# EVALUATION OF RUSINEK-KLAPACZKO MODEL FOR HIGH STRAIN RATE RESPONSE OF STEEL SHEETS

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To my beloved father and mother

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# ABSTRACT

Automotive steel sheet structures are likely to experience high strain-rate loading during impact and crash conditions. A quasi-static stress-strain at low strain rate data alone may not give an accurate numerical prediction of sheet metal structure behaviour at high strain rates. In this study, the response of sheet metal which is low carbon steel with 0.045 C (wt %) and high strength steel, DP600 subjected to high strain rates loading is investigated. The Rusinek-Klapaczko (R-K) constitutive model is employed to predict the material behaviour at varying strain rates because the model incorporates strain, strain rates and temperature evaluation terms. In order to characterize the response of sheet metal at high strain rates, tensile experiments using an Instron machine were carried out at strain rates between 0.001 $s^{-1}$ until 0.1 $s^{-1}$ as a quasi-static rates and together with published high strain rate data up to the range of 500 $s^{-1}$ was employed. These true stress-strain curves are used to extract the parameters of the R-K model. The R-K model predictive capability is then assessed by simulating a tensile test using finite element method (FEM). It was found that the R-K model is able to predict the tensile behaviour of the materials with an error of about 5 %. The validated R-K model was then incorporated into a FE simulation of bending of thin-walled tube made of low carbon steel and the results were compared with the experimental observation. It was found that the deformation of the structure has a good agreement with the experimental observation. The R-K model was also able to adequately capture the variation of the plastic strain rate in the structure.

# ABSTRAK

Struktur kepingan besi automotif kebiasaannya akan mengalami terikan berkadar tinggi ketika hentaman dan perlanggaran. Data tegasan-terikan kuasi-statik pada kadar terikan yang rendah semata-mata tidak dapat memberikan ramalan berangka yang tepat tentang kelakuan struktur kepingan besi pada kadar terikan yang tinggi. Di dalam kajian ini, tindak balas kepingan keluli iaitu keluli karbon rendah dengan kandungan karbon 0.045 C (wt %) dan keluli berkekuatan tinggi, DP600 terhadap bebanan terikan tinggi akan dikaji. Model Rusinek-Klapaczko (R-K) digunakan untuk meramal kelakuan kepingan besi pada terikan yang berbeza-beza kerana model ini menggabungkan terikan, kadar keterikan dan taksiran suhu. Untuk mencirikan tindak balas kepingan kaluli pada terikan berkadar tinggi, eksperimen tegasan menggunakan mesin Instron telah di jalankan pada kadar 0.001 $s^{-1}$ sehingga 0.1 $s^{-1}$ untuk terikan berkadar rendah dan bersama-sama data berterikan tinggi yang telah sedia ada sehingga lingkungan kadar 500 $s^{-1}$ telah digunakan. Graf tegasan-terikan ini digunakan untuk mendapatkan parameter-parameter bagi model R-K. Kebolehan meramal oleh model R-K dinilai dengan mensimulasi ujian tegangan menggunakan kaedah unsur terhingga. Didapati bahawa model R-K boleh meramalkan tingkah laku tegangan bahan dengan ralat sebanyak 5 %. Model R-K yg telah disahkan kemudian digabungkan ke dalam simulasi lenturan tiub berdinding nipis diperbuat daripada keluli karbon rendah dan keputusan yang diperolehi dibandingkan dengan eksperimen. Keputusan menunjukkan bahawa ubah bentuk struktur mempunyai persetujuan yang baik dengan eksperimen. Model R-K juga berkebolehan untuk menangkap variasi terikan plastik di dalam struktur dengan memadai.

