BEARING BEHAVIOUR OF LAP JOINTS TO THIN-WALLED STEEL PLATES AT AMBIENT AND ELEVATED TEMPERATURES

A thesis submitted to The University of Manchester for the degree of Doctor of Philosophy in the Faculty of Engineering and Physical Sciences

2011

YUCHUAN HE

SCHOOL OF MECHANICAL, AEROSPACE AND CIVIL ENGINEERING
CONTENTS

NOTATIONS ...................................................................................................................... 6
LIST OF FIGURES .............................................................................................................. 9
LIST OF TABLES .................................................................................................................. 14
ABSTRACT .......................................................................................................................... 16
DECLARATION .................................................................................................................... 17
COPYRIGHT ....................................................................................................................... 17
ACKNOWLEDGEMENTS ..................................................................................................... 19

CHAPTER 1. INTRODUCTION .............................................................................................. 20
  1.1 BACKGROUND ............................................................................................................ 20
  1.2 ORIGINALITY AND OBJECTIVES ........................................................................... 20
  1.3 LAYOUT OF THESIS .................................................................................................. 21

CHAPTER 2. LITERATURE REVIEW .................................................................................... 23
  2.1 Connection in steel structures .................................................................................... 23
    2.1.1 Introduction ........................................................................................................... 23
    2.1.2 Beam-column connection types .......................................................................... 23
    2.1.3 Quantification of connection behaviour .............................................................. 32
  2.2 Component based modelling ..................................................................................... 33
    2.2.1 Introduction ........................................................................................................... 33
    2.2.2 Basic steps of applying component based methods ............................................ 33
    2.2.3 Behaviour of basic components .......................................................................... 35
    2.2.4 Relevant research studies on plate in bearing behaviour ..................................... 38
  2.3 Originality and aim of research ................................................................................. 40
  2.4 Methodology of research ......................................................................................... 40
CHAPTER 3. EXPERIMENTAL STUDY AND VALIDATION OF FE MODELLING OF BEARING BEHAVIOUR OF SINGLE BOLTED THIN-WALLED PLATES ................................................. 42

3.1 Introduction ........................................................................................................ 42

3.2 Experimental study .......................................................................................... 42
  3.2.1 Test system and connection material ................................................... 42
  3.2.2 Coupon test .......................................................................................... 43
  3.2.3 Single bolted plate in bearing test design and procedure ..................... 45

3.3 Test observations & data processing ...................................................... 47

3.4 Validation of finite element modelling ................................................... 52
  3.4.1 General introduction of ABAQUS ....................................................... 52
  3.4.2 Convergence criteria ............................................................................ 52
  3.4.3 Material properties ............................................................................... 53
  3.4.4 Element types and mesh size ............................................................... 53
  3.4.5 Hourglass effect ................................................................................... 54
  3.4.6 Geometric simplification ...................................................................... 57
  3.4.7 Comparison between simulation and test results ................................. 57

3.5 Conclusions ............................................................................................... 62

CHAPTER 4. PARAMETRIC STUDY AND ANALYTICAL MODEL FOR SINGLE BOLTED PLATES IN SHEAR .......... 63

4.1 Parametric study .............................................................................................. 63

4.2 Determination of key values in analytical load-deflection curve ........... 64
  4.2.1 Initial stiffness ...................................................................................... 64
  4.2.2 Strength ................................................................................................ 66
  4.2.3 Deformation capacity ......................................................................... 68

4.3 Circumferential strain distribution .............................................................. 68
4.3.1 Net section failure ................................................................. 71
4.3.2 End pull-out failure ............................................................. 72
4.3.3 Bearing failure ................................................................. 73

4.4 Failure mode transition ......................................................... 74
4.4.1 Type I: Net-section/end pull-out transition ......................... 74
4.4.2 Type II Net-section/bearing transition ................................. 75
4.4.3 Type III End pull-out/bearing transition ............................... 76

4.5 Compressive strain distribution ............................................. 77

4.6 Summary of calculation procedure ...................................... 83
4.6.1 Circumferential strain ....................................................... 83
4.6.2 Compressive strain ......................................................... 85

4.7 Conclusions .............................................................................. 85

CHAPTER 5. PARAMETRIC STUDY AND ANALYTICAL MODEL FOR MULTIPLE BOLTED PLATES ................. 87

5.1 Introduction .............................................................................. 87

5.2 Finite element modelling and validation .............................. 87
5.2.1 Geometric simplification .................................................. 87
5.2.2 Element type and mesh technique ..................................... 89

5.3 Parametric study ................................................................. 91

5.4 Development of an analytical model .................................. 93

5.4.1 Initial stiffness ................................................................. 94
5.4.2 Load-carrying capacity .................................................. 97
5.4.3 Displacement ................................................................. 103
5.4.4 Summary of displacement calculation procedure ............. 117

5.5 Conclusions .............................................................................. 119

CHAPTER 6. HIGH TEMPERATURE BEHAVIOUR .......... 121

6.1 Introduction .............................................................................. 121
6.2 Brief description of the tests of HIRASHIMA et al[31] ......................... 121

6.2.1 Elevated temperature material properties ........................................ 123

6.2.2 Mesh sensitivity ........................................................................... 129

6.2.3 Initial boundary conditions ......................................................... 130

6.2.4 Comparison between FE modelling and test results ..................... 132

6.3 Parametric study using FE modelling ............................................. 135

6.3.1 Comparison between simulation and proposed calculation results ... 141

6.3.2 Initial stiffness ............................................................................ 142

6.3.3 Load carrying capacity ............................................................... 143

6.3.4 Displacement at ultimate load .................................................... 150

6.4 Comparison between analytical and simulated load-displacement curves 153

6.5 Summary ....................................................................................... 159

CHAPTER 7. CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH ................................................................. 160

7.1 Summary of completed work ......................................................... 160

7.2 Conclusions ................................................................................... 161

7.3 Recommendations for future study ............................................... 168

APPENDIX B. CALCULATION EXAMPLE FOR MULTIPLE BOLTED PLATE IN SHEAR ................................................................. 174

APPENDIX C. STRESS-STRAIN CURVES OF THE TENSILE COUPON TESTS 179

PUBLICATIONS ................................................................................ 182

REFERENCE ..................................................................................... 183
NOTATIONS

$A_n$  Net cross-section area

$B$  Bearing failure mode

$B_1$  Bearing failure load

$d$  Bolt-hole diameter

$D_1$  FE simulated displacement

$D_2$  Proposed calculation displacement

$D_C$  Displacement from compressive pile-up

$D_T$  Displacement from circumferential strain elongation

$e_1$  End distance

$e_2$  Edge distance

$E$  End pull-out failure mode

$E_{a,\theta}$  Slope of the linear elastic range at temperature $\theta$

$f_{p,\theta}$  Proportional limit

$f_u$  Ultimate tensile stress of material

$f_y$  Yield strength of material

$f_{y,\theta}$  Effective yield strength

$F_0$  Simulated failure load from Kim et al.

$F_1$  FE simulated failure load

$F_2$  Failure load from proposed calculation

$F_{b,Rd}$  Bearing failure load

$F_s$  End pull-out failure load
\( F_i \) Net-section failure load

\( I_0 \) The number of equilibrium iterations after which the check is made that the residuals are not increasing in two consecutive iterations

\( I_R \) The number of equilibrium iterations after which the logarithmic rate of convergence check begins

\( k \) Initial stiffness

\( k_0 \) Initial stiffness from test result

\( k_1 \) Initial stiffness from FE simulation

\( k_2 \) Initial stiffness from proposed calculation

\( k_{E, o} \) Reduction factor (relative to \( E_o \)) for the slope of the linear elastic range

\( k_{p, o} \) Reduction factor (relative to \( f_y \)) for proportional limit

\( k_{y, o} \) Reduction factor (relative to \( f_y \)) for effective yield strength

\( N \) Net-section failure mode

\( N_1 \) Net section failure load

\( p_1 \) Spacing of bolt-rows in load transfer direction

\( p_2 \) Bolt spacing of perpendicular to load direction

\( P_{ue} \) Tested failure load

\( S_1 \) End pull-out failure load, Eurocode 3 formula

\( S_2 \) End pull-out failure load, New Zealand/Australia standard formula

\( t \) Plate thickness

\( \varepsilon_c \) Compressive strain

\( \varepsilon_{p, o} \) Strain at the proportional limit

\( \varepsilon_{y, o} \) Yield strain

\( \varepsilon_{t, o} \) Limiting strain for yield strength
\( \varepsilon_{u, o} \)  Ultimate strain

