NUMERICAL STUDY OF LOCALIZATION FAILURE IN STRUCTURAL STEEL UNDER IMPACT LOADING

A THESIS IN CIVIL ENGINEERING
Master of Science in Civil Engineering

Presented to the faculty of the American University of Sharjah
College of Engineering
in partial fulfillment of
the requirements for the degree

MASTER OF SCIENCE

by
Fadi S. Makarem
B.S. 2008

Sharjah, UAE
October 2011
We approve the thesis of Fadi S. Makarem

<table>
<thead>
<tr>
<th>Name</th>
<th>Title</th>
<th>Department/Role</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dr. Faird H. Abed</td>
<td>Associate Professor</td>
<td>Department of Civil Engineering</td>
</tr>
<tr>
<td>Dr. Mohammad Al-Hamaydeh</td>
<td>Assistant Professor</td>
<td>Department of Civil Engineering</td>
</tr>
<tr>
<td>Dr. Basil M. Darras</td>
<td>Assistant Professor</td>
<td>Department of Mechanical Engineering</td>
</tr>
<tr>
<td>Dr. Hisham Ibrahim</td>
<td></td>
<td>Department of Civil &amp; Environmental Engineering</td>
</tr>
<tr>
<td>Dr. Jamal Abdulla</td>
<td>Department Head</td>
<td>Department of Civil Engineering</td>
</tr>
<tr>
<td>Dr. Hany El Kadi</td>
<td>Associate Dean</td>
<td>College of Engineering</td>
</tr>
<tr>
<td>Dr. Yousef Al-Assaf</td>
<td>Dean</td>
<td>College of Engineering</td>
</tr>
<tr>
<td>Dr. Gautam Sen</td>
<td>Vice Provost</td>
<td>Research &amp; Graduate Studies</td>
</tr>
</tbody>
</table>
NUMERICAL STUDY OF LOCALIZATION FAILURE IN STRUCTURAL STEEL UNDER IMPACT LOADING

Fadi Shaker Makarem, Candidate for the Master of Science in Civil Engineering

American University of Sharjah, 2011

ABSTRACT

High quality steels are used as a skeleton supporting many infrastructure constructions like, for example, skyscrapers, arenas, stadiums, bridges and others. The likelihood that these structures could be severely damaged by postulated accidental extreme loading has been increased recently. Such loading may come about due to impact, blast or fluid jet impingement etc., and is usually of high intensity but short duration. Since most steel structures are capable of absorbing a considerable amount of energy beyond the elastic range, analysis has to extend into the inelastic range in order to avoid excessively pessimistic assessments.

This research presents a consistent methodology for the assessment of nonlinear behavior of structural steel under low and high velocity impacts. Three high strength low alloy steels were considered in this study; HSLA-65, DH-36 and HY-100. Four well-known constitutive models for viscoplastic deformation of metals, i.e., Johnson-Cook (JC), Zerilli-Armstrong (ZA), Rusinek-Klepaczko (RK), and Voyiadjis-Abed (VA), were investigated and compared with reference to existing experimental data. The VA constitutive model was chosen among the others as it exhibited dominant performance in describing the thermoplastic deformation of ferrite steel at a wide range of temperatures and strain rates. The VA model was then integrated and implemented into the commercial finite elements code ABAQUS/Explicit via user material subroutine coded as VUMAT.

Finite elements simulation of the formation of shear localizations in a cylindrical hat-shaped specimen was conducted for two ferrite steel alloys, HSLA-65 and DH-36, subjected to certain range of velocity impact. The effect of the VA
microstructure based material parameters on the initiation and propagation of shear localization was also investigated. Several conclusions related to the width of the shear bands considering various velocities and temperatures were thoroughly discussed. Finally, a preliminarily study on localization failure in axially preloaded columns made of high strength steel HY-100 (lowest yield stress = 100 ksi) subjected to transverse impact is presented. The effect of impact velocity, impactor mass, impact location and preloading condition on the behavior and failure modes of the steel columns is investigated in an attempt to develop appropriate design calculation methods for steel columns under such loading conditions.
CONTENTS

ABSTRACT ...................................................................................................................... iii
LIST OF ILLUSTRATIONS .............................................................................................. vii
LIST OF TABLES ........................................................................................................... x
ACKNOWLEDGEMENTS ............................................................................................... xi

1. INTRODUCTION .................................................................................................... 1
   1.1 Introduction ......................................................................................................... 1
   1.2 Problem Statement ........................................................................................... 3
   1.3 Objectives and Scope of the Study ................................................................... 4
   1.4 Thesis Structure ............................................................................................... 5

2. BACKGROUND AND RESEARCH METHODOLOGY .................................... 7
   2.1 Literature Review ............................................................................................ 7
   2.2 Methodology .................................................................................................. 11
       2.2.1 Overview ................................................................................................. 11
       2.2.2 Constitutive Model Implementation into the FE Code ABAQUS .......... 13
       2.2.3 Model Validation and Applications ..................................................... 15

3. COMPARISONS OF CONSTITUTIVE MODELS FOR STEEL OVER A WIDE RANGE OF TEMPERATURES AND STRAIN RATES ........................................ 18
   3.1 Introduction ..................................................................................................... 18
   3.2 Constitutive Models ....................................................................................... 19
       3.2.1 JC Model ............................................................................................... 20
       3.2.2 ZA Model ............................................................................................. 21
       3.2.3 RK Model ............................................................................................ 22
       3.2.4 VA Model ............................................................................................ 23
   3.3 Application of Models to HSLA-65 and DH-36 ............................................. 24
   3.4 Results and Discussions ................................................................................. 26
   3.5 Nomenclature ................................................................................................. 35

4. CONSTITUTIVE MODEL IMPLEMENTATION AND VERIFICATION 36
   4.1 Introduction ..................................................................................................... 36
   4.2 Algorithmic Treatment of the VA Model for 3D Applications .................... 36
   4.3 Axisymmetric Uniaxial Compression Problem ............................................ 37
LIST OF ILLUSTRATIONS

Figure 1. Severe damage in steel building beam due to impact load and fire............................ 2
Figure 2. Damage and distortion in steel bridge beam due to impact with over-height truck... 2
Figure 3. Research Methodology ............................................................................................. 12
Figure 4. Implementation methodology adopted in the User-defined subroutine VUMAT in
  ABAQUS ................................................................................................................................... 14
Figure 5. Geometric description of simple uniaxial compression problem............................ 15
Figure 6. Cylindrical hat-shaped specimen .............................................................................. 16
Figure 7. Geometric description of column impact problem.................................................... 17
Figure 8. True stress-true strain curves produced by ZA, JC, RK and VA models at high strain
  rates and various initial temperatures compared to experimental data for HSLA-65
  ........................................................................................................................................................ 27
Figure 9. True stress-true strain curves produced by ZA, JC, RK and VA models at low strain
  rates and various initial temperatures compared to experimental data for HSLA-65
  ........................................................................................................................................................ 27
Figure 10. True stress-true strain curves produced by ZA, JC, RK and VA models at 77 K
  initial temperature for different strain rates compared to experimental data for HSLA-65
  ........................................................................................................................................................ 28
Figure 11. True stress-true strain curves produced by JC, RK and VA models at high strain
  rates and various initial temperatures compared to experimental data for DH-36.29
Figure 12. True stress-true strain curves produced by JC, RK and VA models at low strain
  rates and various initial temperatures compared to experimental data for DH-36.29
Figure 13. True stress-true strain curves produced by JC, RK and VA models at 77 K initial
  temperature and low and high strain rates compared to experimental data for DH- 36
  ........................................................................................................................................................ 30
Figure 14. Variations of degree of fit for each model with temperatures for HSLA-65 at strain
  rates of: (a) 0.001 s\(^{-1}\), (b) 0.1 s\(^{-1}\), (c) 3000 s\(^{-1}\) and (d) 8500 s\(^{-1}\) ............................ 33
Figure 15. Variations of degree of fit for each model with temperatures for DH-36 at strain
  rates of: (a) 0.001 s\(^{-1}\), (b) 0.1 s\(^{-1}\), (c) 3000 s\(^{-1}\) and (d) 8500 s\(^{-1}\) ............................ 33
Figure 16. Variations of degree of fit with strain rates for different material models (a) HSLA-
  65 and (b) DH-36 ..................................................................................................................... 34
Figure 17. Problem description of simple uniaxial compression ............................................ 38
Figure 18. Axisymmetric simple uniaxial compression modeled in ABAQUS, V=30 m/s and
  T\(_o\)=400 K: (a) Undeformed shape (b) Deformed shape at the end of a time step =
  200 \(\mu\)s. ...................................................................................................................................... 39
Figure 19. Comparisons of the true stress-true strain between experimental and FE results for
  HSLA-65 at different initial temperatures and two strain rates of (a) 0.001 s\(^{-1}\) and
  (b) 0.1 s\(^{-1}\) .................................................................................................................................. 40
Figure 20. Comparisons of the adiabatic true stress-true strain between experimental and FE
  results for HSLA-65 at different initial temperatures and two strain rates of (a)
  3000 s\(^{-1}\) and (b) 8500 s\(^{-1}\) ...................................................................................................... 40
Figure 21. Comparisons of the true stress-true strain between experimental and FE results for
  DH-36 at different initial temperatures and two strain rates of (a) 0.001 s\(^{-1}\) and (b)
  0.1 s\(^{-1}\) .................................................................................................................................... 41
Figure 22. Comparisons of the true stress-true strain between experimental and FE results for DH-36 at different initial temperatures and two strain rates of (a) 3000 s\(^{-1}\) and (b) 8500 s\(^{-1}\). .................................................................41

Figure 23. Comparisons of the true stress-true strain between experimental and FE results for DH-36 at different initial temperatures and two strain rates of (a) 3000 s\(^{-1}\) and (b) 8500 s\(^{-1}\). ..................................................................................................................42

Figure 24. Cut through the cylindrical hat-shaped specimen ........................................................................48

Figure 25. Modeled hat-shaped specimen (a) axisymmetric mesh element (b) a three-dimensional shape corresponding to half of the sample ........................................................................49

Figure 26. Mesh geometry and mesh refinement in the shear zone for a quarter of the sample ...............50

Figure 27. Shear stress for three different meshes configuration at T\(_0\)=77 K ..............................................50

Figure 28. Path-1 through the shear zone of the hat-shaped specimen ..............................................................51

Figure 29. Distribution of the equivalent plastic strain for HSLA-65 across path-1 for different mesh configurations (a) T\(_0\)=296 K (b) T\(_0\)=400 K .................................................................51

Figure 30. Contour plot of the equivalent plastic strain (shear bands) at velocity =25 m/s and T\(_0\) = 296 K ..................................................................................................................52

Figure 31. Contours of the equivalent plastic strain (shear bands) at 0.2 mm axial displacement and different temperatures, HSLA-65 Steel ..........................................................53

Figure 32. Contours of the equivalent plastic strain (shear bands) at 0.2 mm axial displacement and different temperatures, DH-36 steel ..........................................................53

Figure 33. Equivalent plastic strain at V=25 m/s, 0.2 mm axial displacement and different temperatures along path-1: (a) HSLA-65, (b) DH-36 .................................................................54

Figure 34. Contour of the equivalent plastic strain (shear bands) at 0.2 mm axial displacement and different velocities, HSLA-65 Steel ..........................................................55

Figure 35. Contour plot of the equivalent plastic strain (shear bands) at 0.2 mm axial displacement and different velocities, DH-36 steel ..........................................................55

Figure 36. Equivalent plastic strain at initial T=77 K, 0.2 mm axial displacement and different velocities: (a) HSLA-65, (b) DH-36 ...........................................................................56

Figure 37. Contour plot of the equivalent plastic strain (shear bands) at 0.2 mm axial displacement and different values of material constant c\(_2\) ................................................58

Figure 38. Contour plot of the equivalent plastic strain (shear bands) at 0.2 mm axial displacement and different values of material constant c\(_3\) ................................................58

Figure 39. Contour plot of the equivalent plastic strain (shear bands) at 0.2 mm axial displacement and different values of material constant c\(_4\) ................................................59

Figure 40. Contour plot of the equivalent plastic strain (shear bands) at 0.2 mm axial displacement and different values of material constant c\(_6\) ................................................59

Figure 41. Contour plot of the equivalent plastic strain (shear bands) at 0.2 mm axial displacement and different values of material constant c\(_6\) ................................................60

Figure 42. Equivalent plastic strain for HSLA-65 steel when changing the model parameters at 0.2 mm axial displacement: (a) c\(_2\), (b) c\(_3\), (c) c\(_4\), (d) c\(_5\), (e) c\(_6\) ................................................61

Figure 43. Equivalent plastic strain for DH-36 steel when changing the model parameters at 0.2 mm axial displacement: (a) c\(_2\), (b) c\(_3\), (c) c\(_4\), (d) c\(_5\), (e) c\(_6\) ................................................62

Figure 44. (a) Geometric description of the steel column impact problem, (b) Column cross-section. ..................................................................................................................66

Figure 45. Rigid impactor of 0.34x0.5x1.5 m .......................................................................................67

Figure 46. Two Impact locations: (a) 1 m from bottom support (b) 1.5 m from bottom support. ..................................................................................................................67
Figure 47. Column mesh configurations: (a) 20mm mesh, (b) 60mm mesh, (c) 20mm mesh
Figure 48. Axial displacement at top support: (a) 1.0 m impact location, 40 km/h, 1 Ton
impactor, (b) 1.5 m impact location, 40 km/h, 6 Ton impactor
Figure 49. Flange distortion at the location of impact: 1.0 m impact location, 1.0 Ton
impactor: (a) 40 km/hr (b) 80 km/hr
Figure 50. Axial displacement at top support for: 1) 1.0 m impact location, 20 km/hr, 3.0 Ton
impactor, 2) 1.5 m impact location, 80 km/hr, 6.0 Ton impactor
Figure 51. Column deformed shape with time, P/P_d=0.7 (a) 20 km/hr, 1.0 m impact location,
3.0 Ton impactor (b) 80 km/hr, 1.5 m impact location, 6.0 Ton impactor
Figure 52. Equivalent plastic strain at V=40 km/hr, P/P_d=0.7, Impactor 1.0 Ton
Figure 53. Four paths along: (a) flange width and length, (b) web depth and length
Figure 54. Equivalent plastic strain along true path distance at 40 km/hr impact velocity, 1.0
m impact location, 1.0 Ton impactor and P/P_d=0.0, along flange width, (b) along
flange length, (c) along web depth, and (d) along web length
Figure 55. Equivalent plastic strain along true path distance at 80 km/hr impact velocity, 1.0
m impact location, 1.0 Ton impactor and P/P_d=0.0, (a) along flange width, (b)
along flange length, (c) along web depth, and (d) along web length
Figure 56. Equivalent plastic strain along true path distance at 80 km/hr impact velocity, 1.5
m impact location, 3.0 Ton impactor and P/P_d=0.0, (a) along flange width, (b)
along flange length, (c) along web depth, and (d) along the web length
Figure 57. Equivalent plastic strain along true path distance at 80 km/hr impact velocity, 1.5
m impact location, 6.0 Ton impactor and P/P_d=0.0, (a) along flange width, (b)
along flange length, (c) along web depth, and (d) along the web length
Figure 58. Time history at localization area and P/P_d=0.0 of: (a) Temperature (Kelvin), (b)
Equivalent plastic strain
Figure A.1 True stress-true strain experimental data at varying strain rates: (a) HSLA-65, 77
K, (b) HSLA-65, 296 K, (c) HSLA-65, 400 K, (d) HSLA-65, 700 K, (e) DH-36,
77 K, (f) DH-36, 296 K
LIST OF TABLES

Table 1: Johnson-Cook (JC) material constants for HSLA-65 and DH-36 ....................... 25
Table 2: Zerilli and Armstrong (ZA) material model constants for HSLA (H_Nb) steel ...... 25
Table 3: Rusinek-Klepaczko (RK) material constants for HSLA-65 and DH-36 .................. 25
Table 4: Voyiadjis-Abed (VA) material constants for HSLA-65 and DH-36 ................... 25
Table 5: VA model material parameters for HY-100 steel ........................................... 38
Table 6: Dimensions (mm) for ferrite steel hat-shaped sample ..................................... 48
Table 7: Variation in the VA model material parameters for HSLA-65 and DH-36 steel ..... 57
Table 8: Chemical composition of HY-100 steel (by weight %) .................................... 68
ACKNOWLEDGEMENTS

This research project would not have been possible without the support of many people. I would like to express my deepest sense of gratitude to my supervisor Dr. Farid Abed for his genuine concern and continuous support. The valuable advices of Dr. Abed, his patient guidance and encouragement throughout my thesis paved the way to accomplish this work successfully.

