15	Predicted stress-strain RO model with experiment	33
2.16	Stress-strain curves for stainless steel and RO prediction	34
2.17	Comparison with the predicted value of CS model and experimental data for mild steel	36
2.18	Stress-strain curve at T (23 K- 233 K) and strain rates	40

	( $10^{-5}$ /s – $10^{-1}$ /s)	
2.19	Comparison between RK model and experimental result for HSLA-65 steel	42
2.20	Stress-strain curve Hopkinson bar tests with different temperatures	43
2.21	Average shear stress-strain curve of torsion tests at different strain rates	44
2.22	Quasi-static stress-strain curve of tension test for material 4340 steel, Armco Iron and OFHC Copper	45
2.23	Thermal softening Fraction $K_t$ to homologous temperature $T^*$ using Hopkinson Bar Test data	47
2.24	Stress vs strain rate from tension test	48
2.25	Stress –strain curve of tension test	49
2.26	Relationship between (a) $\ln(\sigma - A)$ and $\ln \epsilon(b)$ $\sigma/(A+B\epsilon^n)$ and $\ln \dot{\epsilon}$ (c) $\ln \{1 - (\sigma / A + B\epsilon^n)\}$ and $\ln T^*$	50 51
2.27	Comparison between JC model and experimental result	52
3.1	Research operational framework	54
3.2	Geometry of tension test coupon (all dimension in mm)	57
3.3	Flowchart to determine JC material model parameters	60
3.4	Geometry of the thin-walled tube in axial compression test setup	63
3.5	Drop weight impact experiment setup	64
3.6	Mesh sizes vary from a) coarse mesh b) fine mesh c) very fine mesh	65
3.7	Geometry of tension test specimen with FE mesh	66
3.8	Geometry of set-up for axial compression test and FE mesh for the model assembly	67
3.9	(a) Geometry of set-up for drop weight impact test (b) FE mesh for the model assembly	69
4.1	Average hardness values on the sheet metals surface	74
4.2	Distribution of hardness value for SHS across the surface plane	74
4.3	Engineering stress-strain curve for SGACD	75

4.4	(a) True stress-strain curves of SGACD	76
4.4	(b) True stress-strain curves of SPCC	76
4.4	(c) True stress-strain curves of DP600	77
4.4	(d) True stress-strain curves of SHS	77
4.5	True stress-strain for SHS at strain rate 0.001/s	78
4.6	Dominant modes of failure under tension of sheet metal specimen	80
4.7	(a) Shear bands localization	80
	(b) Ductile “dimples” fracture of sheet metal in tension	
4.8	Parameter $A$ , $B$ and $n$ for JC model	81
4.9	Parameter $C$ for JC model	82
4.10	Comparison of coarse mesh, fine mesh and very fine mesh	84
4.11	Mesh convergence curve	85
4.12	Comparison of predicted stress-plastic strain curves by JC model with test data at strain rate of 0.1/s and the predicted response at 200/s for SGACD	86
4.13	Comparison of predicted stress-plastic strain curves by JC model with test data at strain rate of 0.1/s and the predicted response at 200/s for SPCC	86
4.14	Distribution of von Mises stress corresponding to the end of the applied displacement	87
4.15	Comparison of distributions of equivalent inelastic strain predicted for FE model with a) coarse mesh b) fine mesh c) very fine mesh	88
4.16	Load-Extension curves for axial compression test at displacement rate of 5mm/min	89
4.17	Plan view of the thin-walled tube	90
4.18	Thin-walled tube under compression loading	90
4.19	Acceleration curves for sheet metal during impact test	91
4.20	Predicted inertia force history for the material point at the centre of the sheet metal	92
4.21	Displacement history of the sheet metal during impact	93

	test	
4.22	Evolution of various energy terms during the weight drop impact test	93
4.23	Equivalent plastic strains	94

## 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
$\sigma_{eng}$	-	Engineering stress
$\varepsilon_{eng}$	-	Engineering strain
$\sigma_y$	-	Yield stress
$\sigma_{true}$	-	True stress
$\varepsilon_{true}$	-	True strain
$P$	-	Load
$A$	-	Current cross-sectional area
$A_o$	-	Original cross-sectional area
$L$	-	Current length
$L_o$	-	Original length
$\Delta$	-	Elongation
$d\varepsilon_t$	-	Logarithmic strain
$dL$	-	Change in displacement
$dV$	-	Change in volume
$\sigma_x$	-	Normal stress in $x$ -direction
$\sigma_y$	-	Normal stress in $y$ -direction
$\sigma_z$	-	Normal stress in $z$ -direction
$\sigma_{xy}$	-	Shear stresses in $x$ - $y$ plane
$\sigma_{zx}$	-	Shear stresses in $x$ - $z$ plane
$\sigma_{yz}$	-	Shear stresses in $y$ - $z$ plane
$\tau_{xy}$	-	Shear stresses in $x$ - $y$ plane
$\tau_{zx}$	-	Shear stresses in $x$ - $z$ plane
$\tau_{yz}$	-	Shear stresses in $y$ - $z$ plane