\( \Theta_{o} \) Steel temperature
LIST OF FIGURES

Figure 2.1 Moment-Rotation behaviour of different types of connections ............... 24
Figure 2.2 Typical beam to column classification based on strength[1] ................. 25
Figure 2.3 Typical beam to column classification based on stiffness[1] ............... 26
Figure 2.4 Fin plate connection ............................................................................ 27
Figure 2.5 Details of angle cleat connections ....................................................... 29
Figure 2.6 End plate connections ......................................................................... 30
Figure 2.7 Typical cross sections for thin-walled members[4] ............................... 31
Figure 2.8 Different joining methods of thin-walled members ............................... 32
Figure 2.9 An example of components a beam-column end-plate joint with a extended end-plate connection[8] ................................................................. 34
Figure 2.10 An example to represent an extended end-plate connection using component based method[8] ................................................................. 35
Figure 2.11 Idealized load-displacement curve for a single component ............... 36
Figure 2.12 Different failure modes of standard bolted connection and thin-walled bolted connection ........................................................................... 37
Figure 2.13 Failure modes simulated by Chung and Ip[20] ................................. 39
Figure 3.1 INSTRON 4507 test machine .............................................................. 43
Figure 3.2 Tension coupon dimensions ................................................................. 44
Figure 3.3 Bolted connection test set up ............................................................... 46
Figure 3.4 Location of strain gauges ................................................................. 46
Figure 3.5 A single bolted plate in shear test in progress ....................................... 47
Figure 3.6 Load-displacement curves for all tests ................................................. 48
Figure 3.7 A curled plate in test D14-70-80 .......................................................... 49
Figure 3.8 Test curves after data process .............................................................. 51
Figure 3.9 Typical mesh for plate ....................................................................... 54
Figure 3.10 Hourglass effect .............................................................................. 56
Figure 3.11 Comparison of Test & FE simulated failure modes ............................ 59
Figure 3.12 Comparison of test and simulation load-displacement results for all tests ........................................................................................................ 60
Figure 3.13 Comparison of recorded and simulated load-strain curves ............... 61
Figure 3.14 Damaged strain gauges at point 1 and 2 of Test D14-20-80 .............. 62
Figure 4.1 Assumed analytical load-displacement curve ........................................... 64
Figure 4.2 Example of initial stiffness calculation ..................................................... 65
Figure 4.3 Positions of critical strain points .............................................................. 69
Figure 4.4 Comparison between assumed strain distribution and simulated strain
distribution for different failure modes ................................................................. 70
Figure 4.5 Assumed circumferential strain distribution for net-section failure ...... 71
Figure 4.6 Assumed circumferential strain distribution for end pull-out failure ...... 72
Figure 4.7 Assumed circumferential strain distribution for bearing failure .......... 73
Figure 4.8 Strains at different critical points during transition from net section failure
to end pull-out failure ............................................................................................ 75
Figure 4.9 Strain values at different critical points during transition from net-section
to bearing failure ..................................................................................................... 76
Figure 4.10 Assumed strain values at different critical points for transition from end
pull-out to bearing failure ....................................................................................... 77
Figure 4.11 Compressive strain distribution along plate length ................................ 78
Figure 4.12 Summary of comparison between ABAQUS simulation and analytical
calculation results for bolt-hole elongation ......................................................... 81
Figure 4.13 End pull-out failure displacement comparison .................................... 82
Figure 4.14 Net-section failure displacement comparison ...................................... 82
Figure 4.15 Bearing failure displacement comparison ......................................... 83
Figure 5.1 Kim et al[24] test set-up ........................................................................... 88
Figure 5.2 Half plate for simulation ......................................................................... 88
Figure 5.3 Different mesh sizes ................................................................................ 89
Figure 5.4 Comparison of failure modes between FE simulation and Kim’s test
results ....................................................................................................................... 91
Figure 5.5 Simulation model for plate with multiple bolt-holes ............................... 93
Figure 5.6 Assumed analytical load-displacement curve for a multiple bolt-hole plate
................................ ........................................................................................................ 93
Figure 5.7 Plate with multiple bolt-holes in both directions .................................... 94
Figure 5.8 Load on a plate with multiple bolt-holes in both directions ................. 98
Figure 5.9 Loads on plate with two bolt-holes in loading direction .................... 100
Figure 5.10 Displacement of plate with multiple bolt-holes ................................... 105
Figure 5.11 Assumed circumferential strain distribution for net-section failure .... 106
Figure 5.12 Two components of total displacement ............................................ 107
Figure 5.13: Compressive strain distribution along plate length ........................................ 107
Figure 5.14 Relationship between displacements at different bolt-holes ..................... 108
Figure 5.15 Assumed circumferential strain distribution for end pull-out failure at the outer bolts.................................................................................................................. 109
Figure 5.16 Assumed circumferential strain distribution for bearing failure............. 110
Figure 5.17 Assumed strain values for plate with multiple bolt-holes in both horizontal & vertical directions, n ≥ 3............................................................................................................ 112
Figure 5.18 Assumed strain values at different critical points for transition from net-section to bearing/end pull-out failure ................................................................. 113
Figure 5.19 Simulated displacement VS calculated maximum plate displacement. 116
Figure 6.1 Connection dimensions in the fire tests conducted by HIRASHIMA et al ................................................................................................................................. 122
Figure 6.2 Stress-strain relationship for steel at elevated temperatures allowing strain hardening from Eurocode 3[33].................................................................................. 124
Figure 6.3 Stress-strain curves of SM490A at elevated temperatures according Eurocode 3[33]...................................................................................................................... 125
Figure 6.4 Bolt in shear FE model by Gary and McCarthy[34] .................................... 126
Figure 6.5 Simulated bolt failure ............................................................................. 127
Figure 6.6 Recorded stress-strain curves of bolts at elevated temperatures by HIRASHIMA et al [31] ............................................................................................................. 129
Figure 6.7 Finite element mesh for the elevated temperature tests of HIRASHIMA et al ......................................................................................................................... 130
Figure 6.8 Load-displacement curves taken from HIRASHIMA et al.’s tests ...... 131
Figure 6.9 Initial position of bolt and plate in simulation........................................ 131
Figure 6.10 Comparison of load-displacement curve at 20°C and 300°C ............ 133
Figure 6.11 Comparison of load-displacement curve at 200°C and 400°C ............ 133
Figure 6.12 Comparison of load-displacement curve at 500°C and 600°C ............ 134
Figure 6.13 Comparison of load-displacement curve at 550°C and 650°C ............ 134
Figure 6.14 Simulated load-displacement relationships for set-1 models ............. 137
Figure 6.15 Simulated load-displacement relationships for set-2 models ............. 138
Figure 6.16 Simulated load-displacement relationships for set-3 models ............. 138
Figure 6.17 Simulated load-displacement relationships for set-4 models ............. 139
Figure 6.18 Simulated load-displacement relationships for set-5 models ............. 139
Figure 6.19 Simulated load-displacement relationships for set-6 models ............. 140
Figure 6.20 Simulated load-displacement relationships for set-7 models ............... 140
Figure 6.21 Simulated load-displacement relationships for set-8 models ............... 141
Figure 6.22 Three key values of connection load-displacement curve............... 141
Figure 6.23 Comparison between ABAQUS simulation and analytical calculation results for initial stiffness ............................................................................................................. 143
Figure 6.24 Load on plate with multiple bolts ....................................................... 145
Figure 6.25 Simulated load VS calculated load carrying capacity .................... 147
Figure 6.26 Example of net-section failure comparison ..................................... 149
Figure 6.27 Example of end pull-out failure comparison ..................................... 149
Figure 6.28 Example for bearing failure comparison .......................................... 150
Figure 6.29 Displacement of plate with multiple bolt-holes.................................... 151
Figure 6.30 Simulated displacements VS calculated displacements ................. 153
Figure 6.31 Proposed load-displacement curve for plate in bearing.................. 154
Figure 6.32 Comparison of predicted and simulated load-displacements for set-1-1 to set-1-3 ....................................................................................................................... 155
Figure 6.33 Comparison of predicted and simulated load-displacements for set-1-4 to set-1-7 ....................................................................................................................... 155
Figure 6.34 Comparison of predicted and simulated load-displacements for set-2 models ...................................................................................................................... 156
Figure 6.35 Comparison of predicted and simulated load-displacements for set-3 models ...................................................................................................................... 156
Figure 6.36 Comparison of predicted and simulated load-displacements for set-4 models ...................................................................................................................... 157
Figure 6.37 Comparison of predicted and simulated load-displacements for set-5 models ...................................................................................................................... 157
Figure 6.38 Comparison of predicted and simulated load-displacements for set-6 models ...................................................................................................................... 158
Figure 6.39 Comparison of predicted and simulated load-displacements for set-7 models ...................................................................................................................... 158
Figure 6.40 Comparison of predicted and simulated load-displacements for set-8 models ...................................................................................................................... 159
Figure 7.1 Assumed circumferential strain distribution for net-section failure ...... 163
Figure 7.2 Assumed circumferential strain distribution for end pull-out failure ....... 163
Figure 7.3 Assumed circumferential strain distribution for bearing failure ........ 164
Figure 7.4 Strains at different critical points during transition from net section failure to end pull-out failure ........................................................................................................ 164
Figure 7.5 Strain values at different critical points during transition from net-section to bearing failure .............................................................................................................. 165
Figure 7.6 Assumed strain values at different critical points for transition from end pull-out to bearing failure .............................................................................................................. 165
Figure 7.7 Compressive strain distribution along plate length ........................................ 166
Figure 7.8 Assumed strain values for plate with multiple bolt-holes in both horizontal & vertical directions, $n \geq 3$ .................................................................................................................. 167
Figure 7.9 Assumed strain values at different critical points for transition from net-section to bearing/end pull-out failure .............................................................................................. 168

Figure APX-1 Circumferential strain distribution around bolt hole ........................................ 171
Figure APX-2 Compressive strain distribution ........................................................................... 173
Figure APX-3 Plate with 6 bolt-holes ........................................................................................ 174
Figure APX-4 Critical points on inner bolt-hole ........................................................................... 176
Figure APX-5 Circumferential strain distribution around bolt hole ........................................ 177
Figure APX-6 Compressive strain distribution ........................................................................... 178
Figure APX-7 Stress-strain curve for test S1 .............................................................................. 179
Figure APX-8 Stress-strain curve for test S2 .............................................................................. 179
Figure APX 9 Stress-strain curve for test S3 .............................................................................. 180
Figure APX 10 Stress-strain curve for test S4 ............................................................................ 180
Figure APX 11 Stress-strain curve for test S5 ............................................................................ 181
Figure APX 12 Stress-strain curve for test S6 ............................................................................ 181
## LIST OF TABLES

Table 2.1 Basic components and available design formulas from Eurocode 3 .......... 37
Table 3.1 Coupon test results ..................................................................................... 44
Table 3.2 Main parameters of tests ............................................................................ 45
Table 3.3 Results of mesh sensitivity study ............................................................... 57
Table 3.4 Comparison of test and simulation results for connection failure load ...... 58
Table 4.1 List of parameters in parametric study ....................................................... 63
Table 4.2 Comparison of initial stiffness from test, FE simulation and Eurocode 3 calculation .................................................................................................................. 65
Table 4.3 Comparison between simulated strength and predictions using different design standards ................................................................................................................................. 67
Table 4.4 Comparison between simulation and proposed calculation displacements 79
Table 5.1 Mesh sensitivity for single-hole plates ....................................................... 90
Table 5.2 Comparison between simulation results and test results from Kim et al [24] .................................................................................................................................... 90
Table 5.3 List of assessed parameters ........................................................................ 92
Table 5.4 Comparison of initial stiffness for plates with multiple bolt-holes in both directions .................................................................................................................... 95
Table 5.5 Comparison of maximum load between simulation and calculation results for plates with multiple bolt-holes ........................................................................... 102
Table 5.6 Displacement comparison between ABAQUS simulations & calculation results .................................................................................................................................. 115
Table 6.1 Details of the HIRASHIMA tests ............................................................ 122
Table 6.2 Mechanical properties of SM490A[32] ................................................... 123
Table 6.3 Reduction factors for carbon steel at elevated temperature according to Eurocode 3[33] .................................................................................................................. 128
Table 6.4 Results of High-Temperature Tensile Tests of Bolts [31] ....................... 128
Table 6.5 Comparison between HIRASHIMA’s test & FE simulation results ...... 135
Table 6.6 Details of numerical parametric study cases ............................................ 136
Table 6.7 Comparison for initial stiffness between FE simulation and analytical calculation results at elevated temperatures ................................................................. 142
Table 6.8 Comparison of load carrying capacity between FE simulation and analytical calculation results at elevated temperatures ............................................. 146
Table 6.9 Comparison of predicted failure modes & simulated failure modes ...... 148
Table 6.10 Comparison for displacement at maximum load between FE simulation and the proposed calculation method at elevated temperatures ............................................. 152
Table 7.1 Proposed calculation method for single bolted plate in bearing behaviour ......................................................................................................................... 162
Table 7.2 Proposed calculation method for multiple bolted plate in bearing behaviour ......................................................................................................................... 166
ABSTRACT