Deepest gratitude is also due to the members of the supervisory committee, Dr. Jamal Abdalla, Dr. Mohammad Al-Hamaydeh, Dr. Basil M. Darras and Dr. Hisham Ibrahim for their invaluable assistance, excellent advices and abundant help.

Finally, the author would like to express profound gratitude to his beloved parents and family for their infinite support and understanding during his study.
The difference between ordinary and extraordinary is that little extra
CHAPTER 1

INTRODUCTION

1.1 Introduction

Steel products are used extensively in many fields such as automotive, railways, aerospace, naval and civil engineering structural applications. In fact, steel became one of the most important and necessary products used in the construction industry especially after the effort made by steelmakers to produce new generation of high performance steels. Steel producers fabricate thousands of tons every year to be used in constructing long span bridges such as arched, suspension and cable stayed bridges and skyscrapers. Several cross sections (for plates, beams and columns) can be made of high quality steel. For instance, a specific profile for structural element cross section (i.e. rectangular and I-sections) corresponding to certain size can be fabricated from structural steel. The main reasons behind the widespread of steel products in the civil engineering construction industry can be summarized as follows:

1. High strength/weight ratio (smaller/thinner sections can be used).
2. Durability and resistance to environmental weathering.
3. High ductility and toughness.
4. Ease of construction (weldability, fabrication and installation).
5. Aesthetic reasons (steel formed to build nice shapes).

High strength ferrite steels, which are extensively used in several types of structures due to the reasons mentioned above, are vulnerable to many types of damage during their design life time such as damages due to earthquakes, fire, steel corrosion, overloading, fracture, etc. This study, however, is concerned with localization damage of steel structure under the effect of impact loading. Steel structures that are capable of absorbing considerable amount of energy beyond the elastic range might be subjected to damage due to intentional or accidental impact loads. An example of this could be a vehicle collision (i.e. Cars and Lorries) moving with high velocity against a structural steel column in a parking building or bridge pier. This could induce large deformation and severe distortion in the structural member beyond the elastic limit (see, for example, Figures 1 and 2). In this case, the
analysis has to extend into the inelastic range in order to avoid excessively pessimistic assessments for the effect of impact on these structural members. Besides, non-linear analysis will describe the severe plastic deformation in steel structures components more accurately before they fail under dynamic velocity load. In many industrial applications, safety considerations may make it necessary to assess the response of a structure to such loading. However, conventional design codes are currently not suitable for the assessment of the effects of extreme loading on these structures.

Figure 1. Severe damage in steel building beam due to impact load and fire

Figure 2. Damage and distortion in steel bridge beam due to impact with over-height truck
1.2 Problem Statement

Nowadays, steel construction became one of the most booming industries around the world. This industry involves carrying out large civil engineering projects such as skyscrapers and long span bridges. It also involves construction in real estate properties such as constructing residential and commercial buildings. In order to carry out these projects, the steelmakers are required to manufacture and fabricate great amounts of steel which form the main skeleton of these structures. High-rise steel buildings, for instance, are mainly composed of many steel members connected together to form the main structural frame for the building. Constructing such mega steel structures is actually very expensive and cost a lot of efforts and time. It is, therefore, required to ensure that these structural steel members are well designed, capable of resisting all the types of damages and able to sustain extreme loading conditions even if its probability to happen might be small. This is very important in order to avoid any possible failure in the steel structures due to extreme loading events which may cause progressive collapse in the structure and unavoidable catastrophic losses in both human life and money. Structural members undergo severe deformation and large plastic strains when subjected to extreme impact loading from a high velocity moving object. Studying and understanding dynamic localizations that correspond to short duration impacts are difficult and require implementing special type of analysis where the quasi-static methods developed in the past to study the global response of the structural member are not applicable in this case. Instead, the response of the material locally to dynamic impact should be investigated.

From this perspective, the need to model the non-linear behavior of such structures under impact becomes very significant where available modern computer software helps to recur such events. Nowadays, the finite elements method has been used widely in performing nonlinear simulations to study the localization failure in many types of structures made of different materials. In the same time, this requires thorough understanding of the nonlinear response of the constituents under severe loading conditions. In order to do this, a good constitutive material model that is capable of capturing the true stress-true strain relations at severe loading conditions should be selected carefully from the literature. This task is, however, not easy because of the intricate behavior of steel dominated by the coupling effect of large plastic strains, high strain rates and temperatures during high velocity impact.
This study addresses the problem of localization failure in steel structures under severe loading conditions. It aims at understanding the behavior of high strength structural steel under impact by performing nonlinear finite element analysis using the available commercial software, ABAQUS/Explicit. The thermo-viscoplastic response of the steel material at low and high strain rates and temperatures is also investigated and implemented into the user material subroutine VUMAT. This enables ABAQUS/Explicit to determine the true stress-strain curves at extreme loading conditions. The outcomes of this study could be utilized to provide some guidelines to design codes to come up with simplified method of analysis for steel structures subjected to impact loading.

1.3 Objectives and Scope of the Study

The main objectives of this research can be summarized as follows:

- To investigate the thermo-mechanical nonlinear behavior of high strength steels such as HSLA-65, DH-36 and HY-100 used in naval, building and bridge structures, at low and high temperatures and strain rates.
- To explore and examine the available nonlinear constitutive models in the literature to select an appropriate model that is capable of capturing the complex behavior of high strength steels at extreme loading.
- To formulate a thermo-dynamically consistent three-dimensional model needed for the numerical integration of the selected constitutive equation to be implemented into the commercial finite element code ABAQUS via supported material subroutine VUMAT.
- To develop 3D finite element (FE) models capable of simulating the nonlinear deformation and damage behavior of high strength steel under various velocity impacts.
- To provide preliminary results and guidelines to engineers and design codes to come up with an appropriate procedure to address specifically the nonlinear response of high strength structural steel to impact loading.
The scope of this research included the study of the nonlinear behavior of three types of high strength low alloys structural steel, namely HSLA-65, DH-36 and HY-100, under impact load. Its main focus was to describe the thermo-mechanical behavior of these structural steels during dynamic events that involve high temperatures and strain rates. Constitutive modeling was important to be performed to describe the plastic deformation. This started by comparing four different material models which are: Johnson-Cook model (JC), Rusinek-Klepaczko model (RK), Zerilli-Armstrong model (ZA) and Voyiadjis-Abed model (VA). The study considered comparisons with experimental results to verify the performance of the implemented nonlinear model in ABAQUS/Explicit via user material subroutine coded as VUMAT. The implementation was verified at wide ranges of strain rates (i.e. 0.001, 0.1, 1000, 3000, 8000, 8500 $s^{-1}$) and temperatures (i.e. 77, 200, 213, 296, 400, 500, 700K). The scope of the proposed research utilized the verified implemented constitutive model to study shear localization in hat-shaped cylindrical specimen. In this case, shear band formation were investigated at several dynamic velocities (0.5, 1.0, 10, 20, 25, 30 m/s) and initial temperatures (77, 200, 296, 400, 500 K). The research extended in scope to conduct a preliminary study on the behavior of steel column subjected to transverse impact. The research scope considered I-section steel column with total length equal to 4.0 m and subjected to impact from the transverse direction causing localization failure around the weak axis. The corresponding column behavior and its modes of failure were assessed considering three different impactor masses of 1.0, 2.0 and 6.0 Tons moving with velocities of 20, 40 and 80 km/hr.

1.4 Thesis Structure

The research topic, problem statement, objectives and scope of the work are introduced in this introductory chapter. Chapter 2 which follows the introduction presents a literature review of some of the publications addressing the behavior of steel structures under impact loading, and also refers to some of the non-linear constitutive models that are currently used to describe the thermo-mechanical response of steel over a wide range of strain rates and temperatures. The methodology followed in carrying out the proposed research including some details about the commercial finite element software ABAQUS and its user subroutine VUMAT is also described in this chapter. Chapter 3 illustrates the comparisons carried out among four
constitutive plasticity models; Johnson-Cook model (JC), Rusinek-Klepaczko model (RK), Zerilli-Armstrong model (ZA) and Voyiadjis-Abed model (VA), for steel over a wide range of temperatures and strain rates. In this chapter, the mathematical algorithm of each constitutive model was well explained and the model (VA in this case) that exhibited very good prediction capability of the flow stress was chosen. Chapter 4 goes through the finite element (ABAQUS/VUMAT) implementation and verification of the VA constitutive model including comparisons with experimental data to test and validate the model implementation. Chapter 5 presents a study on dynamic localizations in hat-shaped specimen made of high strength low alloy steel such as HSLA-65 and DH-36 at high strain rates and temperatures. The effects of the VA model parameters on the initiation and propagation of shear localizations are also discussed. Chapter 6 describes the dynamic behavior of axially preloaded steel column subjected to transverse impact after considering different impact scenarios. Finally, summary and conclusion remarks drawn out of this study along with recommendations for future research are presented in chapter 7.
CHAPTER 2

BACKGROUND AND RESEARCH METHODOLOGY

2.1 Literature Review

Civil engineering steel structures and other types of structures are subjected to damage due to intended actions and non-intended accidents such as truck collision with a structural beam or column. The collided structural steel elements may undergo severe damage or plastic deformation before they fail. The increase of such events has motivated many researchers recently to investigate and study the mechanical response of steel structures under high velocity impact. For example, Xinzheng and Jianjing [1] carried out finite element modeling to simulate the collapse of a high-rise building under impact loading. According to them, recurring such special damage process due to impact load can be done through computer codes if proper numerical scheme and parameters are implemented. Moreover, they found out that two main reasons forced the collapse of the building: The softening of the structural elements due to fire and the impact from the progressive collapse of the upper layers. Improving structure fire resistance ability and increasing the ductility of the structural elements would have prevented the collapse of the building.

Quan et al. [2] conducted a large scale numerical simulation to investigate the structural deformation of a tower under impact. The model consisted of 270,000 beam, shell and Lagrange brick continuum elements where all the columns were modeled by beam elements whereas each floor was modeled by shell elements. The numerical simulation was carried out in four stages; the first stage was related to computing the static equilibrium under gravity, the second stage was started when an object impacted the building, the third stage was about modeling the strength and stiffness reduction of the structural elements due to both impact and fire effects and the final stage began when progressive collapse of the weakened building took place due to gravity effect. They found that half of the tower is gone after five seconds from the progressive collapse.

Other researchers such as Ferrer et al. [3] investigated the impact effect of Chevrolet pickup vehicle hitting steel column of a conventional building parking.
Their main purpose was to reassess the expressions addressed by the European regulations including the Eurocode 1 which proposes using an equivalent static approach depending on the mass and velocity of the vehicle to evaluate the response of the structural element due to collision (impact). They were able to determine the maximum displacements in the steel column through dynamic simulation approach with respect to different scenarios of vehicles’ masses and velocities. Hence, validating the accuracy of the equivalent static approach implemented in European codes was possible.

Most recently, Thairy and Wang [4] conducted a numerical finite element study to simulate the effect of transverse impact at different speeds and locations on axially compressed steel columns. The damage and failure models available in ABAQUS/Explicit were utilized to perform numerical modeling of shear and tensile tearing under impact loading. The results computed by the numerical model such as the deformed shape and transverse displacement were validated with experimental data obtained from other authors.

Number of other studies aimed at investigating the mechanical response of individual structural elements subjected to impact. For example, Zheng, et al. [5] conducted a nonlinear finite element numerical study to investigate the collision between over-high truck and bridge superstructure. The response of the bridge girders subjected to impact load was simulated and the damage in the truck and bridge was also studied. Oscar and Eduardo [6] simulated the effect of impact load on advanced high strength steel thin-walled columns using numerical finite element modeling. A failure criterion was implemented to simulate the axial deformation in the steel columns. The mean crushing force, peak load and crushed column length made of Dual Phase (DP) and High Strength Low Alloy (HSLA) steels were examined. Computed numerical results were compared with experimental values. Marzbanrad, Mehdikhanlo and Pour [7] carried out three-dimensional nonlinear finite element simulations for square, circular and elliptic thin-walled steel tubes of varying geometries to compare the energy absorption by each one under the same condition of impact load. One side of the tubes was kept rigid while the other side was modeled to be collided with impactor. The validation of their numerical model was done through comparing the simulation results with real experimental data conducted on square steel tubes. It was found out that ellipse cross section had more capability of
absorbing energy than that of square or circular cross sections. Also, using steel tubes of greater thickness increased their ability to absorb more energy.

It should be mentioned, however, that none of the abovementioned research have considered the thermo-mechanical behavior of steel at high strain rates and temperatures into their finite element numerical simulations of impact problems. Some of them assumed a constant value of yield stress that is independent of strain rate and temperature throughout the dynamic event. Others implemented the elastoplastic behavior of steel using inaccurate strain rate models that are not experimentally validated. These models are built in some of the finite element codes and meant for the use in particular applications. One main objective of the proposed work is to employ the thermo-mechanical response of high strength structural steel into the nonlinear finite modeling to simulate dynamic localizations in structures and structural components subjected to low and high velocity impact. This can be done by implementing a physically based constitutive model that is capable of describing accurately the deformation behavior of steel at complex loading.

Steel alloys properties such as hardness, ductility and weldability are controlled by altering the alloy contents and the method of heat treatment used while manufacturing such as annealing, quenching and tempering. Steels are classified into two main alloys which are ferritic such as HSLA-65, DH-36, HY-100 and Weldox 460-E and austenitic such as AL-6XN, Nitronic-50 and Uranus B66. Ferritic steel which are the main concern of this research are stronger than austenitic stainless steel while austenitic alloys exhibit higher ductility. The mechanical response (deformation, strength and failure) of steel alloys, like many other metal materials, depends on the rate of deformation as well as the evolving temperature. The knowledge of mechanical behavior of steel under low and high temperature and strain rate is required if a component made of steel is subjected to possible high-velocity impact loading. Understanding the mechanical behavior of these materials over a wide range of temperatures and strain rates has been the subject of extensive studies in the past few decades, both experimentally and theoretically (e.g., Ref. [8, 9, 10, 11, and 12]).