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# LIST OF ABBREVIATIONS

| | | |
|---|---|---|
| LCS | - | Low Carbon Steel |
| ASTM | - | American Society for Testing and Materials |
| J-C | - | Johnson –Cook Material Model |
| Z-A | - | Zerilli-Armstrong Material Model |
| R-K | - | Rusinek-Klepaczko Material Model |
| BCC | - | Body Centered Cubic |
| FCC | - | Face Centered Cubic |
| AHSS | - | Advanced High Strength Steels |
| FE | - | Finite Element |
| SEM | - | Scanning Electron Microscope |
| UTS | - | Ultimate Tensile Strength |
| MES | - | Mechanical Equation of State |
| VUHARD | - | Name of user material subroutine |
| GDS | - | Glow Discharge Spectrometer |
| AES | - | Atomic Emission Spectroscopy |
| SHBT | - | Split Hopkinson bar test |
| MOSTI | - | Ministry of Science, Technology and Innovation |

# LIST OF SYMBOLS

| | | |
|---|---|---|
| $E$ | - | Young's modulus |
| $\sigma$ | - | Stress |
| $\sigma_n$ | - | Nominal stress |
| $F$ | - | Force |
| $A_0$ | - | Area of the tension test specimen |
| $A$ | - | Current cross-sectional area of the tension test specimen |
| $l_0$ | - | Original tension test specimen length |
| $l$ | - | Current gauge length of the tension test specimen |
| $\varepsilon$ | - | Strain |
| $\varepsilon_T$ | - | True strain |
| $\varepsilon_p$ | - | Plastic strain |
| $\dot{\varepsilon}$ | - | Strain rate |
| $\dot{\varepsilon}_{max}$ | - | Maximum strain rate |
| $\dot{\varepsilon}_{min}$ | - | Minimum strain rate |
| $T$ | - | Temperature |
| $T_r$ | - | Room temperature |
| $T_m$ | - | Melting temperature |
| $T_0$ | - | Initial temperature |
| $\Delta T$ | - | Temperature increment |
| $n$ | - | Strain hardening coefficient |
| $\sigma_{eq}$ | - | Johnson-Cook equivalent stress |
| $T^*$ | - | Johnson-Cook homologous temperature |
| $A$ | - | Johnson-Cook material constant |
| $B$ | - | Johnson-Cook material constant |
| $C$ | - | Johnson-Cook material constant |

| | | |
|---|---|---|
| $m$ | - | Johnson-Cook temperature sensitivity |
| $\dot{\varepsilon}_p$ | - | Johnson-Cook dimensionless strain rate |
| $\dot{\varepsilon}_{po}$ | - | Johnson-Cook nominal strain rate |
| $C_1$ | - | Zerilli-Armstrong parameters |
| $C_2$ | - | Zerilli-Armstrong parameters |
| $C_3$ | | Zerilli-Armstrong parameters |
| $C_4$ | - | Zerilli-Armstrong parameters |
| $C_5$ | - | Zerilli-Armstrong parameters |
| $\Delta\sigma'_G$ | - | Zerilli-Armstrong additional stress influence of solute and |
| | - | the original dislocation density |
| $k$ | - | Zerilli-Armstrong microstructure stress intensity |
| $l^{-0.5}$ | - | Zerilli-Armstrong inverse square root at the average grain |
| | - | diameter |
| $\bar{\sigma}$ | - | Rusinek-Klepaczko total stress |
| $\sigma_u$ | - | Rusinek-Klepaczko internal stress |
| $\sigma^*$ | - | Rusinek-Klepaczko effective stress |
| $E_0$ | - | Rusinek-Klepaczko Young's modulus at $T = 0K$ |
| $\theta^*$ | - | Rusinek-Klepaczko characteristic homologous temperature |
| $\sigma_0^*$ | - | Rusinek-Klepaczko effective stress at $T = 0K$ |
| $m^*$ | - | Rusinek-Klepaczko material constant |
| $D_1$ | - | Rusinek-Klepaczko material constant |
| $D_2$ | - | Rusinek-Klepaczko material constant |
| $v$ | - | Rusinek-Klepaczko temperature sensitivity |
| $\varepsilon_0$ | - | Rusinek-Klepaczko strain at the yield stress |
| $B_0$ | - | Rusinek-Klepaczko plasticity modulus at $T = 0K$ |
| $n_0$ | - | Rusinek-Klepaczko strain hardening exponent at $T = 0K$ |
| $\beta$ | - | Taylor–Quinney coefficient |
| $\rho$ | - | Material density |
| $C_\rho$ | - | Specific heat |
| $\varepsilon_{1,2}$ | - | Principal in-plane strains |
| $\delta$ | - | Displacement |
| $\dot{\delta}$ | - | Displacement rate |
| $U_x$ | - | Displacement in X-axis |

| | | |
|---|---|---|
| $U_y$ | - | Displacement in Y-axis |
| $UR_z$ | - | Displacement in Z-axis |
| $UR_x$ | - | Rotation about X-axis |
| $UR_y$ | - | Rotation about Y-axis |
| $UR_z$ | - | Rotation about Z-axis |
| $\sigma_{vm}$ | - | von Mises stress |
| Ø | - | Diameter |