This thesis presents the results of a comprehensive research study of the bearing behaviour of single or multiple bolted plates in bolt shear at ambient and elevated temperatures. A total of 18 tests were carried out to provide detailed experimental information on bearing behaviour of plates with single bolt. A series of parametric studies using the commercial finite element package ABAQUS were conducted to investigate the effects of different design parameters on the connected plate bearing behaviour, including initial stiffness, ultimate resistance and deformation at the ultimate resistance. The finite element models were verified by comparing the simulated results against the author’s tests conducted as part of this research and other researchers’ test results. Based on the parametric study results, an analytical model was proposed to predict the bearing load-deformation relationship of bolted plate in bolt shear. It was found that the stiffness and ultimate resistance could be predicted accurately by using existing methods. The main contribution of the analytical study was the development of a simple method to calculate the maximum plate deformation (bolt-hole elongation) at the ultimate resistance, based on proposed strain distributions according to different failure modes. This method has been verified against the parametric study results and has been found to be suitable for ambient and elevated temperature applications.
DECLARATION

No portion of the work referred to in the thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

COPYRIGHT

i. The author of this thesis (including any appendices and/or schedules to this thesis) owns certain copyright or related rights in it (the “Copyright”) and s/he has given The University of Manchester certain rights to use such Copyright, including for administrative purposes.

ii. Copies of this thesis, either in full or in extracts and whether in hard or electronic copy, may be made only in accordance with the Copyright, Designs and Patents Act 1988 (as amended) and regulations issued under it or, where appropriate, in accordance with licensing agreements which the University has from time to time. This page must form part of any such copies made.

iii. The ownership of certain Copyright, patents, designs, trade marks and other intellectual property (the “Intellectual Property”) and any reproductions of copyright works in the thesis, for example graphs and tables (“Reproductions”), which may be described in this thesis, may not be owned by the author and may be owned by third parties. Such Intellectual Property and Reproductions cannot and must not be made
available for use without the prior written permission of the owner(s) of the relevant Intellectual Property and/or Reproductions.

iv. Further information on the conditions under which disclosure, publication and commercialisation of this thesis, the Copyright and any Intellectual Property and/or Reproductions described in it may take place is available in the University IP Policy (see http://documents.manchester.ac.uk/DocuInfo.aspx?DocID=487), in any relevant Thesis restriction declarations deposited in the University Library, The University Library’s regulations (see http://www.manchester.ac.uk/library/aboutus/regulations) and in The University’s policy on Presentation of Theses.
ACKNOWLEDGEMENTS

The 5 years I spent on this PhD research project is the experience I will never forget. Life had never been so hard before.

First and foremost, I am grateful to my supervisor, Professor Yong. C. Wang, for his selfless help, constant inspiration and far-sighted supervision.

I also appreciate the help from the technical staff, Mr Jim Gee and Mr David Mortimer, for assistance with my tests.

During my study, my colleagues in the Fire and Structure Research Group, especially Ashley Park, Ashkan Shahbazian, Dr. Ima Rahmanian, Dr. Jifeng Yuan, Lu Chen, Dr. Pingyu Yan, Xue Li, offered kind help, which is always appreciated.

I would also like to thank my parents for their unconditional support both spiritually and financially.
CHAPTER 1. INTRODUCTION

1.1 BACKGROUND

Cold-formed thin-walled steel has been used in many areas of civil engineering construction. In cold-formed thin-walled steel structures, bolted connection is often used. Currently, design codes for cold-formed thin-walled steel structures may be used to obtain stiffness and load carrying capacity of connections. However, there are very few methods to evaluate the complete load-deflection curve, in particular, the deformation capacity of connections. The current status is acceptable if the designer is only interested in structural strength under normal condition or the loading condition in the structure does not change. However, when a structure is under accidental loading such as fire, the load carrying mechanism may change or the loading condition in the structure may change.

In order to obtain a clear understanding of bearing behaviour of thin-walled steel bolted connections, a research study including experiments and numerical simulations on bolted thin-walled steel connections has been performed. The results of the study will be reported in this thesis. An analytical model has been developed to obtain the load-displacement behaviour of bolted thin-walled steel connections in shear.

1.2 ORIGINALITY AND OBJECTIVES

The aim of this project is to fully understand the in-plane bearing behaviour of thin-walled steel connections, including load capacity, initial stiffness and displacement at the maximum load is required. In thin-walled plates, out-of-plane buckling may occur. This is not considered in this research.

The objectives of this research are:
CHAPTER 1

INTRODUCTION

- To provide detailed experimental information of thin-walled steel bolted connection in bearing;
- To establish accurate finite element models for parametric study;
- To validate available initial stiffness calculation methods;
- To validate available ultimate load calculation methods;
- To develop a simplified calculation method to predict displacement at the maximum load for thin-walled steel bolted connection under bearing at ambient temperature;
- To extend the ambient temperature prediction method to elevated temperatures.

1.3 LAYOUT OF THESIS

This thesis is divided into 7 chapters. A brief outline of each chapter is given below:

Chapter 2 Literature review
This chapter presents a brief literature review including general introduction to steel connections and bearing behaviour of bolted connections at both ambient and elevated temperatures.

Chapter 3 Experimental study and validation of FE modelling on bearing behaviour of single bolted thin-walled plates

This chapter presents details and results of an experimental study of the bearing behaviour of single bolted thin-walled plates, including tensile coupon tests and single bolted thin-walled plate tests.

Chapter 4 Parametric study and analytical model proposal for single bolted plates

This chapter describes a numerical study, using ABAQUS, to establish a finite element model and validation of this numerical model against experimental results obtained in Chapter 3. This is then followed by an extensive parametric study to
investigate the effects of different factors on initial stiffness, load carrying capacity and displacement at the maximum load for single bolted thin-walled steel connections in bearing at ambient temperature. An analytical model is then developed to predict initial stiffness, load capacity and displacement at the maximum load of single bolted thin-walled connections in bearing under ambient temperature. This chapter presents validation of this analytical method, based on the numerical simulation results.

Chapter 5 Parametric study and analytical model for multiple bolted plates
This chapter extends Chapter 4’s work to predict initial stiffness, load carrying capacity and displacement of thin-walled plate with multiple bolt-holes in bearing under ambient temperature.

Chapter 6 High temperature behaviour
This chapter provides a numerical study of multiple-bolted thin-walled steel connections in bearing at elevated temperatures. Validation of finite element simulation models is presented by comparing against elevated temperature test results by other researches. A further parametric study is carried out for the purpose of assessing the applicability of the methods proposed in Chapters 4 and 5 to elevated temperatures.

Chapter 7 Conclusions and Recommendations for Further Research
This chapter summarizes the main conclusions of this thesis and recommends relevant topics for further research.
CHAPTER 2. LITERATURE REVIEW

The research is concerned with the bearing behaviour of thin-walled steel connection, at both ambient and elevated temperatures. This chapter will review where it is necessary to understand this type of behaviour and present a brief introduction to relevant research studies. Detailed review of close relevant publications will be presented in later chapters when dealing with each specific aspect of the research topic.

2.1 Connection in steel structures

2.1.1 Introduction

There are different components in a steel structure and connections provide critical links between the different components to ensure safety of the complete structure. In normal Serviceability Limit State (SLS) and Ultimate Limit State (ULS) design, connection stiffness and strength are the necessary quantities to be obtained. Accidental Limit State (ALS) deals with structural performance when subjected to unforeseeable loading condition, in particular disproportionate collapse. At ALS, deformation capacity is the most important quantity. The literature review of this chapter will be mainly concerned with these three key properties of connections.

2.1.2 Beam-column connection types

Beam to column connection is conventionally divided into 3 different categories: pinned connections, which have no ability to resist moment; rigid connections, which can resist moment without undergoing any rotation; and semi-rigid partial-strength connections, which fall within the aforementioned two extremes. Figure 2.1 illustrates the flexural behaviour of the two extreme types of connection.
Figure 2.1 Moment-Rotation behaviour of different types of connections

a) Pinned connection

b) Rigid connection
Figure 2.2 and Figure 2.3 show different classification boundaries for connections.

Figure 2.2 Typical beam to column classification based on strength[1]
Figure 2.3 Typical beam to column classification based on stiffness[1]
Bearing components in different conventional steel connections

1) Fin plate connection

![Figure 2.4 Fin plate connection](image)

As shown in Figure 2.4, a single plate with pre-punched bolt holes is welded onto the column in workshop to act as a basic connecting component. The beam web is then connected to the welded plate by bolts on site. The easy fabrication and fast assembly have lead to economic construction. Therefore, fin plate connection is popular and is commonly used. It is recommended by Steel Construction Institute and the British Constructional Steelwork Association\[2, 3\] as one of the main standard designs of shear connection. The main load carrying mechanism is bolt bearing on both the fin plate and the web of the beam. Therefore, the results of this research will be directly relevant to fin plate connection.

2) Angle cleat connection

Angle cleat connections use different types of angle cleats to connect the beam and the column. They can be categorized into 3 types for different combinations of cleat position: connection with top and seat angle cleats, as shown in Figure 2.5 a); connection with web angle cleats, as shown in Figure 2.5 b); connection with top, seat and web angle cleats, as shown in Figure 2.5 c). Under shear, bearing is the main load carrying mechanism for the cleats on the column and the beam web. When resisting a bending moment, the bearing mechanism is activated in the cleats on the beam flanges.
3) **End plate connection**

In an end-plate connection, a plate is welded to the beam at the end. This plate is then connected to the flange of the column through bolts. Depending on the length of the end-plate, there are 3 types of end-plate connection: flexible end-plate (end-plate is shorter than the depth of the beam), flush end-plate (bolts are within the depth of the beam) and extended end-plate connections (bolts are beyond the depth of the beam). Detailed connections are shown in Figure 2.6. Plate bearing behaviour is involved for plate and column resistance under vertical shear.
Figure 2.5 Details of angle cleat connections
Figure 2.6 End plate connections

a) Flexible end plate

b) Flush end plate

c) Extended end plate
Connection in thin-walled structures

The hot-rolled steel connection types mentioned above can also be used in thin-walled steel structures. However, thin-walled members usually have a variety of shapes (Figure 2.7), necessitating different joining methods. Figure 2.8 shows a variety of joining methods between thin-walled members. Again, bearing plays an important role in all these joints as noted on each joint type.