Many well-known constitutive material models were developed in the past to describe the nonlinear deformation behavior in metals under different conditions of temperatures and strain rates. Some of them empirically relate the stress to strain, strain rate and temperature such as Steiberg-Guinan model (SG) [13] and Johnson-
Cook model (JC) [14], while others are semi-physical and physically based material models such as Zerilli-Armstrong model (ZA) [15], Rusinek-Klepaczko model (RK) [16], the mechanical threshold model (MTS) [17], and Voyiadjis-Abed model (VA) [18]. The JC model which is widely applied in finite element computer codes due to the simplicity of it form, empirically relates the stress to strain, strain rate and temperature, the ZA model was designed to account for initial dislocation density and dislocation moving mechanism, the RK model uses semi-physical approach to simulate the true stress-true strain curves, and the VA model utilizes the thermal activation analysis and dislocations interactions mechanisms as well as the evolution of mobile dislocation density. More details about the bases and capabilities of some of these models in predicting the flow stress of ferritic steel are discussed later in Chapter 3.

Abed and Voyiadjis [19] pointed out that the degree of success of any model mainly depends on: (i) the physical basis used in the derivation process producing material parameters that are related directly to the nano-/micro-physical quantities; (ii) the flexibility and simplicity of determining material constants from a limited set of experimental data; (iii) capturing the important aspects of static and/or dynamic behavior besides being mathematically and computationally accurate. A comparison study was made among some of the abovementioned constitutive models to define the stress strain response of structural steel at extreme loadings. The main purpose of this comparison was to choose good constitutive model that could be implemented in the finite elements code ABAQUS in order to simulate the nonlinear deformation response of structural steel subjected to low and high velocity impacts.
2.2 Methodology

2.2.1 Overview

One of the main purposes of this study is to present a consistent methodology for the assessment of nonlinear behavior of structural steel under high velocity impacts. A flow chart showing the methodology followed in this proposed work is presented in Figure 3. The first task was to define the different problem aspects and understand their significance so that the target output of this study could be identified. A literature review, discussed earlier, was carried out to search for recent work on the deformation response of steel structures under impact. At the same time, extensive literature search was carried out to identify appropriate constitutive models that could be utilized to define the thermo-mechanical response of steel under extreme loading. The literature was also reviewed to find experimental data that can be used for model verification.

The next task was to select the type of structural steel to be investigated in this study. Three high strength steels were considered in this study: HSLA-65, DH-36 and HY-100 which are widely used in steel structures due to their high toughness. Simulating the behavior of steel over a wide range of strain rates and temperatures necessitates the search for a physically sound non-linear constitutive model. Several well-known constitutive models describing the nonlinear deformation behavior in steel under different conditions of temperatures and strain rates were examined in this study to determine the prediction accuracy for the flow stress of each model. A comparison study was made between four well-known constitutive models: Zerilli-Armstrong (ZA), Voyiadjis-Abed (VA), Rusinek-Klepaczko (RK) and Johnson-Cook (JC) in order to select a proper definition for the stress strain response of structural steel at extreme loadings. The four models were compared with the experimental data for two ferrite steels, HSLA-65 and DH-36, at low and high temperatures and strain rates. The model that demonstrated very good prediction of the isothermal and adiabatic flow stresses was selected to proceed forward to achieve the objectives of this study. The chosen model, VA model in this case, was then implemented into the robust finite element code ABAQUS to simulate dynamic localizations in structural steel under impact loading.
It is known that during a dynamic event the material will undergo adiabatic deformation that is associated with high strain rates. In this case, the plastic work accumulated inside the material will have no time to dissipate outside; and thus, it will be converted into heat. It is very important, therefore, to consider the heat generated inside the material as a temperature input in the proposed finite element simulations.
since this will affect the computed stresses significantly. Isothermal condition has been assumed for low strain rates and adiabatic deformation has been assumed for high strain rates [12].

2.2.2 Constitutive Model Implementation into the FE Code ABAQUS

The finite element code ABAQUS was utilized in the proposed numerical simulation to achieve the objectives of this research. This software is a general purpose program capable of modeling the non-linear behavior of solids and structures under extreme loading conditions. ABAQUS was designed to include many features. It provides the luxury of implementing several types of standard and explicit subroutines such as UMAT and VUMAT allowing the program to simulate particular structural problem. Constitutive models are allowed to be added to the program through user subroutines UMAT in ABAQUS/Standard and VUMAT in ABAQUS/Explicit. Other user subroutines such as UEL in ABAQUS/Standard and VUEL in ABAQUS/Explicit allow adding user-defined elements. Standard constitutive models subroutines use implicit time integration schemes where material stiffness matrix must be provided to form the Jacobian matrix in solving non-linear equilibrium equations. On the other hand, the Jacobian matrix is not necessarily formed in the ABAQUS/Explicit user-defined subroutines. User-defined subroutine of VUMAT type, which is the main concern of this work, was utilized in the finite element implementation of the VA constitutive model. In many cases using user-defined VUMAT is of great importance although ABAQUS constitutive library is very extensive; some models might be missing or not flexible. To explain how VUMAT fits in ABAQUS, Figure 4 shows a simplified diagram for simple cantilever subjected to tension load.
As shown in Figure 4, ABAQUS is first updated with initial boundary and load conditions to solve the equations of equilibrium. After that, the displacement or the strain calculated is fed to user-defined subroutine VUMAT in order to solve the equations of mechanics related to the stress-strain curves. Finally, the calculated true elastic or plastic stress by VUMAT is stored in the memory and another cycle is carried out depending on the defined strain increment at the very beginning of the process. Therefore, VUMAT subroutine (ABAQUS user subroutine manual, [20]):

1- Is used to define how to implement a constitutive model for a material.
2- Will be called for every block at which material calculation point is carried out.
3- Is used to update solution-dependent state variables (i.e. true stress).
4- Can use any field and independent variables (i.e. true strain, strain rate and temperature).

The VA constitutive model selected among the other models was integrated and implemented into the finite element code ABAQUS via user subroutine VUMAT. This was developed within the context of finite deformation plasticity. A previously developed VUMAT subroutine by Voyiadjis and Abed [21] for BCC metals was utilized in this study after employing some modifications related to the new constitutive relations for high strength steel. Numerical simulations were performed by using the Newton-Raphson iteration procedure with a fully backward Euler integration scheme (see for more details, Ref. [21]).
2.2.3 Model Validation and Applications

The finite element implementation of the material model was validated where the adequacy of results computed by the numerical model was checked against experimental data that were obtained from the literature. A good matching between the computed and measured data points toward a well-calibrated model. In this study, a simple axisymmetric uniaxial compression cylindrical specimen shown in Figure 5 was utilized to test and validate the proposed FE implementation. The simple compression problem was modeled in ABAQUS/Explicit to compute the flow stress in three high strength steels. Due to symmetry, only a quarter of the problem was considered and solved using a mesh of one axisymmetric element. The adequacy of the flow stress captured by the constitutive model was checked against experimental data for HSLA-65, DH-36, and HY-100 obtained by different authors and conducted at different loading rates and temperatures.

![Figure 5. Geometric description of simple uniaxial compression problem](image)

The validated VA constitutive model was then employed to perform finite element simulations on two selected impact problems. The first impact problem was conducted to simulate dynamic shear localizations in a cylindrical hat-shaped specimen (see Figure 6). The hat-shaped specimen was subjected to high velocity impact at the top and was fixed at the bottom. The objective of this simulation was to
investigate the initiation and dynamic propagation of adiabatic shear localization (shear bands) in structural steel. Two ferrite steel, HSLA-65 and DH-36, were considered in this study. The effect of the VA model parameters on dynamic localizations inducing high strain rates and temperatures was also investigated. This was done by allowing the variation in one parameter while keeping the others fixed. Five different values for each parameter were considered in this sensitivity analysis. A quarter of the cylindrical specimen meshed with axisymmetric elements was utilized in the finite element simulations. Mesh sensitivity analysis was also conducted in which fine mesh configurations were used at the regions of shear localizations.

![Figure 6. Cylindrical hat-shaped specimen](image)

The second application of the proposed finite element modeling was to simulate the impact of a moving object on an axially preloaded structural column made of high strength HY-100 steel (see Figure 7). The objective of this application was to introduce a preliminary study investigating the behavior and failure modes of structural high strength column subjected to transverse impact. A 4.0 m steel I-column which is common in many structural building was modeled in ABAQUS/Explicit using 3D solid elements. The impactor, however, was assumed to act as a rigid body. A parametric study considering different impact locations, impactor masses, impactor velocities and axial preloading conditions was also conducted.
Figure 7. Geometric description of column impact problem.
CHAPTER 3

COMPARISONS OF CONSTITUTIVE MODELS FOR STEEL OVER A WIDE RANGE OF TEMPERATURES AND STRAIN RATES

3.1 Introduction

As a traditional metal, steel has been the subject of extensive studies in the past few decades, both experimentally and theoretically over a broad range of strain rates and temperatures [12, 22, 23-27]. The mechanical response (deformation, strength and failure) of steel alloys, like many other metal materials, depends on the rate of deformation as well as the evolving temperature. The knowledge of the mechanical behavior of steel structures under low and high temperatures and strain rates is required if a component made of steel is subjected to possible high-velocity impact loading. Two high strength steels were considered in the proposed comparisons: DH-36 and HSLA-65 that are used in naval and other structural applications. They may be subjected, in their naval use, to high-rate loading due to collision or impact which, in turn, requires high toughness and high strength under variable conditions including high temperatures and strain rates. High strength low alloy (HSLA) steels were first used in 1960s by developing alloy of low-carbon steels with Niobium (Nb), Vanadium (V) and Titanium (Ti). HSLA-65 was recently developed with 65 ksi (450 MPa) yield strength allowing the use of thinner plates to reduce the weight of the structure. DH-36 is commonly used in the manufacturing of vessels and submarines. As ship hull steel, especially in high-speed sealift vessels, it may be subjected to high-rate loading due to collision, impact, or explosion. The major alloy content of the two investigated steels is given by Nemat-Nasser and Guo [22, 23]. In addition to more than 97% of iron, the microstructure of HSLA-65 and DH-36 is mainly composed, of 1.4% and 1.37% of Manganese (Mn), 0.24% and 0.22% of Silicon (Si), and 0.08% and 0.14% of Carbon (C), respectively. Moreover, the alloy content of HSLA-65 contains very small portion of copper (<0.01%) as compared to DH-36 (0.14%).

Having quick glance at the literature brings to light the available well known constitutive models describing the nonlinear deformation behavior in metals under
different conditions of temperatures and strain rates. These material models, which have different bases of derivations, were originally developed for the purpose of producing the true stress-true strain curves for finite element codes dealing with static and dynamic finite strain applications. Some of them include, namely, the Steiberg-Guinan model (SG) [13], the Zerilli-Armstrong model (ZA) [15], the Johnson-Cook model (JC) [14], the Rusinek-Klepaczko model (RK) [16], the mechanical threshold model (MTS) [17], and the Voyiadjis-Abed model (VA) [18]. Briefly, the JC model empirically relates the stress to strain, strain rate and temperature, the ZA model was designed to account for initial dislocation density and dislocation moving mechanism, the MTS model was introduced with the interactions of dislocations with obstacles, and the VA model utilizes the thermal activation analysis and dislocations interactions mechanisms as well as the evolution of mobile dislocation density. The accuracy of these models changes with the type of material and loading conditions for which the plastic deformation behavior is modeled. More details about the bases and capabilities of these models in predicting the flow stress of metals will be described in the following section.

A comparison of existing models is important for an accurate numerical simulation of the plastic deformation phenomenon of metals and alloys [28, 29]. Of many constitutive models, this chapter presents a thorough comparison of the prediction capability of four well-known plastic constitutive models for the case of the plastic/viscoplastic deformation of two high strength ferrite steels, HSLA-65 and DH-36. The material models considered in this paper are Voyiadjis-Abed (VA), Johnson-Cook (JC), Zerilli-Armstrong (ZA) and Rusinek-Klepaczko (RK) models. The results obtained from the material models are compared with the experimental data conducted by different authors. It is worth mentioning that other well-known constitutive models were not included in the proposed comparisons due to the unavailability of their material (HSLA-65 and DH-36) constants in the literature.

3.2 Constitutive Models

Accurate determination of plasticity models able to predict the flow stress of metals in general and steel in particular is not easy because of the coupling effects of strain, strain rate and temperature. The flow stress dependency of the above-mentioned three parameters becomes very significant at higher temperatures and strain rates. The four constitutive models compared in the current work are reviewed
hereinafter.

3.2.1 JC Model

The JC model presented by Eq. (1) was first developed in 1983 by Johnson and Cook [14]. It relates the flow stress to strain rate and temperature empirically without considering their coupling effects.

\[ \sigma = (A + B\dot{\gamma}^n)(1 + C \ln \dot{\varepsilon}^*) (1 - T^*m) \]  

(1)

where \( \sigma \) is the equivalent stress, \( \gamma \) is the effective plastic strain, \( \dot{\varepsilon}^* = \dot{\gamma} / \dot{\gamma}_0 \) is the dimensionless strain rate (\( \dot{\gamma}_0 \) is normally taken as 1.0/s), and A, B, C, m & n are material constants. The homologous temperature \( T^* = (T - T_r) / (T_m - T_r) \), where \( T_r \) is the reference temperature or the lowest temperature of the experiments, \( T_m \) is the melting temperature of the material, and \( T \) is the absolute Kelvin temperature that should be greater than or equal to \( T_r \) for the above equation to be valid.

In this model, strain hardening, strain rate hardening, and thermal softening are taken into account in a decoupled multiplication form. The first expression in the first bracket represents the stress as a function of strain when the strain rate = 1 and the homologous temperature = zero. On the other hand, the expression in the second bracket considers the effect of the equivalent plastic strain rate on the flow stress whereas the third bracket represents the effect of temperature. The constant \( A \) is the initial yield stress whereas the constants \( B \) and \( n \) are the strain hardening coefficient and exponent respectively. The multiplier \( C \) is defined as the strain rate constant that can be adjusted to give better agreement with experimental data at large strains whereas \( m \) is defined as thermal softening exponent.

The decoupling effect of temperature and strain rate, one of the shortcomings of JC model, on the flow stress can be clearly noticed by setting the constant \( m \) or the multiplier \( C \) to zero. Metals are known of their viscous behavior especially at high strain rates and temperatures. Their flow stresses are highly affected by the coupled effect of temperature and strain rate. Other shortcomings of JC model are related to the linear relation of the predicted flow stress with temperature while such behavior is often not the case especially at high temperatures. The flow stress at high temperature
does not decrease linearly as the temperature increases. Moreover, the model predicts a linear increase of flow stress with log strain rate. However, some materials, such as tantalum and ferrite steel, are known to show abrupt increase in flow stress at a certain strain rate [18].

The advantage of JC model is related to its simple form and easy implementation in computer codes. It can be readily applied to many materials because it is easy to obtain the five material constants defined earlier and it doesn't require large amount of computational time. However, one must be careful when extrapolating strain, strain rate and temperature beyond the limits of the experimental data from which the five constant were obtained for a material of interest since JC has no physical basis [27].