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# CHAPTER 1

# INTRODUCTION

## 1.1 Background of Study

Many advanced processes in engineering such as high-speed metal forming and cutting, metallic structures under crash and high speed impact, involve complex thermo mechanical and multi axial loading conditions which include large strain, high strain rates, temperature softening and adiabatic processes. Over the last few decades, deformation of metals has been subjected to intensive study since it is of fundamental interest in analysing failure processes. The mechanical behaviour of sheet metals under dynamic loading such as sheet metal forming is different from that under static or quasi-static loading. When a structure deforms in a dynamic state, the material properties such as strength, stiffness and yield stress are affected by strain rate [1]. As strain rate is increased from quasi-static to dynamic, conditions change from isothermal to fully adiabatic, resulting in a gradual decrease in strength with increasing strain rates [2]. However, the flow stress also highly depends on many other factors such as strain path, strain rate and temperature history. This stress-strain response can be represented using a constitutive model with temperature and strain rate dependent variables. Only a model that includes all of these pertinent factors is capable of predicting the complex stress state in material deformation [3].

Thus, the main task of constitutive model is to predict precisely the response of engineering structures under large deformation such as impact loading [4].

In this research sheet metal behaviour under high strain rate loading which is commonly found in the automotive industry is studied. The material properties and behaviour are obtained from tensile testing for quasi-static state and from published data, especially for the high strain rate state. After that, it continued with determination of parameter extraction from experimental data for material model. Rusinek-Klepaczko model is employed to describe the rate-dependent plastic behaviour of sheet metal at various strain rates. Their properties include yield stress, plastic modulus and fracture strain. Then the mechanic behaviour of sheet metal is demonstrated using finite element method with implemented of material model. Then all of these features are applied into thin walled tube flexural deformation test.

## 1.2 Overview

Sheet metals are commonly used in industrial application such as automotive body such as low carbon sheet metal and high strength steel [5]. Most of the auto-body metal parts are produced from sheet metal forming such as stamping process. Moreover, in automotive industries light-weight and safe design of auto-body structures are the main objectives and challenging to achieve in order to increase fuel efficiency, satisfying emission-gas vehicle regulations vehicles and to ensure the safety of passengers in the event of an accident. To achieve these objectives, crash analyses either from experiment or numerical modelling of the high speed material deformation have to be accurately carried out with accurate stress-strain curves at the high strain rate. The dynamic tensile properties of auto-body steel sheets are important since the range of the strain rate is 500 $s^{-1}$ in a real auto-body crash [6] and from 10 $s^{-1}$ to 100 $s^{-1}$ in sheet metal forming [3] at which the dynamic response of steel sheets is different from quasi-static.

The flow stress of a material generally increases as the strain rate increases. It is well known that the behaviour of sheet metals is strongly dependent on the strain rate and temperature. Worked materials in these large deformation processes such as stamping and crashworthiness experience a broad range of strain, strain rate, temperature, and complex loading histories. To describe precisely the behaviour of materials at high strain rates and temperatures, constitutive model which is widely applicable and capable of accounting complex stress state in material deformation was used [3]. The constitutive model will implement into finite element to develop models which are widely applicable and capable of accounting for complex paths of deformation, temperature and strain rate which represents the main requirements of large deformation problems.

There is always a balance between testing and numerical modelling. If one does no testing, which may be a very expensive task then the production becomes a very high-risk effort. If one does no numerical modelling, then all design decisions are based on experience or an expensive testing [7]. Finite element (FE) analysis is an alternative method for investigating the sheet metal behaviour under various loading rate issues. By using FE analysis, the mechanics behaviour of sheet metal such as distributions and evolution of stress and strain can be predicted. Generally, the purpose of using FE analysis is to grow the design space and shrink the test space. For example, one of the goals of the automotive industry is to reduce the cost associated with the safety evaluation of structures. Thus, the industry has increasingly moved towards finite element simulation of crash tests with fewer numbers of actual experiments. Good constitutive model is needed for the accuracy of FE simulation results is highly dependent on material constitutive model, accurate geometry, loading conditions and boundary conditions employed in the FE model [7].