Figure 2.7 Typical cross sections for thin-walled members[4]
2.1.3 Quantification of connection behaviour

Different methods may be used to describe the moment-rotation relationship of a beam-column connection, including mathematic curve-fitting, component based models, finite element simulation and experimental testing. Experimental testing has the potential to observe realistic behaviour of joints, but it is very expensive and time-consuming. Finite element modelling is routinely used by researchers, but it requires specialist expertise which may not be available in practical design. On the other hand, mathematical curve-fitting has limited applicability. As a consequence, the component-based method has evolved as the preferred method of quantifying...
joint behaviour because it combines the flexibility of being able to deal with different types of joints with different construction details and the simplicity of being able to be used by practitioners. The main focus of this research is to develop a plate bearing component model for implementation in component based modelling.

2.2 Component based modelling

2.2.1 Introduction

The “component based model” is also called spring model. It is a simple, yet sufficiently flexible method for modelling connection behaviour for implementation in practical design of steel structures. This method was originally designed for hot-rolled steel structural connections and is now included in Eurocode 3\[7\].

2.2.2 Basic steps of applying component based methods

i Identify basic components

The component based method divides a connection into compression zone, a tension and a shear zone. Shear deformation is usually small so past research studies have mainly focused on developments in the compression and tension zones. The first step is to identify the basic components in these zones. An end-plate connection is shown in Figure 2.9 as an example. The components in the tension zone include: column web in tension, column flange in bending, bolt in tension, end-plate in bending and beam web in tension; the components in the compression zone include: beam web in compression, beam flange in compression, column web in compression.

ii Presenting behaviour of each individual component

The second step of the component based method is to present the behaviour of each identified basic component by a load-displacement curve. These curves can be presented linearly, bi-linearly, tri-linearly or non-linearly. Each component can then be represented by a spring.
Figure 2.9 An example of components a beam-column end-plate joint with a extended end-plate connection[8]

**Assembly of basic components**

After each component is represented by a spring, all springs are connected to represent the whole connection. Figure 2.10 shows the spring model to represent the end-plate connection shown in Figure 2.9. This spring can be further simplified and represented by several springs connected together: for example, one tensile spring to take the axial tensile force for each bolt row and one compressive spring to take the axial compressive force. The column web shear component caused by column web compression and tension is represented by a diagonal spring. Using the compatibility
condition to relate the joint rotation with the component deformations, and the equilibrium condition to relate the component forces with the joint bending moment, the joint moment-rotation relationship can be established.

2.2.3 Behaviour of basic components

In order to obtain accurate behaviour of a connection, the behaviour of the basic components should be accurately predicted. This research contributes to the bearing behaviour of plates at ambient and elevated temperatures.

Figure 2.11 shows a bilinear load-displacement curve to describe the load-deformation behaviour of a basic component. In order to establish this, three important factors need to be known: initial stiffness, ultimate load capacity and ductility.

i Basic components in standard connections

Eurocode 3[7] summarizes in total 20 basic components that need to be considered in conventional connections, as shown in Table 2.1. As can be seen from this table, comprehensive guidance is available for predicting the initial stiffness and load carrying capacity of the listed basic components. However, there is a lack of
information on their ductility. From a total of 20 components, only 8 components have some information on ductility. Even for these 8 components, ductility consideration is restricted to whether or not the component has sufficient ductility in plastic stage analysis, but there is no formula to quantify ductility. Sufficient ductility is important in conventional plastic analysis, but essential when dealing with control of disproportionate collapse under accidental loading situation such as fire exposure because it is high ductility that allows alternative load carrying mechanisms (such as catenary action) to be developed when primary load carrying mechanisms at small deflections (such as bending) are no longer able to sustain the applied load. Ductility is also important in thin-walled structures which tend to develop large displacements and distortions. In particular, in bolted thin-walled plates under bearing (Figure 2.12b), because the bolts are comparatively much stronger and stiffer than the connected plates, plate bearing behaviour is the critical component of this type of connection. Ductility is the main focus of this research.

![Idealized load-displacement curve for a single component](image)

Figure 2.11 Idealized load-displacement curve for a single component
Table 2.1 Basic components and available design formulas from Eurocode 3

<table>
<thead>
<tr>
<th>Component</th>
<th>Formula for initial stiffness</th>
<th>Formula for load capacity</th>
<th>Formula for ductility</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Column web in shear</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes*</td>
</tr>
<tr>
<td>2 Column web in transverse compression</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes*</td>
</tr>
<tr>
<td>3 Column web in transverse tension</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes*</td>
</tr>
<tr>
<td>4 Column flange in bending</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes*</td>
</tr>
<tr>
<td>5 End-plate in bending</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes*</td>
</tr>
<tr>
<td>6 Flange cleat in bending</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes*</td>
</tr>
<tr>
<td>7 Beam or column flange and web in compression</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>8 Beam web in tension</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>9 Plate in tension or compression</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>10 Bolts in tension</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes*</td>
</tr>
<tr>
<td>11 Bolts in shear</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes*</td>
</tr>
<tr>
<td>12 Bolts in bearing</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>13 Concrete in compression including grout</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>14 Base plate in bending under compression</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>15 Base plate in bending under tension</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>16 Anchor bolts in tension</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>17 Anchor bolts in shear</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>18 Anchor bolts in bearing</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>19 Welds</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>20 Haunched beam</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>

Note: denoting being able to be used in plastic analysis

Figure 2.12 Different failure modes of standard bolted connection and thin-walled bolted connection

a) Standard bolted connection (bolt failure)  
   b) Thin-walled bolted connection (plate failure)
2.2.4 Relevant research studies on plate in bearing behaviour

Rex et al[9] conducted a series of single bolt experiments at ambient temperature. Based on the test results, an analytical model was proposed to predict load-deformation behaviour of plate in bearing. This model provided an equation to predict initial stiffness of plate in bearing with an accuracy similar to the equation provided by Eurocode 3; the strength equation provided by AISC LRFD (1993 edition)[10] was found to give the best prediction compared with Rex et al’s test results and therefore adopted for strength prediction; the displacement was predicted using the curve fitting equation developed by Elsalti et al[11]. The main problems with Rex’s model are (1) the initial stiffness equation was derived by assuming a bearing deformation (0.102 mm) of the bolt-hole at the yield stress, which is not suitable in many cases; (2) calculation of the deformation was based on mathematical curve-fitting rather than structural engineering principles. Sarraj[12] further developed Rex et al’s model for predicting the bearing behaviour of plates at elevated temperatures. However, Sarraj’s model suffers from the same limitations of Rex et al. Consequently, it will be difficult to extrapolate this method for more general use.

Rogers et al[13, 14] conducted a large series of bolted connection tests using G300 (Australian steel grade, yield stress = 300MPa) and G550 (yield stress = 550MPa) sheet steel. Unfortunately, the test reports do not include full details of load-displacement relationships. The test results were compared with different load carrying capacity design formulas from different design standards[15-18]. This comparison indicated that the formulas from current design codes[15-18][15-18][15-18][15-18][15-18] could not predict failure load of plate in bearing accurately when plate is very thin (less than 1.0mm). A formula with reduction factor related to bolt-hole/thickness ratio was proposed to increase the accuracy of failure load prediction. However, the formula was only verified by plates with thickness less than 1.0mm.

In addition to experimental testing and analytical development, a few researchers have also conducted numerical simulations using finite element method to investigate thin-walled connections in detail.
Among these research studies, Chung and Ip\cite{19-21} simulated the behaviour of cold formed thin-walled steel bolted connection in shear using the commercial software ANSYS. They were able to simulate all three expected failure modes when a bolted steel plate is loaded by bolt bearing: namely end shear-out (also named end pull-out), net-section fracture and bearing, as shown in Figure 2.13. They concluded that the accuracy of the load-displacement curves generated from their finite element models can be significantly affected by important parameters such as the stress–strain curve of steel, contact stiffness etc.

Kim and Kuwamura et al\cite{22-25} used the general finite element software ABAQUS to conduct 3D finite element simulations of their own tests. They found that due to very small thicknesses of the plates, there was no obvious deformation or damage in the bolts. Therefore, they simplified the bolt as a rigid cylindrical tube without any deformation throughout the whole simulation. In addition to the three failure modes

![Figure 2.13 Failure modes simulated by Chung and Ip\cite{20}](image)

Kim and Kuwamura et al\cite{22-25} used the general finite element software ABAQUS to conduct 3D finite element simulations of their own tests. They found that due to very small thicknesses of the plates, there was no obvious deformation or damage in the bolts. Therefore, they simplified the bolt as a rigid cylindrical tube without any deformation throughout the whole simulation. In addition to the three failure modes
observed in the simulations of Chung and Ip, they also identified occurrence of curling.

Other relevant research studies include the tests and the tests of HIRASHIMA et al at elevated temperatures. Details of the research studies will be given in Chapter 6.

### 2.3 Originality and aim of research

As can be seen above, although there have been many research studies on the load-displacement behaviour of different basic connection components, most of these researches have focused on the initial stiffness and load carrying capacity of the components at ambient temperature. There is a lack of information on the complete load-displacement relationship of plate behaviour in bearing, in particular, there is an almost total lack of investigation on how to calculate the bearing deformation of plates connected by bolts in shear at ambient or elevated temperatures. Conducting an experimental, numerical and analytical investigation to develop a method of quantifying the complete load-deformation relationship of plates in bearing, at both ambient temperature and elevated temperatures, is the specific objective of this research.

### 2.4 Methodology of research

This research will include three parts: a limited amount of experimental testing of plates in bearing connected by single bolt at ambient temperature (Chapter 3); extensive parametric study using a validated simulation model for plates connected by a single bolt and by multiple bolts at ambient (Chapters 4 and 5) and elevated temperatures (Chapter 6) and development and validation of an analytical method to predict the load-displacement of plate in bearing (Chapters 5 and 6). The experimental testing was considered necessary because existing test results do not include complete load-displacement relationships. The parametric study is intended
to broaden the scope of the test results. The analytical model is for future incorporation into the component based model for complete connection behaviour.

2.5 Summary

This chapter has provided a brief review of a number of relevant research studies on component based connection behaviour and bolted steel plates in bearing. Most of these researches have concentrated on the initial stiffness and load carrying capacity. No method exists to enable the bearing displacement of bolted steel plates to be analytically determined. Also there is a lack of research investigating elevated temperature behaviour. The research reported in this thesis is intended to fill these important gaps.
CHAPTER 3. EXPERIMENTAL STUDY AND VALIDATION OF FE MODELLING OF BEARING BEHAVIOUR OF SINGLE BOLTED THIN-WALLED PLATES

3.1 Introduction

In the previous chapter, it was found that there is an important gap in research studies of the load-displacement behaviour of thin-walled bolted connections in shear. In particular, the displacement at the maximum load has not been adequately addressed in any research study. Therefore, an experimental study has been conducted to acquire load-displacement information of single bolted thin-walled steel connections in shear. These tests are intended to provide detailed information for validation of the numerical simulation model that will be used to conduct detailed investigation of the effects of various design parameters. This chapter will present details of the test results, including the coupon test results, the bolted connection test set-up and the test results.