3.2.2 ZA Model

The semi-physical ZA relation was derived in 1987 by Zerilli and Armstrong [14] based on the dislocation mechanism. It utilizes the concept of thermal activation analysis to overcome the local obstacles preventing the dislocation from motion. Therefore, two different relations of ZA model were derived to describe the flow stress in two different classes of metal crystal structures differentiated by their dislocation characteristics. The first class is the body centered cubic (bcc) where the thermal flow stress component is mainly captured by the yield stress, whereas the second type is the face centered cubic (fcc) where the thermal flow stress component is captured by the hardening stress. For the present comparisons, the bcc relation of the ZA model given in Eq. (2) is utilized to predict the flow stress of ferrite steel.

\[
\sigma_i = \sigma_y + \dot{\lambda}_1 \exp(-\lambda_2 T + \lambda_3 T \ln \dot{\varepsilon}_p) + \lambda_4 \dot{\varepsilon}_p^n + kd^{0.5}
\]

Here \(\sigma_i\) is the equivalent stress, \(\varepsilon_p\) is the equivalent plastic strain, \(\dot{\varepsilon}_p\) is the equivalent plastic strain rate, \(T\) is the temperature in Kelvin, \(k\) is a parameter that accounts for the influence of grain boundaries, \(d\) is the grain size, and \(\lambda_1\) to \(\lambda_4\) are the material parameters related to the microstructure physical quantities. In this model, the power-law stress-strain relationship exhibits a continual work hardening without saturation of flow stress at a large strain.
Although ZA model makes use of the coupling effect of temperature and strain rate, there exist some inconsistencies and inaccuracies in its physical bases. For example, the inaccurate assumption used to derive the exponential function describing the temperature and strain rate coupling effect. The inaccuracy of using invalid mathematical expansion used to simplify the physical relations of the model parameters caused the model parameters to lose their physical meaning and interpretation as related to the microstructure physical quantities especially at high temperatures. This was obviously reflected on the model prediction of the flow stress at high temperatures. The model lost its ability to capture the athermal temperature effect that starts after exceeding the critical temperature at which the thermal stress starts to vanish [30].

It should be mentioned here that the ZA model is one of the most applied models in the well-known finite elements dynamic codes. It was used by many authors to investigate different applications under low and high strain rates and temperatures. The ZA model prediction included in the present comparison is for the flow stress of HSLA steel only due to the lack of material constants for the other steel.

3.2.3 RK Model

The RK constitutive model was developed in 2001 by Rusinek and Klepaczko [16]. This semi-physical material model assumes that the strain hardening is strain rate and temperature sensitive and utilizes the concept of the additive decomposing of the total flow stress (the equivalent stress $\sigma$) into internal stress ($\sigma_u$), which is related to the strain hardening of the material, and effective stress ($\sigma^*$) defined as the stress due to thermal activation. The RK constitutive relation to compute the flow stress is presented by Eq. (3) as follows:

$$\sigma = \frac{E(T)}{E_0} \left[ \sigma_u(\varepsilon_p, \dot{\varepsilon}_p, T) + \sigma^*(\dot{\varepsilon}_p, T) \right]$$

$$= \frac{E(T)}{E_0} \left[ B(\dot{\varepsilon}_p, T)(\varepsilon_p + \varepsilon_p) + \sigma_0^* \left\{ 1 - Dl \left( \frac{T}{T_m} \right) \log \left( \frac{\dot{\varepsilon}_p}{\dot{\varepsilon}_{p_{\text{max}}}} \right) \right\}^{m*} \right]$$  \hspace{1cm} (3)

where:
The temperature dependent Young's modulus $E(T)$ expression shown in Eq. (4) is defined to normalize both stress components because of thermal softening of crystalline where $E_0$ is Young's modulus at $T = 0$ (K), $T$ is the current temperature (absolute), $T_m$ is the melting temperature of the material, and $\theta^*$ is the characteristic homologous temperature. The internal stress which represents the strain hardening is introduced through the plastic modulus $B$ and strain hardening exponent $n$ which depends on the strain rate and temperature. In this model, the hardening exponent is not allowed to be less than zero because negative value of $n$ will increase the level of the internal stress as the temperature is increasing at a certain strain rate while this isn’t true. In Eq. (4), $\dot{\varepsilon}_{min}$ is the lowest strain rate of interest, $\dot{\varepsilon}_{max}$ is the maximum strain rate assumed in the model limiting the validity of the equation, $\nu$ is related to sensitivity of the strain rate and temperature, $D_1$ and $D_2$ are material constants, $B_0$ and $n_0$ denote the modulus of plasticity and the strain hardening exponent at $T = 0$ (K), respectively.

The RK model has a complex relation which makes its formulation and implementation into a finite element code more complicated as compared to the other models. In addition, the model in its current form contains some empirical relations such as the variation of the elastic modulus with temperature. In other words, the exponential variation of the elastic modulus with temperature shown in Eq. (4) does not have any physical basis; hence, it cannot be generalized to include all types of metals.

3.2.4 VA Model

Recently, Voyiadjis and Abed [18] developed a new model (VA) to describe the flow stress for pure metals based on the concept of thermal activation analysis and
dislocation mechanism. The physical basis of the microstructure, the crystal structure and atoms distribution inside the lattice were considered which led to three different relations for three different crystal structures; bcc, fcc and hcp metals. The bcc model was modified and utilized to predict the flow stress for ferrite steel at low and high strain rates and temperatures [12]. The modified model considered different evolution equations for the dislocation density resulted in an exponential relation for the strain hardening as shown in Eq. (5).

\[
\sigma = c_1 + c_2 \sqrt{1 - e^{-c_3 \varepsilon_p}} + c_4 \left(1 - (c_5 T - c_6 T \ln \dot{\varepsilon}_p)^{1/q_1}\right)^{1/q_2}.
\]  

The above relation clearly shows the coupling effect of strain rate and temperature on the yield stress where \(\sigma\) is the equivalent stress, \(\varepsilon_p\) is the equivalent plastic strain, \(\dot{\varepsilon}_p\) is the equivalent plastic strain rate, \(T\) is the temperature in Kelvin, and \(q_1\) & \(q_2\) are constants defining the shape of the short-range barriers. The material constants \(c_2\) and \(c_3\) define the strain dependent athermal component of the flow stress, \(c_1\) represents an additional athermal stress, \(c_4\) represents the threshold yield stress at which the dislocation can overcome the barriers without the assistance of thermal activation, \(c_5\) and \(c_6\) are two thermal activation parameters characterizing the thermal component of the flow stress and are related to the reference Gibbs energy at zero absolute temperature, Boltzmann's constant, reference dislocation velocity, and initial dislocation density [18].

In Eq. (6), the thermal component of the flow stress is non-negative; thus, the term \((c_5 T - c_6 T \ln \dot{\varepsilon}_p)\) should be set equal to zero when the temperature exceeds the critical value. The critical temperature defines the stage of deformation at which the thermal stress is completely vanished. This critical value, however, is strain rate dependent and can be defined as follows:

\[
T_{cr} = \left(c_5 - c_6 \ln \dot{\varepsilon}_p\right)^{-1}
\]  

3.3 Application of Models to HSLA-65 and DH-36

Flow stresses were generated by each material model at different conditions of strain rates and temperatures corresponding to available sets of experimental data conducted by Nemat-Nasser and Guo [22, 23]. The material parameters used in the current comparisons are listed in Tables 1-4 for each model with reference citations.
from which they were adopted. The JC model constants for HSLA-65 and DH-36 were identified by Nemat-Nasser and Guo [22, 23] whereas, the RK [25] and VA [12] model constants were calibrated by the same authors. For the ZA material constants, the results provided by Pietrzyk, et al. [26] for HSLA steel were adopted in the present comparisons. The prediction capability of the ZA model for the DH-36 steel was not carried out in this paper due to the lack of its material constants in the literature.

Table 1: Johnson-Cook (JC) material constants for HSLA-65 and DH-36 [22, 23]

<table>
<thead>
<tr>
<th>JC Model</th>
<th>A (MPa)</th>
<th>B (MPa)</th>
<th>n</th>
<th>C</th>
<th>m</th>
<th>T_r (°K)</th>
<th>T_m (°K)</th>
<th>γ_o (s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HSLA-65</td>
<td>790</td>
<td>1320</td>
<td>0.25</td>
<td>0.022</td>
<td>0.35</td>
<td>50</td>
<td>1773</td>
<td>1</td>
</tr>
<tr>
<td>DH-36</td>
<td>1020</td>
<td>1530</td>
<td>0.4</td>
<td>0.015</td>
<td>0.32</td>
<td>50</td>
<td>1773</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Table 2: Zerilli and Armstrong (ZA) material model constants for HSLA (H_Nb) steel [26]

<table>
<thead>
<tr>
<th>ZA Model</th>
<th>σ_g (MPa)</th>
<th>λ₁ (MPa)</th>
<th>λ₂ (MPa)</th>
<th>λ₃ (MPa)</th>
<th>λ₄ (MPa)</th>
<th>n</th>
<th>k</th>
<th>d</th>
</tr>
</thead>
<tbody>
<tr>
<td>HSLA</td>
<td>0</td>
<td>1100</td>
<td>0.0039</td>
<td>0.00028</td>
<td>336</td>
<td>0.298</td>
<td>5</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Table 3: Rusinek-Klepaczko (RK) material constants for HSLA-65 and DH-36 [25]

<table>
<thead>
<tr>
<th>RK Model</th>
<th>B₀ (MPa)</th>
<th>n₀</th>
<th>v</th>
<th>σ₀⁺ (MPa)</th>
<th>m</th>
<th>D₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>HSLA-65</td>
<td>940</td>
<td>0.14</td>
<td>0.2</td>
<td>120</td>
<td>2.8</td>
<td>.19</td>
</tr>
<tr>
<td>DH-36</td>
<td>907</td>
<td>0.2</td>
<td>0.02</td>
<td>491</td>
<td>2.127</td>
<td>.085</td>
</tr>
</tbody>
</table>

Table 4: Voyiadjis-Abed (VA) material constants for HSLA-65 and DH-36 [12]

<table>
<thead>
<tr>
<th>VA Model</th>
<th>c₁ (MPa)</th>
<th>c₂ (MPa)</th>
<th>c₃</th>
<th>c₄ (MPa)</th>
<th>c₅</th>
<th>c₆</th>
<th>q₁</th>
<th>q₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>HSLA-65</td>
<td>250</td>
<td>460</td>
<td>5</td>
<td>1250</td>
<td>0.00189</td>
<td>0.000093</td>
<td>1.5</td>
<td>0.5</td>
</tr>
<tr>
<td>DH-36</td>
<td>170</td>
<td>600</td>
<td>4</td>
<td>1250</td>
<td>0.00169</td>
<td>0.000069</td>
<td>1.5</td>
<td>0.5</td>
</tr>
</tbody>
</table>
During the high strain rate experiments, the dynamic stress strain tests are generally completed in few milliseconds which leave no time for the heat generated during the plastic deformation to dissipate outside the material. Such deformation, therefore, can be regarded as adiabatic. The temperature rise by plastic work during deformation can be calculated by the following relation:

$$\Delta T = \frac{\rho}{\rho c} \int \sigma d \varepsilon_p$$  \hspace{1cm} (7)

where $\rho$ is the density, $c$ is the specific heat constant and $\beta$ is the fraction of the plastic work converted into heat during adiabatic deformation. It is known that during a dynamic event the material will undergo adiabatic deformation because of the high strain rate where the plastic work is converted into non-dissipated heat. In this work, therefore, isothermal deformation was assumed for low strain rates (0.001s$^{-1}$) whereas adiabatic assumption was employed for high strain rates (>100s$^{-1}$) at which 100% of the plastic work is converted into heat. Only 10% of plastic work, however, was converted into heat for the intermediate strain rate 0.1s$^{-1}$. In accordance with Eq. (7), $\beta$ was taken equal to 1.0, 0.1 and 0.0 for high, intermediate, and low strain rates, respectively.

3.4 Results and Discussions

The capabilities of the RK, JC, ZA & VA models to predict the true stress-true strain curves for both steels at strain rates of 0.001 s$^{-1}$ to 8500 s$^{-1}$ are investigated by comparisons with experimental data at a range of initial temperatures between 77K and 800K. Figures 8 through 13 show samples of true stress-true strain curves produced by the four models compared to experimental data conducted on HSLA-65 and DH-36 steel. For the case of HSLA-65 steel, Figure 8 shows the capability of these models to predict the adiabatic stress-strain curves compared with the experimental data obtained at initial temperatures of 500K and 700K. While the four models seem to predict the experiment fairly well at $T_o = 500K$ and strain rate of 3000s$^{-1}$, only the VA model is reliable to predict the adiabatic deformation at the higher initial temperature of 700K and strain rate of 8000s$^{-1}$. As the strain rate decreases to 0.1s$^{-1}$ and 0.001s$^{-1}$ (Figure 9), only the VA and RK compare well with the experimental data at initial temperatures of 296K and 400K. Conversely, the JC
model overestimates the isothermal stress strain results, and the prediction capability of the ZA model indicates huge underestimation of the experiment.

Figure 8. True stress-true strain curves produced by ZA, JC, RK and VA models at high strain rates and various initial temperatures compared to experimental data for HSLA-65

Figure 9. True stress-true strain curves produced by ZA, JC, RK and VA models at low strain rates and various initial temperatures compared to experimental data for HSLA-65

Figure 10 compares the flow stress prediction of the four models with the experiment performed at a very low initial temperature of 77K with low (isothermal) and high (adiabatic) strain rates. Although the critical temperature is strain rate dependent, this low initial temperature ensures the existence of thermal stresses throughout the test for the four mentioned strain rates. That is, the temperature evolution of the deformation heat is still beyond its critical value at which thermal stresses vanish. At this low temperature, the RK and ZA models failed to predict the experiments as they clearly underestimates the flow stresses at low and high strain rates particularly at the initial stages of deformation (Figure 10). The RK model
appears to have some difficulty to predict good results at this low temperature for all strain rates whereas the ZA model slightly improves as the strain rate increases. On the other hand, both the VA and JC models predict the experiment well at low initial temperatures for any strain rate.

For the case of DH-36 steel, only the VA, JC and RK models were included in the comparisons. The prediction capability of the ZA model was not investigated in the present work due to the lack of the model constants for this type of steel. The models prediction of the flow stress for DH-36 show almost similar capability as observed in the case of HSLA-65 steel. The three models predict the experiment very well at initial temperature of 400 K and strain rate of 3000 s$^{-1}$. As the temperature and strain rate increase to 700 K and 8000 s$^{-1}$ respectively, only the VA model is able to compare well with the experiment while the RK and JC models clearly underestimate the experiment (Figure 11).
As the strain rate decreases to 0.1 s\(^{-1}\) and 0.001 s\(^{-1}\), the JC model overestimates the flow stresses whereas the VA model predicts the experiment well at the room temperature. The RK model slightly underestimates the experiment at 0.1 s\(^{-1}\) then its prediction capability improves at 0.001 s\(^{-1}\) (Figure 12). The capability of the three models in predicting the relationship between flow stress and the equivalent strain for DH-36 at an initial temperature of 77 K and strain rates of 8500 s\(^{-1}\), 3000 s\(^{-1}\), 0.1 s\(^{-1}\) and 0.001 s\(^{-1}\) is now illustrated in Figure 13. In all of the four different strain rates, the VA predicts the flow stress very well as compared to the RK, which clearly underestimates the flow stress at this low temperature, and the JC which slightly overestimates the flow stresses especially at higher range (above 25\%) of strains.

\[ \dot{\varepsilon} = 8000 \text{ s}^{-1} \]  
\[ \dot{\varepsilon} = 3000 \text{ s}^{-1} \]  

Figure 11. True stress-true strain curves produced by JC, RK and VA models at high strain rates and various initial temperatures compared to experimental data for DH-36

\[ \dot{\varepsilon} = 0.1 \text{ s}^{-1} \]  
\[ \dot{\varepsilon} = 0.001 \text{ s}^{-1} \]  

Figure 12. True stress-true strain curves produced by JC, RK and VA models at low strain rates and various initial temperatures compared to experimental data for DH-36
Figure 13. True stress-true strain curves produced by JC, RK and VA models at 77 K initial temperature and low and high strain rates compared to experimental data for DH-36

It can be concluded, after evaluating the above samples of comparisons (Figures 8-13), that the VA constitutive model exhibited very good performance during static and dynamic events when compared to other models over wide ranges of initial temperatures. Examples of true stress-true strain curves over a wide range of strain rates at the same initial temperature are presented in Figure A.1 in Appendix A. Unlike the other models, the exponential definition of the work hardening used by the VA model was very effective to describe the flow stresses at equivalent strains up to 0.6. The saturation of mobile dislocations at higher strain was accounted for. Moreover, the concept of thermal activation energy along with the dislocation interactions mechanisms employed in the derivation of the thermal component of the flow stress facilitated the very good performance of predicting the hardening and softening behavior at different combinations of temperatures and strain rates. In
contrast, the three other models of JC, RK and ZA failed to predict the experiment at several initial temperatures and strain rates.