To develop FE model the thermo-visco-plastic behaviour of sheet metal under higher strain rates, several constitutive relations can be found in the literature such as Johnson-Cook (J-C) [8] model and Zerilli-Armstrong (Z-A) [9] model. However, J-C [8] models and Z-A [9] models for work hardening of metals are not physically based, their usage is limited only to the range of deformation conditions at which they were curve fitted, and the accuracy is often not satisfactory. What is missing in these models is the ability to capture history effects of temperature, strain rate, and load path in manufacturing processes [3]. Temperature history effects are magnitude in lower hardening behaviour and properties as the material. Prolonged exponent to temperature induces creep of the material. Thus, the more sophisticated material model which is a function of strain hardening, strain rate and temperature sensitivities of flow stress have been proposed by Rusinek and Klepaczko (R-K) [6] model. The R-K constitutive relation is used because the precise constitutive modelling can predict the loading rate effects in terms of strain rate and temperature sensitivity [6].

## 1.3 Problem Statement

Sheet metals such as low carbon steel and high strength steel are commonly used to fabricate the auto-body structures. Under large deformation such as stamping and crashworthiness, structural materials are subject to very high rates of strain and complex loading histories. Many material properties, including those of the sheet metal are strain rate sensitive. Consequently, quasi-static stress-strain data may not produce accurate predictions of behaviour at high strain rates, and the use of such data in the analysis and design of dynamically loaded structures can lead to cautious overweight designs or premature structural failure. Because of its high flow stress, the thermal coupling in the form of adiabatic heating leading the thermal softening and material instabilities cannot be neglected, especially at high strain rates and large deformation. In order to examine deformation fields under different conditions of loadings, expensive process and testing were involved. Thus, finite element (FE) analysis is an alternative method for investigating the sheet metal behaviour under various loading rate issues by implementing the sophisticated constitutive model. Therefore, to establish the model parameters and to validate the constitutive model, experimental and FE simulation techniques are presented. The FE results then will validate with experiments to demonstrate prediction capability of FE and constitutive model. The R-K model is chosen in this study to accumulate predict material response at varying strain rates because the model incorporates hardening, strain rates and temperature evaluation terms.

## 1.4 Objectives

The objectives of this research project are:

1. To determine the properties and quantify behaviour for automotive sheet metals of low carbon and high strength steels.
2. To validate true stress-plastic strain behaviour of sheet metal at strain rates in the range of up to $200s^{-1}$ for low carbon sheet metal and $500s^{-1}$ for high strength steel.
3. To establish a predictive capability of Rusinek-Klepaczko (R-K) constitutive model through FE simulation of a thin-walled tube under flexural loading.
4. To develop FORTRAN coding of the R-K model for use in FE simulation software

## 1.5 Scope of Study

The present study focuses on sheet metal behaviour and is limited to the following scope of work:

1. The nominal sheet thicknesses for low carbon steel and DP600 are 0.7mm and 1.2mm, respectively while for thin-wall tube the thickness of the sheet is 1mm.
2. Mechanical properties and behaviour of sheet metal will be established in accordance to ASTM E8/E8M standards or equivalent. These tests

will be conducted at room temperature and at straining rates ranging from $0.001667s^{-1}$ to $0.1667s^{-1}$.

3. Rusinek-Klepaczko (R-K) constitutive model parameters will be extracted from three experimental tension test data at $0.001667s^{-1}$, $0.1667s^{-1}$ and $200s^{-1}$ for low carbon steel while three tension test data at $0.0001s^{-1}$, $0.001667s^{-1}$ and $500s^{-1}$ for DP600.
4. A subroutine of the R-K constitutive model will be constructed writing and implement in Abaqus software for general loading FE.
5. Finite element model on flexural test of a thin - walled tube made of low carbon steel is simulated for prediction capability of the R-K constitutive model.

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