$\varepsilon_x$	-	Normal strain in $x$ -direction
$\varepsilon_y$	-	Normal strain in $y$ -direction
$\varepsilon_z$	-	Normal strain in $z$ -direction
$\varepsilon_{xy}$	-	Shear strain in $x$ - $y$ plane
$\varepsilon_{xz}$	-	Shear strain in $x$ - $z$ plane
$\varepsilon_{yz}$	-	Shear strain in $y$ - $z$ plane
$\gamma_{xy}$	-	Shear strain in $x$ - $y$ plane
$\gamma_{xz}$	-	Shear strain in $x$ - $z$ plane
$\gamma_{yz}$	-	Shear strain in $y$ - $z$ plane
$G$	-	Shear modulus
$\nu$	-	Poisson's ratio
$P_c$	-	Euler load or critical buckling load
$A$	-	Ferrite
$\Gamma$	-	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
$\sigma_\mu$	-	Internal stress
$\sigma^*$	-	Effective stress
$\theta^*$	-	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
$\nu$	-	Rusinek-Klepaczko temperature sensitivity
$m^*$	-	Rusinek-Klepaczko coefficient temperature and strain rate

		effect
$\sigma_o^*$	-	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.

This work is a collaboration project between PROTON and UTM in the development of Conceptual Optimization Fuel Efficiency Car (COFEC) which is supported by Ministry of Science, Technology and Innovation (MOSTI) Malaysia.

## 1.2 Problem Definition

Crash is considered a complex problem here 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.

## REFERENCES

1. Huh, H., and J. H. Song, *Crashworthiness Assessment of Auto-body Members Considering the Fabrication Histories*.2003, Korea Advanced Institute of science and Technology Science Town.
2. Automotive Applications Committee American Iron and Steel Institute (2004). *Vehicle Crashworthiness and Occupant Protection*. Michigan: AISI
3. Frederick. Y. M. *Fundamental of Linear Theory of Elasticity*. 1982. 1: p.82-17.
4. ASTM. *Standard Test Methods for Tension Testing of Metallic Materials*.USA,E8/E8M-11. 2012.
5. Roylance, D., *Stress-Strain Curves*.2001, Massachusetts Science and Engineering.
6. Hartsuijker, C., and Welleman, H., *Mechanics of Structures; Introduction into Continuum Mechanics*. 2008: TU-Delft.
7. Jerome, R., and Ganesan, N., *Generalized Plane Strain Finite Element Formulation for Thermal and Electrical Buckling Analysis*. 2008, Mechanics of Materials and Structures: p. 1625-1640.
8. Johnson, W., and Mellor, P. B., *Engineering Plasticity*.1972: Ellis Horwood Limited.
9. Lagace, P. A., *Plane Stress and Plane Strain*. 2001, Aeronautics & Astronautics and Enginnering Systems.CIVL.,
10. *Development of the Plane Stress and Plane Strain Stiffness Equations*. Finite elemnt Methods in Structural Mechanics: p. 250-285.
11. Lim, J. H., *High Speed Tensile Test of Automotive Steel Sheets at the Intermediate Strain Rate*.Posco Technical Report, 2007. **10** (1): p 116-122.



12. Armstrong, R. W., and Walley, S.M., *High Strain Rate Properties of Metals and Alloys*. International Material Reviews. 2008.**53**(3): p 105-128.
13. Rohr, I., and Nahme, H., *Material Characterization and Constitutive Modelling of Ductile High Strength Steel for a Wide Range of Strain Rates*. International Journal of Impact Engineering. 2005. **31**: p 401-433.
14. Nicolas, T., *Material Behaviour at High Strain Rates.*, Impact Dynamics. 1982: John Wiley & Sons.
15. Reyes, A., Hopperstad, O.S., *Modeling of Textured Aluminium Alloys Used in a Bumper System: Material Tests and Characterization*. Computational Materials Science, 2006. **37**: p 246-268.
16. Ramesh, K. T., *High Strain Rate and Impact Experiments*. Experimental Solid Mechanics, 2008.**1098**(33): p 874.
17. Abdelraouf, A. S., *Behaviour of Thin-walled Structures under combined Loads*. 1985, Loughborough University of Technology.
18. Mohri, F., and Bouzerira, C., *Lateral buckling of Thin-walled Beam-column Elements under Combined Axial and Bending Loads*. Thin-walled Structures. 2008.**46**: p 290-302.
19. Derrick, C. Y., and Yap, B. E., *Interaction Buckling and Postbuckling in the Distorsional Mode of Thin-walled Sections*. 2006., University of Sydney.
20. Teter, A., *Static and Dynamic Interactive Buckling of Isotropic Thin-walled Closed Columns with Variable Thickness*. Thin-walled Structures, 2007.**45**: p 936-940.
21. Nina, M. A., *Torsional Analysis of Open Section Thin-walled Beams*. FME Transactions, 2012.**40**: p 93-98.
22. Lee, J. H., *Local Buckling Behaviour and Design of Cold-Formed steel Compression Members at Elevated Temperatures*. 2004, Queensland University of Technology.
23. Maxwell, J. C., *Anisotropy and Demagnetization Factors*. **3**: p 60-120.
24. Banabic, D., *Plastic Behaviour of Sheet Metal*. Sheet Metal Forming Processes. 2010. **15**: p27-140.
25. Choi, Y., and Walter, M. E., *Observations of Anisotropy Evolution and Identification of Plastic Spin Parameters by Uniaxial Tensile Tests*. Mechanics of Materials and Structures. 2006. **1**: p303-325.