The empirical relation of the JC model was able to predict the experiment at the very low temperature of 77K. However, its prediction capability was poor at higher temperatures in which the experimental results were overestimated at up to 500 K and underestimated above that. This, in fact, could be attributed to the purely empirical bases of its material constants. In addition, the strain rate and temperature decoupling effect on the model prediction capability along with the exclusion of the significance of critical temperature at which the thermal stresses vanish was evident. In spite of its empirical bases and shortcomings, this model, unfortunately, is still being used by many authors to simulate dynamic localizations at very high strain rates and elevated temperatures for its easiness to implement in finite elements codes.

The RK model with its complicated relations was very poor in predicting the flow stress with the equivalent strain at the very low temperature of 77 K. The underestimation of the isothermal and adiabatic stress-strain results was noticeable in both materials. The model prediction was better at the ambient temperature up to 500 K. However, it again underestimated the experiment at higher temperatures up to 700 K in which the strain hardening failed to predict accurate matching. This unreliable prediction of the RK model could be attributed to some of the inaccurate assumptions and empirical relations embedded with the physically based relations. Additionally, the model with its large number of constants makes it undesirable to implement in finite element simulations.

It should be mentioned here that the HSLA-65 material constants for the case of ZA model was calibrated using different set of experimental data [26] and; therefore, its predicting capability of the flow stress was not comparable with the experiment in most cases. However, the inconsistency and inaccurate assumptions used in deriving the final form of this model is worth mentioning. For example, the exponential form used to define the thermal component of the flow stress means that the thermal stress vanishes only when the temperature reaches infinity. This, in fact, is in violation with the thermal activation concept originally used in the derivation of this model which states that the thermal stress vanishes at certain critical temperature that is strain rate dependent (see for more details Ref. [30]). Several recent attempts were made to modify this model to overcome some of the inconsistencies found in its original relation [30-32]. These attempts not only were limited to fit certain alloys at
specific loading conditions, but also resulted into more complicated forms that are undesirable for finite element implementations.

For quantitative results for the fitting errors of the prediction capability of these models, a comparison was carried out among the four models in the plastic region of the true stress-true strain curves. Several ways were suggested by different authors to compare computed results from a material model with the experimental data. Some authors [33, 34] suggested using a parameter $\delta$ defined below to indicate the degree of fit.

$$\delta = \frac{1}{n} \sum_{i=1}^{n} \left| \frac{\sigma_{\text{exp}} - \sigma_{\text{eq}}}{\sigma_{\text{exp}}} \right|$$

Others [35] preferred to deal with the root mean square error ($RMS$) where the averaged sum of the residual square was calculated as follows:

$$RMS = \sqrt{\frac{\sum_{i=1}^{m} (\sigma_{\text{exp}} - \sigma_{\text{eq}})^2}{m}}$$

where $\sigma_{\text{exp}}$ and $\sigma_{\text{eq}}$ denote, respectively, the experimental results and the theoretical values predicted by the model. The variations of the fitting errors, using Eq. (8), with temperature at the four different strain rates for all models are shown in Figures 14 for HSLA-65 and Figures 15 for DH-36. The bar charts clearly show the prediction capability of each model as the temperature increases at a fixed strain rates. Furthermore, the variation of the fitting errors of each model with the increase or decrease of the strain rates at certain initial temperature is also shown in Figures 16. These results indicate that the VA model can be used for the description of the deformation behavior of HSLA-65 and DH-36 steel in a wider range of temperatures, strains, and strain rates than any of the other models.
Figure 14. Variations of degree of fit for each model with temperatures for HSLA-65 at strain rates of: (a) 0.001 s\(^{-1}\), (b) 0.1 s\(^{-1}\), (c) 3000 s\(^{-1}\) and (d) 8500 s\(^{-1}\)

Figure 15. Variations of degree of fit for each model with temperatures for DH-36 at strain rates of: (a) 0.001 s\(^{-1}\), (b) 0.1 s\(^{-1}\), (c) 3000 s\(^{-1}\) and (d) 8500 s\(^{-1}\)
In order to capture localizations during dynamic events in three-dimensional problems, the uniaxial form of the VA model can be treated as the rate and temperature dependent yield surface (i.e., dynamic yield surface) and incorporated into one of the well-known viscoplastic models. Implementation of the VA constitutive model into three-dimensional formulations can be developed within the context of finite deformation plasticity based on the additive decomposition of the rate of deformation into elastic and viscoplastic components. In this regard, incremental integration scheme in which the stress objectivity is preserved for finite rotation increments to rewrite the constitutive relations in a corotational moving frame can be used [12].
3.5 Nomenclature

- $\sigma$ = equivalent flow stress
- $\sigma_u$ = internal stress
- $\sigma^*$ = effective stress
- $\sigma^*_o$ = effective stress at $T = 0 K$
- $\sigma_{th}$ = thermal stress
- $\sigma_{ath}$ = athermal stress
- $\gamma^p$ = effective plastic strain
- $\varepsilon_p$ = equivalent plastic strain
- $\dot{\varepsilon}_p$ = equivalent plastic strain rate
- $\dot{\varepsilon}_{\max}$ = the maximum strain rate assumed in the model limiting the validity of the equation
- $\dot{\varepsilon}_{\min}$ = the lowest strain rate of interest
- $T$ = absolute Kelvin temperature
- $T_m$ = melting temperature of the material
- $T_r$ = room or reference temperature
- $T_{cr}$ = critical temperature
- $E(T)$ = temperature dependent Young's modulus
- $E_o$ = Young’s modulus at $T = 0$ (K)
- $\theta^*$ = characteristic homologous temperature
- $B$ = plastic modulus
- $B_o$ = modulus of plasticity at $T = 0$ (K)
- $q_1, q_2$ = constants defining the shape of the short-range barriers
- $n$ = strain hardening exponent
- $n_o$ = strain hardening exponent at $T = 0$
- $k$ = parameter accounts for the influence of grain boundaries
- $d$ = grain size
- $D_2, D_1$ = material constants
- $m^*$ = constant represents the strain rate sensitivity
- $v$ = related to sensitivity of the strain rate to temperature
- $\lambda_1 - \lambda_4$ = material constants for ZA model
- $c_1 - c_5$ = material constants for VA model
CHAPTER 4

CONSTITUTIVE MODEL IMPLEMENTATION AND VERIFICATION

4.1 Introduction

Choosing a robust constitutive material model capable of resolving the nonlinear behavior of steel under wide ranges of temperatures and strain rates was a main step before carrying out simulations for scenarios of interest. This was also very important knowing that the performance of the several available material models developed by different authors varies considerably when it comes to describe plasticity in materials like steel. The available models might behave differently at complex loading conditions that involve high temperatures and strain rates. The variation in the performance of some material models was discussed broadly in Chapter 3, and a conclusion was made to utilize the VA constitutive model in the proposed finite element simulations of impact problems. To do this, the VA constitutive model needs to be numerically integrated then implemented into the commercial finite elements code ABAQUS. A simple axisymmetric uniaxial compression problem was utilized to check the accuracy of the FE implementation of the VA model. This is done by comparing the true stress-true strain results predicted by the finite elements simulations using the VA model with the available experimental results conducted by other authors. Experimental results conducted at different loading conditions by Nemat-Nasser and Guo [22, 23] for both HSLA-65 and DH-36 steels and by Marchand and Duffy [36] for HY-100 steel were utilized to verify the model implementation.

4.2 Algorithmic Treatment of the VA Model for 3D Applications

In any numerical scheme employed for the analysis of elasto-viscoplastic problems, it eventually becomes necessary to integrate the constitutive equations governing the material behavior. The precision with which the constitutive relations are integrated has a direct impact on the overall accuracy of the analysis.
Implementation of the proposed constitutive model into three dimensional formulations is developed within the context of finite deformation plasticity.

It should be emphasized here that the three-dimensional (3D) formulation and implementation of the VA constitutive model developed for ferrite steel in the finite elements code ABAQUS/Explicit via user material subroutine VUMAT was followed as done by Voyiadjis and Abed [21]. In this regard, the 3D formulation model was developed based on the additive decomposition of the rate of deformation and use was made of the incremental integration scheme in which the stress objectivity was preserved for finite rotation increments to rewrite the constitutive relations in a corotational moving frame. Numerical simulations were performed by using the Newton-Raphson iteration procedure with a fully backward Euler integration scheme (see for more details, Ref. [21]).

4.3 Axisymmetric Uniaxial Cylindrical Compression Problem

A uniaxial example is necessary here to validate and test the finite element implementation of the proposed computation framework and numerical algorithm used in ABAQUS/Explicit via user subroutine VUMAT. In this regard, an axisymmetric uniaxial compression problem subjected to low and high velocities and initial temperatures was considered as shown in Figure 17(a). This example was conducted in order to demonstrate the capability of the FE formulation to capture the stress-strain curves as compared with the experimental results for the three types of ferrite steels; DH-36, HSLA-65 and HY-100. Due to symmetry, only a quarter of the cylindrical specimen is considered and solved using a mesh of one axisymmetric element (CAX4R ABAQUS type) with the boundary conditions defined in Figure 17(b). In this case, the displacement is set to zero in the x-direction at the left side and in the y-direction at the bottom of the one-element problem in order to maintain the full symmetry. The loading history that allows for driving the test under a certain constant strain rate is defined in Figure 17(c).
Figure 17. Problem description of simple uniaxial compression
(a) A cylindrical specimen subjected to symmetric velocity loading, (b) A quarter of the specimen with specific boundary conditions to ensure the problem symmetry, (c) The time history for the applied velocity.

It should be mentioned here that the reason behind using a compressive loading instead of a tensile loading is to maintain the same condition used in the experiments conducted by Nemat-Nasser and Guo [22, 23] for both HSLA-65 and DH-36 steels and by Marchand and Duffy [36] for HY-100 steel. In these experiments, compression tests for cylindrical specimens with equal nominal diameter and height were carried out at different strain rates and temperatures using a split Hopkinson pressure bar with momentum trap. Results from the FE implementation of the VA model are obtained for three steel alloys subjected to several velocities (strain rates) and initial temperatures using the material parameters listed in Table 4 (in Chapter 3) for the case of DH-36 and HSLA-65 and Table 5 for the case of HY-100.

Table 5: VA model material parameters for HY-100 steel

<table>
<thead>
<tr>
<th>VA Model</th>
<th>$c_1$ (MPa)</th>
<th>$c_2$ (MPa)</th>
<th>$c_3$</th>
<th>$c_4$ (MPa)</th>
<th>$c_5$</th>
<th>$c_6$</th>
<th>$q_1$</th>
<th>$q_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>HY-100</td>
<td>530</td>
<td>400</td>
<td>7</td>
<td>1100</td>
<td>0.00189</td>
<td>0.000073</td>
<td>1.5</td>
<td>0.5</td>
</tr>
</tbody>
</table>
For the case of HSLA-65 and DH-36, the effect of the initial temperature on the stress-strain curves is studied for two low velocities of 10\(\mu\)m/s, 1.0mm/s and two high velocities of 30m/s and 85m/s that is equivalent, for the present problem dimensions, to a strain rate of 0.001s\(^{-1}\), 0.1s\(^{-1}\), 3000s\(^{-1}\), and 8500s\(^{-1}\), respectively. This compression velocity is kept constant during certain time steps that achieve about 50% -60% true straining of the sample in the axial direction. Figure 18 demonstrates the deformed shape of an example of the simple uniaxial compression test modeled in ABAQUS/Explicit after achieving a total displacement of 6 mm.

![Figure 18](image)

Figure 18. Axisymmetric simple uniaxial compression modeled in ABAQUS, \(V=30\) m/s and \(T_0=400\) K: (a) Undeformed shape (b) Deformed shape at the end of a time step = 200 \(\mu\)s.

The available experimental data for the three considered steel alloys were obtained at a wide range of initial temperatures and strain rates. The initial temperatures considered in the case of HSLA-65 and DH-36 steels were 77, 213, 296, 400, 500, 700 K and strain rates were 0.001, 0.1, 3000, 8000, 8500 s\(^{-1}\). In the case of HY-100 steel, experimental data conducted at the following conditions were available: Initial temperatures of 83, 200, 296, 343, 407, 523 K and strain rates of 0.0001, 1000 s\(^{-1}\). The ABAQUS model described in Figure 18 was updated with these conditions in order to compute the stress-strain curves corresponding to each set of experimental data. The von Misses stress was plotted with the axial true strain for the
above-considered range of strain rates and initial temperatures as shown in Figures 19-22 for HSLA-65 and DH-36 steels and Figure 23 for HY-100 steel.

Figure 19. Comparisons of the true stress-true strain between experimental and FE results for HSLA-65 at different initial temperatures and two strain rates of (a) 0.001 s\(^{-1}\) and (b) 0.1 s\(^{-1}\).

Figure 20. Comparisons of the adiabatic true stress-true strain between experimental and FE results for HSLA-65 at different initial temperatures and two strain rates of (a) 3000 s\(^{-1}\) and (b) 8500 s\(^{-1}\).

Figure 19 and 20 show comparisons carried out at several initial temperatures between the FE results and experimental data for HSLA-65 steel at low (0.001 and 0.1 s\(^{-1}\)) and high (3000 and 8500 s\(^{-1}\)) strain rates, respectively. A good comparison between the computed results using VUMAT subroutine and experimental data was observed in all the cases especially when it comes to high strain rates and temperatures. The same conclusion can be drawn out for DH-36 steel as shown in Figures 21 and 22 at low (0.001 and 0.1 s\(^{-1}\)), high (3000 and 8000 s\(^{-1}\)) strain rates and over a wide range of initial temperatures.
Figure 21. Comparisons of the true stress-true strain between experimental and FE results for DH-36 at different initial temperatures and two strain rates of (a) 0.001 s$^{-1}$ and (b) 0.1 s$^{-1}$.

Figure 22. Comparisons of the true stress-true strain between experimental and FE results for DH-36 at different initial temperatures and two strain rates of (a) 3000 s$^{-1}$ and (b) 8500 s$^{-1}$.