3.2 Experimental study

3.2.1 Test system and connection material

Both the coupon tests and the connection tests were performed in the universal loading frame INSTRON 4507 shown in Figure 3.1. The steel plates were cold formed and the nominal steel grade was S275 and the tension coupon specimen thickness was 1.5mm. Grade 8/8 M12 bolts are commonly used in thin-walled steel structures and they were used in this research so that the results can be compared with the other researches.
3.2.2 Coupon test

The coupons were cut from the same piece of plate from which the tested plates were cut from. The dimensions of the coupons followed the recommendation in BS-EN 10002-1[26]. Figure 3.2 shows the detailed dimension of the tension coupons.

Six coupons were tested. Because the material was cold formed, there was not obvious yield point. The yield stress was taken at 0.2% proof strain position. The final material properties are taken as the mean value of the six sets of recorded data, as shown in Table 3.1. In Appendix C, all the recorded stress-strain curves are included.
It is noticed from Table 3.1 that the measured Young’s modulus values are somewhat different from the nominal value of 210 GPa. The measured values were directly obtained from the tensile coupon testing software which was based on the initial tangent to the measured stress-strain curve. The results obtained this way can be sensitive to the calculation scheme. Nevertheless, since the focus of this research is the bearing performance of plates which start to undergo plastic deformation at small loads, no attempt was made to further refine the Young’s modulus values.

<table>
<thead>
<tr>
<th>Sample number</th>
<th>Young’s modulus (MPa)</th>
<th>Stress at max load (N/mm²)</th>
<th>Strain at max load (%)</th>
<th>Stress at 0.2% proof strain (N/mm²)</th>
<th>Strain at failure (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>224165.22</td>
<td>326.32</td>
<td>23.67</td>
<td>201.41</td>
<td>27.30</td>
</tr>
<tr>
<td>S2</td>
<td>209851.98</td>
<td>322.40</td>
<td>23.73</td>
<td>198.47</td>
<td>35.89</td>
</tr>
<tr>
<td>S3</td>
<td>210822.03</td>
<td>319.69</td>
<td>24.10</td>
<td>195.56</td>
<td>34.00</td>
</tr>
<tr>
<td>S4</td>
<td>242220.27</td>
<td>321.94</td>
<td>24.16</td>
<td>198.93</td>
<td>34.15</td>
</tr>
<tr>
<td>S5</td>
<td>215721.70</td>
<td>325.28</td>
<td>24.60</td>
<td>200.42</td>
<td>34.97</td>
</tr>
<tr>
<td>S6</td>
<td>244118.61</td>
<td>323.10</td>
<td>23.65</td>
<td>199.45</td>
<td>35.10</td>
</tr>
<tr>
<td>Mean</td>
<td>224483.30</td>
<td>323.12</td>
<td>23.99</td>
<td>199.04</td>
<td>33.57</td>
</tr>
</tbody>
</table>
3.2.3 Single bolted plate in bearing test design and procedure

The tests were designed to investigate the effects of different end/edge distance combinations and their effects on failure modes. Table 3.2 lists the main parameters of these tests. As mentioned above, these tests used 1.5mm thick cold-formed carbon steel plates and 12mm bolts with 14mm bolt-holes.

Table 3.2 Main parameters of tests

<table>
<thead>
<tr>
<th>Test ID</th>
<th>Number of replicate tests</th>
<th>Bolt diameter (mm)</th>
<th>Bolt hole diameter d (mm)</th>
<th>End distance (mm)</th>
<th>Edge distance (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D14-14-28</td>
<td>3</td>
<td>12</td>
<td>14</td>
<td>14 (1d)</td>
<td>14 (1d)</td>
</tr>
<tr>
<td>D14-21-42</td>
<td></td>
<td></td>
<td></td>
<td>21 (1.5d)</td>
<td>21 (1.5d)</td>
</tr>
<tr>
<td>D14-20-80</td>
<td></td>
<td></td>
<td></td>
<td>20 (1.43d)</td>
<td>40 (2.86d)</td>
</tr>
<tr>
<td>D14-28-80</td>
<td></td>
<td></td>
<td></td>
<td>28 (2d)</td>
<td>40 (2.86d)</td>
</tr>
<tr>
<td>D14-70-40</td>
<td></td>
<td></td>
<td></td>
<td>70 (5d)</td>
<td>20 (1.43d)</td>
</tr>
<tr>
<td>D14-70-80</td>
<td></td>
<td></td>
<td></td>
<td>70 (5d)</td>
<td>40 (2.86d)</td>
</tr>
</tbody>
</table>

Figure 3.3 shows the experimental set up with indication of the locations of displacement and strain measurement. The displacement transducer was attached on the plate to track the movement of the bolt head due to bolt-hole elongation. Two thick plates were placed on two sides of the thin-walled steel plate to prevent curling. In order to understand strain distribution around the bolt-hole area, in each test, 3 strain gauges were attached close to the edge of the bolt-hole on the tested plate, including two one-way gauges to measure the tensile strains at cross-section and one 2-way gauge to measure both compressive and tensile strains at bolt and plate contact point, as shown in Figure 3.4.

Figure 3.5 shows a test in progress.
Figure 3.3 Bolted connection test set up

Figure 3.4 Location of strain gauges
Test results, along with data processing are presented in the next section.

### 3.3 Test observations & data processing

Figure 3.6 shows the raw load-displacement curves for all the tests.
The test curves of D14-70-40 and D14-20-80 show a very small amount of negative displacement at the beginning of the test. This is because the reading of the potential meter was not adjusted to zero at the beginning of these tests. In post test data
The measured load-displacement curves for test D14-70-80 exhibit slight oscillation. This was the result of a small amount of curling of the plates. In the tests, the test plates were clamped between two thick steel blocks, with the intention of eliminating curling. However, because the bolts were hand-tightened, a very small gap still existed in between the plates these tests. Figure 3.7 shows appearance of one of these test specimens after test. The amount of curling is very small.

![A curled plate in test D14-70-80](image)

The load-displacement curve of one test of D14-70-40 indicates that slip occurred at the beginning of this test. The slip was caused by a loose grip at the end of the plates where they were clamped by the loading machine. This slip should be taken away when analysing the behaviour of this plate.

Based on the above explanations, the raw load-displacement curves were processed to ensure consistence among the test results. Figure 3.8 shows the resulting curves after this process. It can be seen that the 3 duplicated load-displacement curves for test D14-28-80, D14-14-28 and D14-20-80 have very similar load capacity and
displacement at ultimate load. The difference of initial stiffness in these test curves can be observed but is very slight. For test D14-70-40, one curve showed slight difference compared to the other 2 curves. The initial stiffness in the 3 test curves matches each other. To sum up, the three duplicated load-displacement curves for each arrangement are very similar. Therefore, the average of these three curves can be used to represent each test arrangement. These average curves will be used in the next section for comparison with FE simulation results.
Figure 3.8 Test curves after data process
3.4 Validation of finite element modelling

In order to progress the research in a more efficient way, a finite element model using the commercial software ABAQUS has been established for further parametric investigation.

3.4.1 General introduction of ABAQUS

ABAQUS offers two types of solutions for simulation: implicit analysis and explicit analysis. The implicit analysis uses iterative solution to solve a set of simultaneous non-linear equations. It is used commonly to solve static problems that are not time-related. The Newton-Raphson method (General static analysis) is applied until the determinant of the stiffness matrix becomes zero or negative. The explicit method is designed to solve dynamic impact problems that are time-related. It uses explicit integrations to solve nonlinear complicated contact problems. In this research, the implicit static method is used for analysis. This section describes the main points of the simulation model and compares the simulation and test results.

3.4.2 Convergence criteria

Convergence difficulties may arise when large-deformation and complicated contact problems happen in implicit analysis. Therefore, ABAQUS offers “General Solution Controls” to help the convergence of iterations during the solution. There are many control parameters associated with the convergence and integration accuracy algorithms in ABAQUS. These parameters are categorized into 4 sections: Field Equations, Line Search Control, Constraint Equations and Time Incrementation. The default solution control parameters defined in ABAQUS are designed to provide reasonably optimal results to solve most nonlinear and complicated contact problems and normally the default settings give the best simulation result. However, when convergence problem happens, change the parameters ($I_0$ and $I_R$) in Time Incrementation section to a great value is a good way to help the calculation reaches convergence. $I_0$ is the number of equilibrium iterations after which the check is made.
that the residuals are not increasing in two consecutive iterations and $I_R$ is the number of equilibrium iterations after which the logarithmic rate of convergence check begins.

The default settings in ABAQUS are $I_0=4$ and $I_R=8$. In this research, the default setting is able to deal with the convergence problem and provide sufficient accuracy. Therefore, the default settings were applied.

### 3.4.3 Material properties

It should be noted that the data attained from tensile coupon tests are engineering stress and strain. They should be transferred into true stress and true strain according to the following formulas:

\[
\sigma_t = \sigma_n (1 + \varepsilon_t) \tag{3.1}
\]

\[
\varepsilon_t = \ln (1 + \varepsilon_n) \tag{3.2}
\]

### 3.4.4 Element types and mesh size

The ABAQUS simulation model used C3D8R element, which is a three-dimensional, 8 nodes solid hexahedral brick element with 1 integration point. This element is suitable to be used in both linear and non-linear analysis at large strain and deformation. The reduced integration gives good control of hourglass effect and reduces calculation time. Using brick elements gives detailed information on failure mode, failure load, strain and stress results.

Smaller mesh size should give better accuracy to simulation result but the calculations are more time-consuming. An optimal mesh size should be used to achieve the best accuracy without consuming too much computation time. It is critical that the mesh size is small enough not to affect simulation result, i.e. the simulation result is insensitive to mesh size. A mesh sensitivity study was carried out to determine the best mesh size. Mesh size of $\frac{1}{4}$ plate thickness was found to be sufficient and was applied to places in the structure where a fine mesh was required, i.e. the area around the bolt-hole. For example, Table 3.3 compares the simulation results using different mesh sizes for one of the tests by Kim et al (2007) and one of
the author’s own tests, using different mesh sizes. The difference in connection failure load is very small, less than 2%. Figure 3.9 shows a typical finite element mesh used.

![Typical mesh for plate](image)

Figure 3.9 Typical mesh for plate

### 3.4.5 Hourglass effect

It should be noticed that hourglass effect may happen when using first order reduced integration element. The hourglass effect is also called “zero energy mode”. As can be seen in Figure 3.10 b), the reduced integration element detects deformation via the change of lengths from the integration point to the element edges. If using a single element through the thickness direction, the reduced integration element will not detect the change of lengths, i.e. no strain (energy) change is detected.