26. Ogawa, K., *HREM Observations of Continuously Changing Intermediate Structures between f.c.c and b.c.c at the Austenite-Martensite Interface*. 1997, Journal de Physique IV.
27. Greer, J. R., *Comparing the strength f.c.c. and b.c.c. sub-micrometer pillars: Compression Experiments and dislocation dynamics simulations*. Materials Science and Engineering, 2008. p 21-25.
28. Kumar, S. R., *Design of Steel Structures*. 2006, Indian Institute of Technology Madras.
29. George, F. V. V., *Microstructures of Hot and Cold Worked Metals and Alloys*. Buehler Ltd., USA, 2009.
30. Ronald, J. P., *Fractographic Features in Metals and Plastic*. Advanced Materials and Process. 2003. p 37-40.
31. *Failure*, 2004, University of Tennessee.
32. Kossa, A. (2011). *Exact Stress Integration Scheme for Elastoplasticity*. Degree of Doctor of Philosophy, University of Technology and Economis.
33. White, C. (1988). *A combined Isotropic- Kinematic Hardening Model for Large Deformation Metal Plasticity*. Degree of Doctor of Philosophy, US Army Laboratory Command.
34. Dieter, G. E., *Mechanical Metallurgy*, McGraw Hill, 2009.
35. *Constitutive Theory*, 2005.
36. Barlat, F., *Constitutive Modeling for Metals, Advanced Methods in Material Forming*. 2007.**362**: p298.
37. Liu, I. S., *Constitutive Theories: Basic Principles*. 2002. Continuum Mechanics.
38. Kenneth, S. L., *Experimental Study of Inelastic Stress Concentration around a Circular Notch*. 1996, Naval Postgraduate School.
39. Kim, J. R., *Full-range Stress-strain Curves for Stainless Steel Alloys*. 2001, Research Report N0 R811.
40. Marais, S. T., *Material Testing using the Split Hopkinson Pressure Bar*. American Journal of Solids and Structure. 2004. **1**: p 319-339.
41. Cunat, P. J., *Stainless Steel Properties for Structural Automotive Applications*. 2000, The European Stainless Steel Development Association,

42. Buyuk, M., and Dietenberger, M., *Development of a High Strain-Rate Dependent Vehicle Model*. 2005, LS-DYNA Anwemderforum, Bambewrg, Crash III.
43. Rusinek, A., and Klepaczko, J. R., *Constitutive relations in 3-D for a wide range of strain rates and temperatures – Application to mild steels*. International Journal of Solids and Structures. 2007. **44**: p 5611-5634.
44. Klepaczko, J., *Thermally Activated Flow and Strain Rate History Effects for Some Polycrystalline FCC Metals*. 1974, National Technical Information Service.
45. Klepaczko, J. R., *Quasi-static and Dynamic Shearing of sheet metals*. Eur. J. mech. A/Solids. 1999. **18**: p 271-289.
46. Johnson, G. R., and Cook, W. H., *A Constitutive Model and Data for Metals subjected to Large Strains*. High Strain Rates and High Temperatures, Proc. Seventh Int. Symp. on Ballistic, 1983. p 541-547.
47. Lin, Y. C., and Chen, X. M., *A Modified Johnson-Cook Model for Tensile Behaviors of Typical High-Strength Alloy Steel*. Materials Science and Engineering A 2010. **527**: p 6980-6986.
48. JFE Steel Corporation. *Cold Rolled Steel Sheet* . Japan. Brochure. 2007.
49. Mohamad Suhaimi Bin Samsudin (2007). *Investigation on the Different Types of Materials of Joining for Automotive Panel*. Bachelor Degree, University Malaysia Pahang.
50. Steel Tube Institute. *Hollow Structural Sections Dimensions and Sections Properties*. North America. Brochure. 2005.
51. Charles, L. M. Glow Discharge Atomic Emission Spectrometry. *ILAP Conference*. 2008.
52. Leco Corperation. *Glow Discharge Spectroscopy*. Lakeview Avenue. Brochure. 2004.
53. Pace Technologies. *Metallographic Specimen Preparation Basics*. Tucson. Brochure. 2005.
54. Pace Technologies. *Compression mounting*. Tucson. Brochure. 2010.
55. Sullivan, J. F. *Technical Physics*, Wiley, 1998.