Figure 23 presents the comparisons carried out between the results obtained from the FE simulations and the available experimental data for HY-100 steel. The comparisons included low strain rate (i.e. 0.0001 s$^{-1}$) and high strain rate (i.e. 1000 s$^{-1}$) conditions at wide ranges of initial temperatures. A good matching was observed between the computed results and experimental data especially at high strain rates.
Figure 23. Comparisons of the true stress-true strain between experimental and FE results for DH-36 at different initial temperatures and two strain rates of (a) 3000 s$^{-1}$ and (b) 8500 s$^{-1}$. 
CHAPTER 5

EFFECTS OF THE VA MODEL PARAMETERS ON DYNAMIC LOCALIZATIONS IN STEEL AT HIGH STRAIN RATES AND TEMPERATURES

5.1 Introduction

Numerous studies on the formation of shear bands (shear localization) were conducted due to their importance as deformation mechanism especially during high speed loading (i.e. impact loading). The high concentration of strains in a particular location of a steel structure is a physical phenomenon that can be observed in reality and in laboratory testing. Areas of high strain concentrations can be developed in specimens prepared in the lab and tested under wide ranges of strain rates and temperatures. Even when the strain rate is low, the increase of strains in the areas of strain concentration is fast and associated with higher than average dissipation of energy. Studying dynamic localizations particularly the development of shear bands is very important because they dominate the deformation and fracture modes in many metals. It is usual to observe strain localization in ductile materials like metals, but also can be observed in composite structures made of brittle and ductile components.

The VA physically based constitutive viscoplastic model was utilized in investigating shear localization in ferrite steel over wide ranges of temperatures and strain rates. This proposed model was verified and implemented in the well-known commercial finite elements software ABAQUS through the material subroutine VUMAT as explained in the previous chapter. This implementation was utilized to investigate the dynamic simulation of adiabatic shear localization in a cylindrical hat-shaped sample where large shear strains are generated in a small region during compression mode [37]. Moreover, the effects of the VA model parameters on the initiation and propagation of shear band localizations at high strain rates and temperatures were investigated.

Two high strength steels were considered in the proposed hat-shaped samples: DH-36 and HSLA-65 that are used in naval and other structural applications. They may be subjected, in their naval use, to high-rate loading due to collision or impact
which, in turn, requires high toughness and high strength under variable conditions including various temperatures and strain rates. High strength low alloy (HSLA) steels were first used in 1960s by developing alloy of low-carbon steels with Niobium (Nb), Vanadium (V) and Titanium (Ti). HSLA-65 was recently developed with 65 ksi (450 MPa) yield strength allowing the use of thinner plates to reduce the weight of the structure. DH-36 is commonly used in the manufacture of vessels and submarines [12]. As ship hull steel, especially in high-speed sealift vessels, it may be subjected to high-rate loading due to collision, impact, or explosion. The major alloy content of the two investigated steels is given by Nemat-Nasser and Guo [22, 23]. In addition to more than 97% of iron, the microstructure of HSLA-65 and DH-36 is mainly composed, of 1.4% and 1.37% of Manganese (Mn), 0.24% and 0.22% of Silicon (Si), and 0.08% and 0.14% of Carbon (C), respectively. Moreover, the alloy content of HSLA-65 contains very small portion of copper (<0.01%) as compared to DH-36 (0.14%).

5.2 Microstructure-Based Viscoplasticity in Ferritic Steel –VA Model

Accurate determination of plasticity models capable of predicting the flow stress of metals in general and steel in particular is not easy because of the coupling effects of strain, strain rate and temperature. The flow stress dependency of the above-mentioned three parameters becomes very significant at higher temperatures and strain rates. It was observed experimentally by different authors that the variation of stress-strain curves at a certain strain rate and different temperatures or at a certain temperature and different strain rates appear at yielding point and almost no variation was noticed in the hardening curves. Recently, Voyiadjis and Abed [19] developed a new model (VA) to describe the flow stress for pure metals based on the concept of thermal activation analysis and dislocation mechanism. The physical basis of the microstructure, the crystal structure and atoms distribution inside the lattice were considered which led to three different relations for three different crystal structures; bcc, fcc and hcp metals. The bcc model was modified and utilized to predict the flow stress for ferrite steel at low and high strain rates and temperatures [12]. The developed model additively decomposes the flow stress into athermal and thermal components which coincides with the experimental observation. The athermal component is independent of strain rate and related to strain hardening, \( R(p) \), and

\[ R(p) = \text{thermal component} \]
small portion of the yield stress, \( Y_a \). The thermal component is mainly controlled by yield stress and shows a coupling effect of temperature and strain rate. The static definition of the yield function represented by the athermal flow stress is shown in Eq. (10):

\[
f = \sigma_{eq} - Y_a - R(p)
\]  

(10)

The thermal component represents the dynamic stress that exceeds the static yield surface. This stress is related to the reference viscosity, \( \eta_o^{vp} \), and threshold yield stress, \( \hat{Y} \). The reference viscosity is the minimum value that can be achieved at very high temperature. The viscosity parameter (known as relaxation time), \( \eta^{vp} \), is very important when it comes to finite element implementation of viscoplasticity because it helps in introducing a physical length scale that is used in regularizing some problems encountered in finite elements computations. It also allows the spatial difference operator in the governing equations to retain its ellipticity. The dynamic stress is presented by Eq. (11) and viscoplastic multiplier is shown in Eq. (12), after rearranging Eq. (11).

\[
\sigma^{\tau}_{th} = \hat{Y}(1 - (\beta T \ln(\eta_o^{vp} \hat{Y}^{vp}))^{\frac{1}{\eta}}) \frac{1}{\eta^{vp}(T)}
\]  

(11)

\[
\hat{Y}^{vp} = \frac{1}{\eta^{vp}(T)} \varphi(\sigma^{\tau}_{th}, T, \hat{Y})
\]  

(12)

The over stress function \( \varphi \) presented in Eq. (13) and the viscosity parameter \( \eta^{vp} \) shown in Eq. (14) are explicitly temperature related variables. \( \hat{Y} \) is chosen in normalizing the over stress function.

\[
\varphi(\sigma^{\tau}_{th}, T, \hat{Y}) = \exp(1 - \frac{\sigma_{th}}{\hat{Y}})^{\eta} - 1
\]  

(13)

\[
\eta^{vp} = \eta_o^{vp} \exp\left(-\frac{1}{\beta T}\right)
\]  

(14)
The hardening $R(p)$ which is strain dependent component of flow stress is defined in Eq. (15).

$$R(p) = B(1 - e^{-kp})^{\frac{1}{2}}$$ (15)

Where the reference viscosity parameter, the threshold yield stress, the athermal yield stress and the parameters $\beta_2$ and $B$ are related to the microstructure physical quantities as follows:

$$\dot{B} = m\alpha\mu b \left(\frac{m}{k}\right)^{\frac{1}{2}}; \quad \eta_o^{\nu} = (m b \rho_d d)^{-1} t_{wo}$$

$$\dot{Y} = m\alpha_o\mu_o b^2 A_0; \quad Y_a = \alpha\mu \left(\frac{b}{D_g}\right)^{\frac{1}{2}}; \quad \beta_2 = \frac{K}{G_o}$$ (16)

Where $b$ is the magnitude of the Burger vector, $m$ is the orientation factor that relates the shear stress to the normal stress $\sigma = m \tau$ where $m = \sqrt{3}$ for the case of the von Mises flow rule, $\mu$ is the shear modulus; $a$ is an empirical coefficient, $K$ is the Boltzmann's constant, $G_o$ is the Gibbs energy at zero Kelvin temperature, $M$ represents the dislocation multiplication factor, $k$ is the annihilation factor, $D_g$ is the grain size, $t_w$ is the time that a dislocation wait at an obstacle and $t_{wo}$ is its lowest value, $\tilde{m} = \sqrt{M_gM_g}$ where $M_g$ is the Schmidt orientation tensor, $d$ is average distance the dislocation moves between the obstacles, $\rho_i = l_i^{-2}$ is the initial dislocation density and $l_i$ is the initial dislocation distance. An explicit definition of the length scale parameter $l$ which is taken as initial value of dislocation distance can be derived in terms of microstructure physical quantities by rearranging the definition of the viscosity parameter in Eq. (16) as follows:

$$l = \left(\frac{a c \eta_o^{\nu}}{c}\right)\frac{1}{2}$$

where: $a = \tilde{m} b ; \quad c = d / t_w$ (17)

The $c$ parameter in Eq. (17) is actually the elastic wave propagation velocity in the material whereas the $a$ parameter is a proportional factor that depends on the particular initial boundary value problem under consideration.

Once the viscosity parameter is calculated, the viscoplastic strain tensor is obtained by the following relation:
\[ \dot{\lambda}^{\text{eq}} = \frac{\dot{\lambda}^{\text{eq}}}{\partial \tau} N = \dot{\lambda}^{\text{eq}} \frac{\partial f}{\partial \tau} = \frac{\dot{\lambda}^{\text{eq}}}{\partial \tau} \]  

(18)

Where: \( \frac{\partial \sigma^{\text{eq}}}{\partial \tau} = (3\tau_{ij} \tau_{ij} / 2)^{1/2} \) represents the equivalent stress, which is defined based on von Mises yield criterion in terms of the deviatoric stress, \( \tau_{ij} = \sigma_{ij} - \sigma_{mm} \delta_{ij} / 3 \).

In the modified VA model which is applicable for ferrite steel, a new evolution equation for the dislocation density was considered. This resulted in an exponential relation for the strain hardening as shown in Eq. (19) which shows the combined athermal and thermal stresses.

\[ \sigma = c_1 + c_2 \sqrt{1 - e^{-c_6 \dot{\varepsilon}_p}} + c_4 (1 - (c_5 T - c_6 T \ln \dot{\varepsilon}_p)^{1/2})^{1/2} \]  

(19)

The material parameters \( c_1-c_6 \) appeared in the above constitutive relations are related to the microstructure physical quantities as explained before in Eq. (16) as follows:

\[
\begin{align*}
  c_1 &= Y_c ; \\
  c_2 &= \bar{B} \\
  c_3 &= k ; \\
  c_4 &= \hat{Y} \\
  c_5 &= \beta_2 \ln \left( \frac{1}{\eta^{\text{eq}}} \right) ; \\
  c_6 &= \beta_2 
\end{align*}
\]

(20)

The numerical values obtained for material parameters defined in Eq. (20) and used in this study were discussed in Chapter 3 and listed in Table 4.

The above relation clearly shows the coupling effect of strain rate and temperature on the yield stress where \( \sigma \) is the equivalent stress, \( \varepsilon_p \) is the equivalent plastic strain, \( \dot{\varepsilon}_p \) is the equivalent plastic strain rate, \( T \) is the temperature in Kelvin, and \( q_1 \) & \( q_2 \) are constants defining the shape of the short-range barriers. The material constants \( c_2 \) and \( c_3 \) define the strain dependent athermal component of the flow stress, \( c_1 \) represents an additional athermal stress, \( c_4 \) represents the threshold yield stress at which the dislocation can overcome the barriers without the assistance of thermal activation, \( c_5 \) and \( c_6 \) are two thermal activation parameters characterizing the thermal component of the flow stress and are related to the reference Gibbs energy at zero absolute temperature, Boltzmann's constant, reference dislocation velocity, and initial dislocation density [19]. In Eq. (19), the thermal component of the flow stress is non-negative; thus, the term \( (c_5 T - c_6 T \ln \dot{\varepsilon}_p) \) should be set equal to zero when the
temperature exceeds the critical value. The critical temperature defines the stage of deformation at which the thermal stress is completely vanished. This critical value; however, is a strain rate dependent and can be defined as follows:

\[ T_{cr} = \left( c_5 - c_6 \ln \dot{\varepsilon}_p \right)^{-1} \]  

(21)

5.3 Shear Localization in Cylindrical Hat-Shaped Steel Samples

ABAQUS/Explicit along with the user material subroutine VUMAT which includes the numerical integration of the VA constitutive model are used to perform finite elements simulation of hat-shaped specimens and to investigate the formation of shear bands in two ferrite steels, HSLA-65 and DH-36. Numerical simulations of the dynamic deformation response of hat-shaped specimen shown schematically in Figure 24 were tackled by different authors. The dimensions of the specimens used in other studies differ from one author to another. The dimensions of the hat-shaped sample used in this study, however, correspond to a study done by Perez-Prado [37] as presented in Table 6. The geometry was chosen in such a way that the inner diameter of the brim is shorter than the inner diameter of the hat by approximately 4.5% in order to sustain large amount of shear strain.

Table 6: Dimensions (mm) for ferrite steel hat-shaped sample

<table>
<thead>
<tr>
<th>( r_1 )</th>
<th>( r_2 )</th>
<th>( r_3 )</th>
<th>( h_1 )</th>
<th>( h_2 )</th>
<th>( h_3 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.53</td>
<td>4.85</td>
<td>5.08</td>
<td>15</td>
<td>7.0</td>
<td>6.97</td>
</tr>
</tbody>
</table>

Figure 24. Cut through the cylindrical hat-shaped specimen
The cylindrical shape of the hat-shaped specimen enables the use of four-node axisymmetric elements of CAX4R ABAQUS type in the FE modeling. The advantage of the hat-shaped specimen is that the location of shear localization preceding shear band formation is forced to be between the upper hat and the brim portions. This is because the dimensions of the specimen were chosen in this study so that there is mismatching between inner radius of the brim (r\(_2\)) and the hat radius (r\(_3\)) to create an overlapping region of high strain concentration. The axisymmetric specimen is subjected to compression dynamic velocity load from the top at the hat and movement is restrained at the bottom as illustrated in Figure 25.

![Figure 25. Modeled hat-shaped specimen (a) axisymmetric mesh element (b) a three-dimensional shape corresponding to half of the sample](image)

Three different mesh configurations were used to mesh the region of shear deformation as shown in Figure 26. Mesh 1 represents a coarse mesh whereas Mesh 2 and Mesh 3 are of higher resolution. Simulations were carried out using the three mesh configurations to study results sensitivity to mesh refinement. Not much variation in the shear stress-displacement curves was noticed between Mesh 2 and Mesh 3 as shown in Figure 27 plotted for an element located in the middle of the shear zone. Figure 28 shows true path distance (path-1) passing through the shear zone and perpendicular to the shear band. The same observation regarding mesh sensitivity was noticed when plotting the equivalent plastic strain along path-1 as presented in Figure 29. It is obvious that the coarse mesh (Mesh 1) is not able to
capture a reasonable value for the equivalent plastic strain along the same true path and is of no match to the results obtained from Mesh 2 and Mesh 3. As a result, Mesh 2 was chosen to carry out the rest of the dynamic simulations since it offers a balance between the accuracy of the results and optimum computational time especially when it comes to dynamic explicit integration computational scheme.