The hourglass effect can be reduced as long as there are multiple layers in the thickness direction. As can be seen in Figure 3.10 c), with multiple layers through the
thickness direction, the change of lengths from integration point to element edges can be detected by the elements.

ABAQUS also offers enhanced hourglass control method to reduce the hourglass effect. The enhanced hourglass control approach is a refined pure stiffness method. It gives more accurate displacement solutions for linear elastic materials and increased resistance to hourglass effect for nonlinear materials. In ABAQUS, when the “enhanced hourglass control” option is turned on, the refined pure stiffness formulas are used.

In the FE models of this research, the “enhanced hourglass control” option was turned on; multiple layers were defined through the thickness direction. Therefore, the hourglass effect was minimized.
Figure 3.10 Hourglass effect

a) Normal element deformation

b) Reduced integration element detected deformation

c) Solution for hourglass effect
CHAPTER 3  

EXPERIMENTAL STUDY

3.4.6 Geometric simplification

The tested thin-walled steel plate was much more flexible and weaker than the bolt used. In fact, in all tests the bolt showed no visible deformation after the tested plate failed. Therefore, in the simplification, the bolt was modelled using rigid hollow shell elements which did not deform during the entire simulation. This considerably reduced the element number in simulation models and simulation time.

Table 3.3 Results of mesh sensitivity study

<table>
<thead>
<tr>
<th>Test SB2-4 of Kim et al [24]</th>
<th>Finite element size (width * length)</th>
<th>No. of Elements</th>
<th>Increase in mesh size</th>
<th>Simulation time(sec)</th>
<th>Test strength $P_e$(KN)</th>
<th>Simulation strength $P_s$(KN)</th>
<th>$P_s/P_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>t/2 * t/2</td>
<td>7188</td>
<td>0%</td>
<td>1603</td>
<td>85.62</td>
<td>92.17</td>
<td>1.077</td>
<td></td>
</tr>
<tr>
<td>t/3 * t/3</td>
<td>15015</td>
<td>109%</td>
<td>5006</td>
<td>90.95</td>
<td>1.062</td>
<td></td>
<td></td>
</tr>
<tr>
<td>t/4 * t/4</td>
<td>25527</td>
<td>255%</td>
<td>8961</td>
<td>90.57</td>
<td>1.057</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Author’s test D14-70-40

<table>
<thead>
<tr>
<th>Finite element size (width * length)</th>
<th>No. of Elements</th>
<th>Increase in mesh size</th>
<th>Simulation time(sec)</th>
<th>Test strength $P_e$(KN)</th>
<th>Simulation result $P_s$(KN)</th>
<th>$P_s/P_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>t/2 * t/2</td>
<td>5833</td>
<td>0%</td>
<td>633</td>
<td>13.65</td>
<td>13.99</td>
<td>1.025</td>
</tr>
<tr>
<td>t/3 * t/3</td>
<td>9709</td>
<td>66%</td>
<td>3025</td>
<td>13.75</td>
<td>1.007</td>
<td></td>
</tr>
<tr>
<td>t/4 * t/4</td>
<td>15325</td>
<td>163%</td>
<td>6221</td>
<td>13.53</td>
<td>0.991</td>
<td></td>
</tr>
</tbody>
</table>

3.4.7 Comparison between simulation and test results

As mentioned above, the duplicate tests for each arrangement were represented by an average curve. Table 3.4 compares the recorded and simulated plate failure loads. Figure 3.11 compares the observed and simulated failure modes. It can be seen that all three failure modes (net section failure, end pull-out, plate bearing) were successfully revealed from the tests. Figure 3.12 compares the averaged and simulated plate load-deflection relationships. The plate deflection was the bolt-hole elongation. Figure 3.13 presents a selection of recorded and simulated load-strain results.
Table 3.4 Comparison of test and simulation results for connection failure load

<table>
<thead>
<tr>
<th>Test ID</th>
<th>End distance (mm)</th>
<th>Edge distance (mm)</th>
<th>Recorded failure load (KN)</th>
<th>Simulated failure load (KN)</th>
<th>Recorded failure mode</th>
<th>Simulated failure mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>D14-14-28</td>
<td>14</td>
<td>14</td>
<td>7.41</td>
<td>6.49</td>
<td>End pull-out</td>
<td>End pull-out</td>
</tr>
<tr>
<td>D14-20-80</td>
<td>20</td>
<td>40</td>
<td>12.00</td>
<td>10.92</td>
<td>End pull-out</td>
<td>End pull-out</td>
</tr>
<tr>
<td>D14-28-80</td>
<td>28</td>
<td>40</td>
<td>15.96</td>
<td>14.43</td>
<td>End pull-out</td>
<td>End pull-out</td>
</tr>
<tr>
<td>D14-21-42</td>
<td>21</td>
<td>21</td>
<td>11.58</td>
<td>10.88</td>
<td>End pull-out</td>
<td>End pull-out</td>
</tr>
<tr>
<td>D14-70-40</td>
<td>70</td>
<td>20</td>
<td>13.65</td>
<td>13.46</td>
<td>Net-section</td>
<td>Net-section</td>
</tr>
<tr>
<td>D14-70-80</td>
<td>70</td>
<td>40</td>
<td>19.52</td>
<td>19.48</td>
<td>Bearing</td>
<td>Bearing (see Figure 3.11)</td>
</tr>
</tbody>
</table>
Figure 3.11 Comparison of Test & FE simulated failure modes
The results in Table 3.4, Figure 3.11 and Figure 3.12 confirm that the finite element model was able to accurately predict the failure mode, failure load and load-deformation curves of all the tests.
Figure 3.13 Comparison of recorded and simulated load-strain curves

The results in Figure 3.13 show that the finite element model accurately simulated all the load-strain relationships except for one case (end pull-out strain at point 1 and 2 in test D14-20-80) which was caused by strain gauge failure due to large deformation of the plate at the strain gauge area, as shown in Figure 3.14.
3.5 Conclusions

This chapter has presented details of an experimental study on behaviour of single bolted thin-walled plate in shear, followed by validation of finite element modelling.

The following conclusions can be drawn:

- The test results have successfully shown different failure modes as a result of different combinations of the following parameters: end distance, edge distance, bolt-hole diameter.
- The FE model using the commercial package ABAQUS is sufficiently accurate and can be used to investigate the behaviour of this type of structure for the development of an analytical method.
CHAPTER 4. PARAMETRIC STUDY AND ANALYTICAL MODEL FOR SINGLE BOLTED PLATES IN SHEAR

4.1 Parametric study

Following verification of the finite element model described in chapter 3, in order to develop an analytical model to predict the load-deflection behaviour of thin-walled steel plates loaded by a single bolt in shear, an extensive set of parametric studies were performed to establish a comprehensive database of results. Table 4.1 lists the parameters investigated, intended to assess the effects of the following parameters: bolt-hole size, end distance, edge distance and ultimate strain of steel. In total 56 simulations are performed.

Table 4.1 List of parameters in parametric study

<table>
<thead>
<tr>
<th>Bolt size</th>
<th>Bolt hole size d</th>
<th>End distance e₁</th>
<th>Edge distance e₂</th>
<th>Thickness t</th>
<th>Ultimate strain of steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>8mm</td>
<td>10mm</td>
<td>1d</td>
<td>1d, 1.5d, 2d, 2.5d</td>
<td>1.5mm</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2d</td>
<td>1d, 1.5d, 2d, 2.5d</td>
<td>1.5mm</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3d</td>
<td>1d, 1.5d, 2d, 2.5d</td>
<td>1.5mm</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4d</td>
<td>1d, 1.5d, 2d, 2.5d</td>
<td>1.5mm</td>
<td>0.35</td>
</tr>
<tr>
<td>12mm</td>
<td>14mm</td>
<td>1.5d</td>
<td>1d, 1.5d, 2d, 2.5d</td>
<td>1.5mm, 3mm</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2d</td>
<td>1d, 1.5d, 2d, 2.5d</td>
<td>1.5mm</td>
<td>0.25, 0.35</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3d</td>
<td>1d, 1.5d, 2d, 2.5d</td>
<td>1.5mm</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4d</td>
<td>1d, 1.5d, 2d, 2.5d</td>
<td>1.5mm</td>
<td>0.35</td>
</tr>
<tr>
<td>18mm</td>
<td>20mm</td>
<td>1d</td>
<td>1d, 1.5d, 2d, 2.5d</td>
<td>1.5mm</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2d</td>
<td>1d, 1.5d, 2d, 2.5d</td>
<td>1.5mm</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3d</td>
<td>1d, 1.5d, 2d, 2.5d</td>
<td>1.5mm</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4d</td>
<td>1d, 1.5d, 2d, 2.5d</td>
<td>1.5mm</td>
<td>0.35</td>
</tr>
</tbody>
</table>
4.2 Determination of key values in analytical load-deflection curve

The analytical load-deflection curve is assumed to be linear-elastic-plastic, as shown in Figure 4.1. Therefore, three values are required to determine the analytical curve: initial stiffness, strength and deformation capacity.

![Figure 4.1 Assumed analytical load-displacement curve](image)

4.2.1 Initial stiffness

Eurocode 3[7] provides the following equation for calculating bolt bearing initial stiffness:

\[
k = 24n_b k_b k_d f_u
\]  

(4.1)

Where \(k_b\) is a factor that considers the effect of end distance and bolt row spacing and \(k_b = \min[k_{b1}, k_{b2}, 1.25]\), with

\[
k_{b1} = \frac{0.25e_1}{d} + 0.5
\]

\[
k_{b2} = \frac{0.25p_1}{d} + 0.375
\]
$k_t = 1.5t_j/d_{M16}$ which is a reduction factor for steel plate thickness

$d_{M16}$: Nominal diameter of a M16 bolt

This formula is intended for use with hot-rolled steel connection. Table 4.2 compares calculation results using the above equations with ABAQUS simulation results and test results. The initial stiffness of test and ABAQUS simulation is determined by measuring the secant slope of the elastic part of the load-displacement curve at the position of 1/3 of the ultimate load, as shown in Figure 4.2. Based on this definition of initial stiffness, Eurocode 3 calculation results are generally higher than the results from test and simulation when predicting initial stiffness of single bolted plate in bearing. It may be necessary to apply a modification factor in practical design.