Figure 26. Mesh geometry and mesh refinement in the shear zone for a quarter of the sample

Figure 27. Shear stress for three different meshes configuration at $T_0=77\,\text{K}$
5.4 Numerical Simulations Results

The axisymmetric model was subjected to a wide range of velocities and initial temperatures. The displacements were applied at velocities of 0.5 m/s, 1 m/s, 10 m/s, 20 m/s, 25 m/s and 30 m/s at initial temperatures of 77 K, 200 K, 296 K, 400 K and 500 K. The modeled specimen was dynamically compressed up to a total displacement of 0.20 mm. It was observed that the shear stress first reaches a peak value before it decreases with increasing displacement which means that the hardening mechanism of ferrite steel prevails at the initial stage during plastic deformation. When the plastic deformation evolves, the softening mechanism becomes dominant as heat is accumulating in the shear zone especially when the specimen is subjected to high rate of adiabatic deformation. Figure 30 shows a contour plot of the equivalent plastic strains (shear bands) in three-dimensional shape corresponding to three fourths of the hat-shaped specimen. The plastic strain
concentration is obvious in the shear zone region. A comparison between shear bands corresponding to simulations at different temperatures at the same velocity load is presented in Figures 31 and 32 for both HSLA-65 and DH-36 steels. It is obvious that the widths of the shear bands increase with temperature increasing. Figure 33 presents the distribution of the equivalent plastic strain in both steels at the end of the applied displacement along Path-1 passing through the center of the shear zone at 25 m/s velocity and different temperatures. The distribution of the equivalent plastic strain is interpreted as the shear band width. The Figures show that that the plastic strain peak is greatest when the temperature is lowest. For instance, the largest plastic strain is achieved at 77 K (lowest temperature). They also show the variation of shear band with respect to each initial temperature at the same velocity. The widths of the shear zones range approximately from 0.5 to 1.0 mm in both steels depending on the initial temperatures and applied velocities. It can also be concluded that the width of the shear band (localization) varies considerably with different initial temperatures. No considerable variation in the shear bands widths was noticed at different velocities for the same initial temperature as illustrated in Figures 34 to 36 which show contour plots for the equivalent plastic strain and its distribution along Path-1 at initial temperature of $T_o=77$ K and different velocities for both steels.

Figure 30. Contour plot of the equivalent plastic strain (shear bands) at velocity =25 m/s and $T_o = 296$ K
Figure 31. Contours of the equivalent plastic strain (shear bands) at 0.2 mm axial displacement and different temperatures, HSLA-65 Steel

Figure 32. Contours of the equivalent plastic strain (shear bands) at 0.2 mm axial displacement and different temperatures, DH-36 steel
Figure 33. Equivalent plastic strain at $V=25$ m/s, 0.2 mm axial displacement and different temperatures along path-1: (a) HSLA-65, (b) DH-36
Figure 34. Contour of the equivalent plastic strain (shear bands) at 0.2 mm axial displacement and different velocities, HSLA-65 Steel

Figure 35. Contour plot of the equivalent plastic strain (shear bands) at 0.2 mm axial displacement and different velocities, DH-36 steel
Figure 36. Equivalent plastic strain at initial $T=77$ K, 0.2 mm axial displacement and different velocities: (a) HSLA-65, (b) DH-36

5.5 Effects of the VA Model Parameters on Dynamic Localizations

Simulating the effect of impact load on steel structures requires choosing a robust plasticity finite elements constitutive model. These models are either empirical
relations or physically based. In other words, the material parameters of some models are obtained empirically such as JC model whereas the material parameters in some other models are related to the micro-structure quantities of the material such as Voyiadjis-Abed (VA) model. Complex statistics methods could be applied on a set of experimental data to determine the material parameters of a plasticity model. However, inaccuracy in the value of the determined material parameter might be encountered during the process of identifying them which depends also on the accuracy of the experimental data. Hence, it is recommended to study the sensitivity of a certain output to a change in one or more of the material constants. In this study, the effect of five constants of the VA model $c_2$, $c_3$, $c_4$, $c_5$ and $c_6$ on the initiation and propagation of shear localization is performed. It is expected to detect a change in the shear band width at certain velocity and temperature when changing one of the model parameters while keeping all others constant. Table 7 shows different simulation runs that were carried out at several selected values of the material model parameters.

Table 7: Variation in the VA model material parameters for HSLA-65 and DH-36 steel

<table>
<thead>
<tr>
<th>Constant</th>
<th>Value 1</th>
<th>Value 2</th>
<th>Value 3*</th>
<th>Value 4</th>
<th>Value 5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HSLA65</td>
<td>DH36</td>
<td>HSLA65</td>
<td>DH36</td>
<td>HSLA65</td>
</tr>
<tr>
<td>$c_2$</td>
<td>350</td>
<td>500</td>
<td>400</td>
<td>550</td>
<td>460</td>
</tr>
<tr>
<td>$c_3$</td>
<td>4.0</td>
<td>3.0</td>
<td>4.5</td>
<td>5.0</td>
<td>4.0</td>
</tr>
<tr>
<td>$c_4$</td>
<td>1050</td>
<td>1050</td>
<td>1150</td>
<td>1150</td>
<td>1250</td>
</tr>
<tr>
<td>$c_5$</td>
<td>0.00109</td>
<td>0.00089</td>
<td>0.00149</td>
<td>0.00189</td>
<td>0.00189</td>
</tr>
<tr>
<td>$c_6$</td>
<td>0.000053</td>
<td>0.000029</td>
<td>0.000073</td>
<td>0.000049</td>
<td>0.000093</td>
</tr>
</tbody>
</table>

* Original value of the material constant

Comparisons between formed shear bands corresponding to simulations at the same conditions (velocity = 10 m/s and temperature = 77 K) are presented in Figures 37 to 41 for HSLA-65 steel. These figures show contour plots for the equivalent plastic strains whose concentration indicates the width of the shear band at varying material constants. The results are obtained at axial displacement of 0.2 mm.
A change in the shear band width can be observed when comparing the contours of equivalent plastic strain corresponding to higher or lower values than the original value of the material parameters. The middle plot in Figures 35-39 represents the original value of the material parameter.
Figure 39. Contour plot of the equivalent plastic strain (shear bands) at 0.2 mm axial displacement and different values of material constant $c_4$

Figure 40. Contour plot of the equivalent plastic strain (shear bands) at 0.2 mm axial displacement and different values of material constant $c_5$
For better quantification for the shear band width sensitivity to changes in the material parameters, the equivalent plastic strains were plotted along path-1 which is perpendicular to the shear band. This is presented in Figures 42 and 43 for simulations at 10 m/s velocity and 77 K initial temperature for both HSLA-65 and DH-36 steels. Figures 42(a) and 43(a) show that increasing the value of material parameter $c_2$ reduces the plastic strain values along path-1 and less width of the shear band is measured. Figure 42(b) and 43(b) shows that width of the shear band is not very sensitive to changes in constant $c_3$. These two parameters $c_2$ and $c_3$ are directly related to the athermal stress component of VA constitutive model. On the other hand, increasing the material constants $c_4, c_5$ and $c_6$ which are related to the thermal stress component of the VA model leads to increasing the value of the equivalent plastic strain as illustrated in Figures 42 (c, d, e) and 43 (c, d, e). The width of the shear zone is increased consequently.
Figure 42. Equivalent plastic strain for HSLA-65 steel when changing the model parameters at 0.2 mm axial displacement: (a) \( c_2 \), (b) \( c_3 \), (c) \( c_4 \), (d) \( c_5 \), (e) \( c_6 \).
Figure 43. Equivalent plastic strain for DH-36 steel when changing the model parameters at 0.2 mm axial displacement: (a) $c_2$, (b) $c_3$, (c) $c_4$, (d) $c_5$, (e) $c_6$
CHAPTER 6

PRELIMINARY STUDY ON LOCALIZATION FAILURE IN SHORT STEEL COLUMN UNDER DYNAMIC IMPACT LOADING

6.1 Introduction

Columns are main components in structures like multistory residential buildings, parking and bridges. Structural columns located in busy area especially those belong to the ground level are very vulnerable to impact load (e.g., collision of vehicle with bridge pier). Recent publications on damage, crash and failure in structural members in general and columns in particular show increasing interest among researchers, designers and industries in understanding the behavior of structural components under the effect of dynamic impact loading. Structural members undergo severe deformation and large plastic strains when subjected to impact loading from high velocity moving object. The deformation in structural elements which is considered a global response has been studied extensively by many authors including the cases of dynamic impact loading. The failure due to impact loading, on the other hand, could occur locally in structures which makes it difficult phenomenon to understand and interpret. Studying dynamic localization requires implementing special type of analysis where some of the traditional methods applied successfully in studying global mechanical response are not applicable for local analysis [38]. Nowadays, the finite elements method has been used widely in performing nonlinear simulations to study the localization failure in many types of structures made of different materials. For instance, Thairy and Wang [4] used the commercial available nonlinear finite element package, ABAQUS, to conduct a parametric study on the failure of axially pre-loaded structural steel columns due to transverse impact loading. Several parameters that were assumed to have an effect on the mechanical response and failure of steel columns such as impact velocity, impactor mass, impact location, axial compressive load and slenderness ratio were investigated. Thorough understanding of the effect of these parameters would enable developing more simplified methods of analysis that can be implemented in practical design codes for column design under dynamic impact load. Zeinoddini, et al. [39, 40] studied the effect of lateral impact on axially pre-loaded steel tubes both
experimentally and numerically. A non-linear finite element model was implemented in their study to simulate the failure of steel tubes subjected to impact at mid-span by an object dropped at a velocity of 7.0 m/s. They found out that the level of damage in steel tubes when subjected to lateral impact is affected by the pre-loading conditions. It was also observed that the strain rate in the material has considerable effect on the behavior of steel tubes under lateral impact loading. Another finite element analysis study was carried out by Sastranegara, et al. [41] to examine the buckling behavior of axially loaded steel column when subjected to different peaks and durations of transverse impact loads. It was found out that the structural stiffness of the column was reduced instantaneously during the transverse impact. The column became instable and buckled given that it was well designed column and achieved Euler's criteria (axial load is less than Euler's buckling load). The external work (impact) applied on the column determined the critical conditions to cause buckling.

Damage or failure in the column due to intentional or accidental impact events may cause progressive collapse in the structure and unavoidable catastrophic losses. For this reason, columns that are most susceptible to impact events during the structure life time must be well designed to sustain large deformations and plastic strains before failure. This requires thorough understanding of the thermo-mechanical behavior of the material made of these columns (in this case high strength steel) at extreme loading conditions involving high strain rates and temperatures. Some codes provide an equivalent static design approach to design columns under transverse impact. These simplified analysis methods which consider the impact as lateral load on the column might be inaccurate and might not provide rational column design [4]. The main purpose of this chapter is to introduce a preliminary study on the thermo-visco-plastic behavior of structural elements (e.g., columns) made of high strength steel under impact loading. The accumulation of the plastic strains and consequently the heat at localized regions which trigger the overall structural failure are of the authors’ main interest. This is done after utilizing the implementation of the VA model into the commercial software ABAQUS via user material subroutine VUMAT as discussed in the previous chapter. Impact load is usually of high intensity and occurs for short duration resulting in large deformation. The short duration impact prevents the energy generated inside the material due to large permanent deformation from dissipation. This energy, in turn, will be converted into heat inside the material.
As a result, material weakness and localization failure will occur especially at the location of localized temperature increase.

I-sections steel columns which are very common in practice are considered in this study because of their high efficiency in carrying bending and shear in web plane. In contrast, their capacities are insufficient in the transverse direction and have low torsion resistance. A 3D finite element modeling is followed in this study for more understanding of the behavior of steel column under impact loading using the ABQUS/Explicit elements library. The column was axially pre-loaded before the transverse impact. Different impact locations, impactor masses and impact velocities are considered in this preliminary study. The finite elements modeling and simulation results are discussed in the following sections.

6.2 Numerical Model Setup

A 4.0 m length I-section steel column which is known in the British Universal Columns as UC305x305x118, equivalent to W12x79 steel section in the American Institute of Steel Construction Manual (AISC) [42], was selected in this study to perform the nonlinear numerical simulations in ABAQUS/Explicit. The column is designed according to the British Standard BS 5950: Part 1:2000 to sustain a total axial load of 3800 kN. This is equivalent to an interior column in the ground floor of a 5-story commercial steel building [4]. Figure 44(a) shows schematically the geometric description and the main characteristics of the impact problem. The dimensions of the selected steel I-section including the flange and web widths, thicknesses and depths are also given in Figure 44(b). The column was modeled in ABAQUS as simply supported using 8-node ABAQUS solid elements, C3D8R, throughout its 4 m length. It was allowed to move only in the axial direction (free axial movement). The advantage of considering a short column is to reduce the effect of the slenderness ratio on the analysis. The axial load was first applied in a separate analysis step using smooth amplitude [43] to make sure that the axial load effect is fully developed before transverse impact. Impact load was then applied on the transverse direction of the column which is the weak axis by using a rigid impactor moving in a certain velocity and perpendicular to the column.
The impactor was modeled as a non-deformable solid object. This could be done in ABAQUS by assigning high modulus of elasticity for the material definition. The mass of the impactor, of known volume, was altered by changing the density of the impactor material. Only one geometry with dimensions of 0.34x0.5x1.5 m was considered in this study as depicted in Figure 45. The velocity impact was applied at the outside surface of the impactor which was then transferred to the column through the surface to surface contact interaction defined between the column and the impactor.
The effect of impact load was examined at two different locations along the steel column; at 1.0 m and 1.5 m from the bottom support (see Figure 46). This can be explained by the fact that the column might be subjected to impact with vehicles of different heights.

Figure 46. Two Impact locations: (a) 1 m from bottom support (b) 1.5 m from bottom support.

The selection of a proper element size and its sensitivity is an important factor to be considered in this study. A good mesh is the one that can achieve a balance among refinement at the areas of interest, an optimum computational time required to complete the simulation and an accurate results. For instance, using very fine mesh beyond a certain limit will increase the computational time and might not improve the accuracy of the results. Using unreasonable coarse mesh, on the other hand, will reduce both the computational time and the accuracy of the results. In this study, fine mesh of 20 mm element size was considered in the regions of interest, i.e., at the
impact location and at 0.25 m from the supports, whereas, coarse mesh of 60 mm element size was used elsewhere (see Figure 47).

![Figure 47. Column mesh configurations: (a) 20mm mesh, (b) 60mm mesh, (c) 20mm mesh](image)

The type of the high strength steel used in this study was HY-100 which is common in structural applications. It has a tensile yield strength of 689 MPa (100 ksi), modulus of elasticity of 205 GPa (29700 ksi), shear modulus of 80 GPa (11600 ksi), Poissons ratio of 0.28 and density of 7879 kg/m$^3$. The chemical composition of HY-100 alloy is presented in Table 8 (see Ref. [36] for more details). The VA constitutive model implemented in ABAQUS/Explicit via material user-subroutine VUMAT was used to describe the nonlinear behavior of the steel column subjected to impact from the transverse direction. The VA model parameters for this high strength steel are given in Table 5 in Chapter 4.

<table>
<thead>
<tr>
<th>C</th>
<th>Si</th>
<th>S</th>
<th>Mn</th>
<th>P</th>
<th>Ni</th>
<th>Cr</th>
<th>Mo</th>
<th>Cu</th>
<th>Ti</th>
<th>Va</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.18</td>
<td>0.20</td>
<td>0.005</td>
<td>0.25</td>
<td>0.003</td>
<td>2.51</td>
<td>1.63</td>
<td>0.43</td>
<td>0.037</td>
<td>0.001</td>
<td>0.005</td>
</tr>
</tbody>
</table>
6.3 Simulations Scenarios

Finite elements simulations were carried out using ABAQUS/Explicit along with the user-subroutine VUMAT in view of several scenarios related to different considered impact conditions:
1. Impact location (1.0 and 1.5 m from bottom support).
2. Impact velocity (20, 40, 80 km/hr).
3. Impactor mass (1.0, 3.0, 6.0 Ton).
4. Axial load: $P_{\text{applied}}/P_{\text{design}}$ ratio (0.0, 0.3, 0.5, 0.7).