![Figure 4.2 Example of initial stiffness calculation](image)

### Table 4.2 Comparison of initial stiffness from test, FE simulation and Eurocode 3 calculation

<table>
<thead>
<tr>
<th>Test ID</th>
<th>$k_0$</th>
<th>$k_1$</th>
<th>$k_2$</th>
<th>$k_1/k_0$</th>
<th>$k_2/k_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>D14-14-28</td>
<td>11132</td>
<td>9366</td>
<td>11290</td>
<td>0.84</td>
<td>1.01</td>
</tr>
<tr>
<td>D14-20-80</td>
<td>13198</td>
<td>14709</td>
<td>12945</td>
<td>1.11</td>
<td>0.98</td>
</tr>
<tr>
<td>D14-28-80</td>
<td>12566</td>
<td>15774</td>
<td>15053</td>
<td>1.26</td>
<td>1.20</td>
</tr>
</tbody>
</table>
### 4.2.2 Strength

There are three possible failure modes: net section tensile fracture, end pull-out and bearing failure.

The net section tensile fracture capacity is:

\[
F_t = A_n \cdot f_u = (2e_2 - d) \cdot t \cdot f_u
\]  

(4.2)

In an earlier version of Eurocode 3 [16], the end pull-out capacity was calculated using:

\[
F_s = t \cdot e_1 \cdot f_u / 1.2
\]  

(4.3)

And the bearing resistance was calculated using:

\[
F_b = 2.5d \cdot t \cdot f_u
\]  

(4.4)

But \(F_b \leq t \cdot e_1 \cdot f_u / 1.2\)

In the latest version of Eurocode 3 [27], the above two equations are combined to give the following single equation:

\[
F_b = 2.5\alpha_b \cdot k_t \cdot d \cdot t \cdot f_u
\]  

(4.5)

where \(k_t\) is 1 if there is no net-section failure. \(\alpha_b\) is taken as the smaller value of \(e_1 / 3d\) (end pull-out) and 1 (bearing).

In the Australian/New Zealand [17] and North American design standards [28], the end pull-out resistance formula is similar, only the reduction factor 1.2 is excluded, i.e.

\[
F_s = t \cdot e_1 \cdot f_u
\]  

(4.6)

Table 4.3 compares the ABAQUS simulation results with predictions for connection strength from the different prediction methods. It appears that for end pull-out, the
New Zealand/Australian standard of not including a modification factor of 1.2 gives better results.

The design calculation results are within 10% of the test and simulation results in all cases. For both net-section failure and end pull-out failure modes, the design calculation results are on the safe side. The design calculation results for bearing failure mode are slightly higher than the results from test and simulation. However, considering the simplicity of the design calculation equations and the small error produced, it is acceptable to use the design calculation method.

From the comparisons for initial stiffness and load carrying capacity under different failure modes, it can be confirmed that the existing design calculation methods for these two quantities are able to be applied.

Table 4.3 Comparison between simulated strength and predictions using different design standards

<table>
<thead>
<tr>
<th>Model</th>
<th>End(mm)</th>
<th>Edge(mm)</th>
<th>Failure mode</th>
<th>N1(KN)</th>
<th>B1(KN)</th>
<th>S1(KN)</th>
<th>S2(KN)</th>
<th>F1(KN)</th>
<th>S1/F1</th>
<th>S2/F1</th>
</tr>
</thead>
<tbody>
<tr>
<td>D14-17.5-56</td>
<td>17.50</td>
<td>28.00</td>
<td>E</td>
<td>20.16</td>
<td>16.8</td>
<td>7</td>
<td>8.40</td>
<td>9.18</td>
<td>0.76</td>
<td>0.92</td>
</tr>
<tr>
<td>D14-21-80</td>
<td>21.00</td>
<td>40.00</td>
<td>E</td>
<td>31.68</td>
<td>16.8</td>
<td>8.40</td>
<td>10.08</td>
<td>11.40</td>
<td>0.74</td>
<td>0.88</td>
</tr>
<tr>
<td>D14-28-80</td>
<td>28.00</td>
<td>40.00</td>
<td>E</td>
<td>31.68</td>
<td>16.8</td>
<td>11.20</td>
<td>13.44</td>
<td>14.43</td>
<td>0.78</td>
<td>0.93</td>
</tr>
<tr>
<td>Model</td>
<td>End(mm)</td>
<td>Edge(mm)</td>
<td>Failure mode</td>
<td>N1(KN)</td>
<td>B1(KN)</td>
<td>S1(KN)</td>
<td>S2(KN)</td>
<td>F1(KN)</td>
<td>N1/F1</td>
<td></td>
</tr>
<tr>
<td>D14-21-28</td>
<td>21</td>
<td>14</td>
<td>N</td>
<td>6.72</td>
<td>16.8</td>
<td>8.4</td>
<td>10.08</td>
<td>7.39</td>
<td>0.91</td>
<td></td>
</tr>
<tr>
<td>D14-35-35</td>
<td>35</td>
<td>17.5</td>
<td>N</td>
<td>10.08</td>
<td>16.8</td>
<td>14</td>
<td>16.80</td>
<td>10.96</td>
<td>0.92</td>
<td></td>
</tr>
<tr>
<td>d14-56-35</td>
<td>56</td>
<td>17.5</td>
<td>N</td>
<td>10.08</td>
<td>16.8</td>
<td>22.4</td>
<td>16.80</td>
<td>11.03</td>
<td>0.91</td>
<td></td>
</tr>
<tr>
<td>Model</td>
<td>End(mm)</td>
<td>Edge(mm)</td>
<td>Failure mode</td>
<td>N1(KN)</td>
<td>B1(KN)</td>
<td>S1(KN)</td>
<td>S2(KN)</td>
<td>F1(KN)</td>
<td>B1/F1</td>
<td></td>
</tr>
<tr>
<td>d14-35-56</td>
<td>35</td>
<td>28</td>
<td>B</td>
<td>20.16</td>
<td>16.8</td>
<td>14</td>
<td>16.80</td>
<td>15.80</td>
<td>1.06</td>
<td></td>
</tr>
<tr>
<td>d14-42-56</td>
<td>42</td>
<td>28</td>
<td>B</td>
<td>20.16</td>
<td>16.8</td>
<td>16.8</td>
<td>16.80</td>
<td>16.61</td>
<td>1.01</td>
<td></td>
</tr>
<tr>
<td>d14-56-49</td>
<td>56</td>
<td>24.5</td>
<td>B</td>
<td>16.80</td>
<td>16.8</td>
<td>22.4</td>
<td>16.80</td>
<td>15.53</td>
<td>1.08</td>
<td></td>
</tr>
</tbody>
</table>

Note:
S1: End pull-out failure load, Eurocode 3 formula
S2: End pull-out failure load, New Zealand/Australian Standard formula
F1: FE model simulated failure load
N1: Net-section failure load
B1: Bearing failure load
E: End pull-out failure mode
N: Net-section failure mode
B: bearing failure mode
4.2.3 Deformation capacity

The main focus of the analytical load-deflection development is to determine the connection deformation at the ultimate capacity.

Here the connection deformation refers to elongation of the bolt hole. Due to symmetry, bolt-hole elongation is the tensile deformation of half of the bolt-hole circumference plus any compressive pile up in front of the bolt, as indicated in Figure 4.3. Therefore, to calculate the bolt-hole elongation, it is necessary to obtain the tensile strain distribution around the bolt hole and the compressive strain distribution in front of the bolt.

4.3 Circumferential strain distribution

After detailed investigation of strain distributions around the bolt hole based on the parametric study results, it was found that the circumferential strain distribution around the bolt hole may be assumed to be multi-linear between five key points, as shown in Figure 4.3. The strain at points D and E may be assumed to be 0.

The circumferential strain values at points A, B and C are dependent on the connection failure mode. As explained in the previous section, there are three pure failure modes: net section tension failure, end pull-out and bearing failure. For strain calculations, the following three failure mode transitions should also be considered to avoid a step change in strain values at the critical points: net section tension/end pull-out, net section tension/bearing and end pull-out/bearing. Figure 4.4 compares the assumed circumferential strain distributions around the hole (to be presented in the next section) with the numerical simulation results for different failure modes. The assumed strain distributions can be considered acceptable.
Figure 4.3 Positions of critical strain points
CHAPTER 4  PARAMETRIC STUDY FOR SINGLE BOLTED PLATES

Figure 4.4 Comparison between assumed strain distribution and simulated strain distribution for different failure modes
4.3.1 Net section failure

For net section failure, it is assumed that the strain at point C is equal to the ultimate tensile strain of steel. For example, Figure 4.5 shows that the ultimate tensile strain of steel was 0.35. The strain at points A, B, D and E is zero. Figure 4.5 also shows the assumed strain distribution around the bolt hole.

\[
F_t = A_n \cdot f_u = (2e_2 - d) \cdot t \cdot f_u < F_s = t \cdot e_1 \cdot f_u
\]

\[
F_t < F_b = 2.5d \cdot t \cdot f_u
\]

Re-arranging the above equations gives:

\[
e_2 < (e_1 + d)/2 \quad (4.7)
\]

\[
e_2 < 1.75d \quad (4.8)
\]
4.3.2 End pull-out failure

End pull-out failure happens when \( F_s < F_t \) and \( F_s < F_b \). Therefore:

\[
F_s = t \cdot e_1 \cdot f_u \leq F_t = A_n \cdot f_u = (2e_2 - d) \cdot t \cdot f_u
\]

\[
F_s \leq F_b = 2.5d \cdot t \cdot f_u
\]

Re-arranging the above equations gives:

\[
e_1 \leq 2e_2 - d \quad \text{(4.9)}
\]

\[
e_1 \leq 2.5d \quad \text{(4.10)}
\]

When end pull-out happens, it is assumed that the strain at point C, D and E is zero but the strain at B reaches \( \varepsilon_B = \varepsilon_t + \mu \cdot \varepsilon_r \), where \( \varepsilon_t \) is the ultimate tensile strain of steel, \( \mu \) Poisson’s ratio (0.3) and \( \varepsilon_r \) is the radial compressive strain due to bearing. It is assumed in this research that the compressive strain can reach a value of 1.0, representing complete shortening from the original length to zero. Therefore, \( \varepsilon_r = 1.0 \). This assumption is similar to that made by Chung and Ip[19] who proposed a compressive strain of 3 times the ultimate tensile strain. At \( \varepsilon_r = 1.0 \), in Figure 4.6, the circumferential strain at point B is \( 0.35 + 0.3 \times 1.0 = 0.65 \).

Figure 4.6 Assumed circumferential strain distribution for end pull-out failure
CHAPTER 4  PARAMETRIC STUDY FOR SINGLE BOLTED PLATES

The circumferential strain at point A equals to the ultimate tensile strain of the steel material, e.g. 0.35 in Figure 4.6.