Investigating the effects of the above parameters on the material and overall structural behaviors develops comprehensive understanding of the response and failure modes of axially compressed steel column under transverse impact. This, in turn, enables Engineers to develop simple methods of analysis and design. In this chapter, however, only brief results related to the nonlinear material behavior including the accumulation of plastic strain and temperatures at localized regions are presented. The overall structural behavior and failure modes will be studied extensively by another graduate student.

6.4 Preliminary Results and Discussions

Structural columns subjected to transverse impact could fail under different failure mechanisms such as tensile tearing, shear failure and global plastic failure. Tensile tearing is usually developed at the support especially when it is fully fixed. In this study, however, free axial movements were allowed; thus, tensile tearing failure was not expected to develop. Shear failure mechanisms, on the other hand, are expected to take place in columns that are subjected to high velocity transverse impact. Thairy and Wang [4] concluded in their study which included several impact scenarios on structural steel column (yield stress = 345 MPa (50 ksi)) that shear failure could be developed only at impact velocities above 80 km/hr with very heavy impactor mass. Their conclusion, however, may not be generalized to other types of steel alloys (e.g., yield stress >>50 ksi) since their results were attributed mainly to the selected definition of their criterion for shear damage failure which may have a significant effect on the overall shear failure. Therefore, a proper definition for the shear damage criterion is very crucial particularly in defining the initiation and propagation of damage (shear bands, voids and cracks) inside the material. For this
reason, the shear failure mechanism was not investigated in this preliminary study, and was left for future research. The global plastic failure mechanism, which implies that there is high chance for the column to undergo global instability, is the dominant failure for a pre-loaded steel column subjected to low and intermediate velocity transverse impact (buckling around the weak axis).

Figure 48 illustrates the time history of axial displacements calculated in columns at two impact locations and using two different impactor masses. The development of axial displacement history in columns can be used as a criterion to judge on the column stability. Figure 48(a), for instance, shows that steel columns subjected to 40 km/hr impact velocity at 1.0 m impact location and 1 Ton impactor mass exhibited accelerated rate of deformation after 25 msec at all the pre-loading conditions (0.0, 0.3, 0.5, 0.7 \( P/P_{	ext{design}} \) ratios). This might mean that global plastic failure mode was developed in the column (4.0 m length) after 25 msec. The same observation could be noticed in Figure 48(b) at higher impactor mass of 6.0 Ton and impact location of 1.5 m away from the bottom support.
Flange distortion is usually associated with plastic global buckling where the flange of the column experiences severe deformation locally at the location of impact. Figure 49 shows examples of flanges distortions in the impact region at different $P/P_{\text{design}}$ ratios, different velocities and at 1.0 m impact location. It is obvious from these figures that the flange experienced severe deformation when subjected to higher velocity impact. It was also noticed that increasing the pre-loading condition increased the flange distortion. This distortion generally occurs in the flange before the initiation of the global plastic failure. This could be verified by comparing Figure 50 with Figure 51. Figure 50 shows that accelerated deformation in a column pre-loaded with $P/P_d$ ratio=0.7 and subjected to 20 km/hr velocity impact by 3 Ton impactor at 1.0 m location was initiated at 30 msec. Figure 51-a, however, shows that flange distortion occurred before 30 msec. The same observation was noticed by comparing Figures 50 with 51-b. The accelerated deformation started at 20 msec in the column subjected to 80 km/hr impact velocity by 6.0 Ton impactor at 1.5 m location. The flange distortion, on the other hand, started before 20 msec of deformation. Hence, the flange distortion happened before column instability (global plastic failure).
Figure 49. Flange distortion at the location of impact: 1.0 m impact location, 1.0 Ton impactor: (a) 40 km/hr (b) 80 km/hr

Figure 50. Axial displacement at top support: 1) 1.0 m impact location, 20 km/hr, 3.0 Ton impactor, 2) 1.5 m impact location, 80 km/hr, 6.0 Ton impactor
Figure 51. Column deformed shape with time, $P/P_d=0.7$ (a) 20 km/hr, 1.0 m impact location, 3.0 Ton impactor (b) 80 km/hr, 1.5 m impact location, 6.0 Ton impactor
The regions of localizations are dominated mainly by the accumulation of plastic strain and heat. Figure 52 presents an example of plastic strain contours showing higher concentrations at the impact region and the bottom support. This case was for a column pre-loaded up to 0.7\(P_{\text{design}}\) and corresponding to 40 km/hr impact velocity with 1.0 Ton impactor at 1.0 m location.

![Figure 52. Equivalent plastic strain at V=40 km/hr, P/P_d=0.7, Impactor 1.0 Ton](image)

The accumulation of the permanent deformation was also studied along the flange and web lengths and depths. Four different paths as shown in Figure 53 were considered; 1) along flange width, 2) along flange length, 3) along web depth, and 4) along web length.

![Figure 53. Four paths along: (a) flange width and length, (b) web depth and length](image)
Figure 54-57 present examples of the plastic stain distribution along the flange width, flange length, web depth and web length at different loading conditions. It was clear that most of the plastic strain was accumulated at the edges and middle of the flange. Figure 54 shows that during 40 km/hr impact action at 1.0 m impact location with 1.0 Ton impactor, the concentration of permanent deformation was higher at the edges close to the impactor. The plastic strain along the length of the flange was accumulated mainly at the impact region and the bottom support that is closest to the impactor. It can also be observed from Figure 54(c) that the plastic strain along the web depth was accumulated at the two ends of the web which are connected to the flange. The middle part of the web seems to be intact. Figure 54(d) shows that some plastic strain along the web length was accumulated at impact region.

![Graphs showing plastic strain distribution](image)

Figure 54. Equivalent plastic strain along true path distance at 40 km/hr impact velocity, 1.0 m impact location, 1.0 Ton impactor and P/P_d=0.0, along flange width, (b) along flange length, (c) along web depth, and (d) along web length.
At higher velocity (see Figure 55), the same localization behavior was observed along the flange length and width with higher peak values of accumulated plastic strains. The web, on the other hand, experienced permanent deformation along the entire depth. By shifting the impact location only 0.5 m from the bottom support (1.5 m away from bottom support), the permanent deformation at the top support was noticeably increased as shown in Figure 56. In this case, the plastic strain accumulation was more distributed between the two supports of the column along the flange when impacted with the same velocity as compared to the results shown in Figure 55.

![Figure 55](image-url)

Figure 55. Equivalent plastic strain along true path distance at 80 km/hr impact velocity, 1.0 m impact location, 1.0 Ton impactor and P/P_d=0.0, (a) along flange width, (b) along flange length, (c) along web depth, and (d) along web length
Figure 56. Equivalent plastic strain along true path distance at 80 km/hr impact velocity, 1.5 m impact location, 3.0 Ton impactor and $P/P_d=0.0$, (a) along flange width, (b) along flange length, (c) along web depth, and (d) along the web length.

It should also be mentioned that most of the impact energy was absorbed by the flanges especially when higher impactor mass was considered. Figure 57 shows localization results for higher impactor mass of 6.0 Ton, but with the same loading conditions given in Figure 56. At the impact location, the web seems to be intact away from the flanges and less permanent deformation was noticed at the connected regions between the flanges and the web as compared to the results shown in Figure 56.
Figure 57. Equivalent plastic strain along true path distance at 80 km/hr impact velocity, 1.5 m impact location, 6.0 Ton impactor and $P/P_d=0.0$, (a) along flange width, (b) along flange length, (c) along web depth, and (d) along the web length.

As was explained before, during adiabatic and short duration intense impact, the column will undergo large nonlinear deformation which will prevent the energy generated inside the steel alloy due to plastic work increase from dissipation. The plastic work accumulated inside the material will be converted into heat causing material weakening and failure especially at the impact and support regions. To explain this, Figure 58 presents the temperature and plastic strain evolution at selected localization areas for different velocities, 20, 40, and 80 km/hr, and at an initial temperature of 296 K ($23^\circ$C). For instance, it was clear from the figure that the temperature increased within few milliseconds to 344 K ($70^\circ$C) when the impact velocity was 80 km/hr. This increase in the temperature would contribute to the localization failure of the steel material. At higher impact velocities (i.e. 300 km/hr and more), the temperature effect would be much more significant. The figure also shows that the heat and plastic strain accumulation was much faster when the impact
velocity was larger (i.e. 80 km/hr) which represents the most severe impact velocity in this study.

![Figure 58. Time history at localization area and P/P_d=0.0 of: (a) Temperature (Kelvin), (b) Equivalent plastic strain](image)

The strain rate inside the HY100 steel column during the impact events was also investigated for the three different velocities. It can be observed from Figure 58(b) that the evolution rate of plastic strain at these localization zones increases as the impact velocity increases. The highest recorded strain rate was about 105 s\(^{-1}\) in the case of 80 km/hr impact velocity whereas it was about 78 s\(^{-1}\) and 36 s\(^{-1}\) for velocities of 40 km/hr and 20 km/hr, respectively.
CHAPTER 7

CONCLUDING REMARKS

7.1 Summary and Conclusions

Steel became one of the most important and necessary products used in the construction industry. It is found in many civil engineering structural applications such as long span bridges and high-rise buildings. Structures made of high strength steel especially those located in congested areas are vulnerable to localization damage due to intentional or accidental impact loads. During such events large deformation and severe distortion occur beyond the elastic limit; hence, the analysis has to extend into the inelastic range to describe the plastic deformation more accurately in the structural steel before failure. Localization failure in structural steel is very important phenomenon to be studied, yet complicated to understand. The importance to understand localization arises in particular during impact events on structural steel. High velocity impacts induce large deformation in the structure leading to accumulation of plastic work at localized region within very short time. The corresponding large amount of heat generated inside the steel material will not have enough time to dissipate causing a progressive reduction in the carrying capacity of the steel structural member locally.

The main objective of this research was to present a consistent methodology for the assessment of nonlinear behavior of structural steel under low and high velocity impacts. After extensive comparisons with the experimental data for high strength steel, the Voyiadjis and Abed (VA) nonlinear constitutive model was selected among other available material models in the literature. The VA constitutive model was then implemented in ABAQUS/Explicit to perform nonlinear simulations of dynamic localizations in hat-shaped specimen and pre-loaded I-column subjected to transverse impact. Several outcomes and conclusions were drawn out of the proposed research as summarized below:
7.1.1 Constitutive Modeling and Finite Element Implementation

The prediction capability of the flow stress of four well-known nonlinear constitutive models which are Voyiadjis-Abed (VA), Johnson-Cook (JC), Zerilli-Armstrong (ZA) and Rusinek-Klepaczko (RK) were examined in this study. The four models were compared with the experiments for two ferrite steels; HSLA-65 and DH-36 over a wide range of temperatures and strain rates.

- While the capability of the ZA, JC and RK models were inconsistent in predicting the experiments, the VA model demonstrated very good prediction for the isothermal and adiabatic deformation of both steels at low and high strain rates and elevated temperatures.
- The exponential definition of the work hardening used by the VA model was very effective to describe the flow stresses at low and high equivalent strains.
- Thus, the VA constitutive model was selected and implemented into three-dimensional finite elements formulation to accurately simulate dynamic localizations in structures made of HSLA-65, DH-36 and/or HY-100 steel.
- The implementation of the VA constitutive model in ABAQUS/Explicit via material user-subroutine coded as VUMAT was proved to be successful. A good comparison between the computed results using VUMAT subroutine and experimental data for HSLA-65, DH-36 and HY-100 steels was observed especially when it comes to high strain rates and temperatures.

7.1.2 Shear Localizations in Hat-Shaped Specimen

The shear band formation in hat-shaped specimen was studied at dynamic velocities of 0.5, 1.0, 10, 20, 25 and 30 m/s and initial temperatures of 77, 200, 296, 400, and 500 K. The simulations were carried out using the implemented VA constitute model in ABAQUS via VUMAT user subroutine.

- It was observed that the width of the shear band increases with increasing the initial temperature in both HSLA-65 and DH-36 steels.
- The width of the shear band doesn't vary considerably when changing the applied dynamic velocities.
- Sensitivity analysis was also performed on five constants of the VA material model, $c_2$, $c_3$, $c_4$, $c_5$ and $c_6$, to study their effects on the width of the shear band.
• It was observed that increasing the value of material parameter $c_2$ reduced the width of the shear band whereas increasing the value of material constants $c_4$, $c_5$ and $c_6$ increased the width of the shear band.

• The width of the shear band was not very sensitive to changes in constant $c_3$.

7.1.3 Preliminary Study on Localization Failure in Short Steel Column

A preliminary nonlinear finite element study to investigate the behavior of short column made of HY-100 steel under transverse impact was conducted using the implemented VA constitutive model via user material subroutine VUMAT in ABAQUS/Explicit.

• The behavior of this column under different impact locations (1.0 m and 1.5 m from the bottom support), impact velocities (20, 40, and 80 km/hr), impactor masses (1.0, 3.0, and 6.0 Tons) and pre-loading conditions (0.0, 0.3, 0.5, and 0.7 $P/P_{\text{design}}$) were assessed.

• Rapid increase in the axial displacement along the column was used as an indication for global plastic failure in column.

• Flange distortion occurred before the initiation of global plastic failure.

• The location of localization failure where the plastic strain and heat accumulated were also investigated along the flange width, flange length web depth and web length.

• The plastic strain accumulated mainly along the length of the flange at the impact region and the bottom support, the closest to the impact location. The plastic strain along the web depth was accumulated at the two ends of the web which are connected to the flange.

• By shifting the impact location only 0.5 m (1.5 m away from bottom support), the permanent deformation at the top support was noticeably increased. The plastic strain accumulation was more distributed between the two supports of the column along the flange.

• During adiabatic and short duration impact, the energy was converted to heat and the material was weakened by high velocity impact action causing localization failure especially at the impact area.
7.2 Recommendations for Future Research

The following recommendations for future research are suggested in order to expand this study:

- Collecting more experimental data for better determination for the VA model parameters. This will also help carrying out more validation for the model performance in nonlinear finite element simulations.
- Determining VA model parameters for other types of structural steels.
- Studying the behavior of longer columns under impact loading and including the effect of the slenderness ratio in the analysis.
- Introducing imperfection in the column to see its effect on the column behavior under transverse impact.
- Considering the axial pre-loading with eccentricity to study the combined effect of moment and axial pre-loading on the column during impact.
- Extending the finite elements model for the individual column to study the behavior of more complex structure under impact loading. These structures could be a single frame or 3D building frame.
- Including fire effect in addition to the impact load since the elevated temperature is a main cause for localized failure in steel structures.
REFERENCES


APPENDIX A

COMPARISON OF TRUE STRESS-TRUE STRAIN RESULTS AT DIFFERENT STRAIN RATES AND SAME INITIAL TEMPERATURE

Figure A.1 True stress-true strain experimental data at varying strain rates: (a) HSLA-65, 77 K, (b) HSLA-65, 296 K, (c) HSLA-65, 400 K, (d) HSLA-65, 700 K, (e) DH-36, 77 K, (f) DH-36, 296 K
VITA

Fadi Shaker Makarem was born on December, 1985, in Ajman, UAE. He is from Syria. He studied in Abu Dhabi during high school and was honored to be ranked the tenth in class over UAE and the fourth over Abu Dhabi in 2004. He was awarded Abu Dhabi Water and Electricity Authority (ADWEA) Scholarship to study Civil Engineering in the American University of Sharjah and received his Bachelor degree in 2008 with Magna Cum Laude distinction.

Fadi joined The National Energy and Water Research Center/ADWEA as research engineer and started his master degree at the American University of Sharjah in 2008. Fadi was awarded a Master degree in Civil Engineering Science in 2011.