4.3.3 Bearing failure

Bearing failure happens when \( F_b \leq F_t \) and \( F_b \leq F_s \). These conditions are met when:

\[
e_2 \geq 1.75d \tag{4.11}
\]

\[
e_1 \geq 2.5d \tag{4.12}
\]

When bearing failure happens, it is assumed that the strains at point C, D and E are zero. The strain at point A is \( \varepsilon_B = \varepsilon_t + \mu \varepsilon_r \), owing to combined tension and compression in front of the bolt. For example, in Figure 4.7, the strain at point A is 0.35 + 0.30 \times 1.0 = 0.65. The strain distribution between A and C is linear so the strain at point B is half of that at point A. Figure 4.7 shows the complete assumed circumferential strain distribution around the bolt hole under bearing failure.

![Figure 4.7 Assumed circumferential strain distribution for bearing failure](image)

Figure 4.7 Assumed circumferential strain distribution for bearing failure
4.4 Failure mode transition

In the previous section, strain distributions are given for one single failure mode. One single failure mode occurs when the load carrying capacity under this failure mode is much lower than those of the other two failure modes. However, when the calculated failure loads under two different failure modes are similar, using the above strain distributions would introduce artificial step changes. Modifications are therefore necessary to allow a smooth and gradual transition from one failure mode to another. It is hard to decide the exact bounds of transition between two single failure modes. In order to determine the critical point strain values, approximate boundaries are assumed based on the simulation results.

4.4.1 Type I: Net-section/end pull-out transition

According to equations (4.7) and (4.9), net section/end pull-out failure is determined by the ratio of $e_1/(2e_2 - d)$. When this value is less than 1, end pull-out dominates and when this is greater than 1, net section failure dominates. Also since bearing failure does not happen, therefore, $e_1 < 2.5d$ and $e_2 < 1.75d$. It is assumed that at $e_1/(2e_2 - d) = 1$, the strain values at critical points A, B and C are according to end pull-out failure. The transition period is from when $e_2 = (e_1 + d)/2$ to a reduction in $e_2$ by 0.25d when the strain values at critical points A, B and C are calculated for net-section failure. Within the transition region, linear interpolation is used.

Figure 4.8 shows the assumed strain distributions at points A, B and C as function of $e_2$. 
Figure 4.8 Strains at different critical points during transition from net section failure to end pull-out failure

4.4.2 Type II Net-section/bearing transition

For net-section/bearing failure transition, end pull-out failure does not occur. Therefore, \( e_1 > 2e_2 - d \) and \( e_1 > 2.5d \). According to equation (4.8) and (4.11), the condition \( e_2 = 1.75d \) marks the separation of net-section failure from bearing failure. It is assumed that at \( e_2 = 1.75d \), the strain distribution is according to bearing failure. Pure net-section failure happens when \( e_2 < 0.75d \). During the transition period of \( 0.75d < e_2 < 1.75d \), linear interpolation can be used. Figure 4.9 shows the assumed strain values at increasing \( e_2 \).
4.4.3 Type III End pull-out/bearing transition

For this transition, net-section failure does not occur. Therefore, according to equations (4.9) and (4.11), $e_1 < 2e_2 - d$ and $e_2 > 1.75d$. The boundary between end pull-out failure and bearing failure is at $e_1 = 2.5d$. It is assumed that at $e_1 = 2.5d$, bearing failure starts to control. The transition zone is between $e_1 = 1.5d$ and $e_1 = 2.5d$. At $e_1 = 1.5d$, end pull-out governs and the strain values are according to end pull-out failure. Figure 4.10 shows the strain values at the different critical points at increasing $e_1$. 

Figure 4.9 Strain values at different critical points during transition from net-section to bearing failure
4.5 Compressive strain distribution

Compression strain is used to calculate plate pile up, therefore, compressive strain is only considered at point C (directly in front of the bolt). Although compression in front of the bolt will exist in all cases, significant compressive strain occurs under bearing or end pull-out failure. This happens when $e_2 > (e_1 + d)/2$ and $e_2 > 1.75d$. It is assumed that when the end distance is at $e_1 = 1.2d$, end pull-out failure controls and the maximum compressive strain value is equal to the steel ultimate tensile strain. At $e_1 = 2d$, bearing failure governs and the compressive strain reaches 1.0. Linear interpolation applies during the transition phase.

Nevertheless, for plates that experience net-section failure mode, there is some compression strain, although the compressive strain is reduced compared to the other two failure modes. According to equation (4.7) and (4.8), net-section failure occurs when $e_2 < (e_1 + d)/2$ and $e_2 < 1.75d$. Within this failure mode, the numerical
simulation results suggest that when $e_2 \leq 0.75d$, the compressive strain equals 0. When $e_2 \geq (e_1 + d)/2$, the edge distance is sufficient to achieve the maximum compressive strain specified in the last paragraph. When the edge distance falls between these two values, linear interpolation can be applied to determine the reduced compressive strain value.

In order to calculate the bolt hole elongation due to compressive pile up, it is assumed that that the compressive strain changes from the maximum value at the bolt/plate contact point to zero at a distance of one bolt diameter away (or the actual edge of the plate if less), as shown in Figure 4.11.

![Figure 4.11 Compressive strain distribution along plate length](image)

It should be pointed out that some of the low values of edge and end distances may be outside the range of the permitted edge and end distances by design standards. However, these limits were not enforced so that the proposed analytical mode is generally applicable, including when the end and edge distances fall within the permitted ranges.

An example is provided in the Appendix to show how to calculate the strains at the various critical locations and the resulting bolt-hole elongation.

To validate the above proposed analytical method, a series of parametric studies have been carried out using ABAQUS, covering different end and edge distances. In most simulations, the bolt diameter was 12mm, the plate thickness 1.5mm and the steel ultimate tensile strain 0.35. But simulations using other values of bolt diameter (8mm and 18mm), plate thickness (3mm) and steel ultimate tensile strain (0.25) were also
performed to check applicability of the proposed analytical method to different bolt sizes, plate thickness and steel ultimate tensile strain.

Table 4.4 compares the ABAQUS simulation results and the analytical results. Figure 4.12 summarizes the overall comparison for all failure modes. The agreement between these two sets of results is generally acceptable, with an average difference of 17.4% and standard deviation of 11.5%. Figure 4.13-Figure 4.15 present separate results for the three different failure modes. It can be seen that for end pull-out failure, the results from proposed calculation and simulation give an average difference of 13.2% and standard deviation of 14.8%; for bearing failure, the two sets of results have an average difference of 26.2% and standard deviation of 13.7%; for net-section failure, as can be seen from Figure 4.14, the two sets of results distribute uniformly around the “$D_1=D_2$” trend, give an average difference of 13.3% and standard deviation of 15.8%, which is acceptable for structure design. The higher difference between simulation and analytical results for the bearing failure mode, with the hand calculation results tending to be higher than the simulation results, may be attributed to using a high value of compressive strength (1.0). However, considering the complexity of the problem and simplicity of the proposed analytical method, no further refinement of the analytical method was pursued.

Table 4.4 Comparison between simulation and proposed calculation displacements

<table>
<thead>
<tr>
<th>End-edge distance</th>
<th>Model name</th>
<th>End distance $e_1$(mm)</th>
<th>Edge distance $e_2$(mm)</th>
<th>Bolt hole d(mm)</th>
<th>Ultimate strain t(mm)</th>
<th>Failure modes</th>
<th>FE model Displacement $D_2$(mm)</th>
<th>Calculated result $D_2$(mm)</th>
<th>$D_2/D_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5d-1d</td>
<td>21-28</td>
<td>21</td>
<td>14</td>
<td>14</td>
<td>0.35</td>
<td>1.5</td>
<td>N/E</td>
<td>4.42</td>
<td>4.02</td>
</tr>
<tr>
<td>1.5d-1.5d</td>
<td>21-42</td>
<td>21</td>
<td>21</td>
<td>14</td>
<td>0.35</td>
<td>1.5</td>
<td>E</td>
<td>7.93</td>
<td>8.67</td>
</tr>
<tr>
<td>1.5d-2d</td>
<td>21-56</td>
<td>21</td>
<td>28</td>
<td>14</td>
<td>0.35</td>
<td>1.5</td>
<td>E</td>
<td>7.29</td>
<td>8.67</td>
</tr>
<tr>
<td>1.5d-2.5d</td>
<td>21-80</td>
<td>21</td>
<td>40</td>
<td>14</td>
<td>0.35</td>
<td>1.5</td>
<td>E</td>
<td>8.67</td>
<td>8.67</td>
</tr>
<tr>
<td>1.5d-1d</td>
<td>21-28</td>
<td>21</td>
<td>14</td>
<td>14</td>
<td>0.35</td>
<td>3</td>
<td>N/E</td>
<td>4.42</td>
<td>4.02</td>
</tr>
<tr>
<td>1.5d-1.5d</td>
<td>21-42</td>
<td>21</td>
<td>21</td>
<td>14</td>
<td>0.35</td>
<td>3</td>
<td>E</td>
<td>8.51</td>
<td>8.67</td>
</tr>
<tr>
<td>1.5d-2d</td>
<td>21-56</td>
<td>21</td>
<td>28</td>
<td>14</td>
<td>0.35</td>
<td>3</td>
<td>E</td>
<td>8.65</td>
<td>8.67</td>
</tr>
<tr>
<td>1.5d-2.5d</td>
<td>21-80</td>
<td>21</td>
<td>40</td>
<td>14</td>
<td>0.35</td>
<td>3</td>
<td>E</td>
<td>7.24</td>
<td>8.67</td>
</tr>
<tr>
<td>2d-1d</td>
<td>28-28</td>
<td>28</td>
<td>14</td>
<td>14</td>
<td>0.35</td>
<td>1.5</td>
<td>N/E</td>
<td>3.58</td>
<td>4.56</td>
</tr>
<tr>
<td>2d-1.5d</td>
<td>28-42</td>
<td>28</td>
<td>21</td>
<td>14</td>
<td>0.35</td>
<td>1.5</td>
<td>E/B</td>
<td>10.40</td>
<td>9.79</td>
</tr>
<tr>
<td>2d-2d</td>
<td>28-56</td>
<td>28</td>
<td>28</td>
<td>14</td>
<td>0.35</td>
<td>1.5</td>
<td>E/B</td>
<td>9.22</td>
<td>9.79</td>
</tr>
<tr>
<td>2d-2.5d</td>
<td>28-80</td>
<td>28</td>
<td>40</td>
<td>14</td>
<td>0.35</td>
<td>1.5</td>
<td>E/B</td>
<td>8.31</td>
<td>9.79</td>
</tr>
</tbody>
</table>
## CHAPTER 4  PARAMETRIC STUDY FOR SINGLE BOLTED PLATES

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Distance 1</th>
<th>Distance 2</th>
<th>Distance 3</th>
<th>Material</th>
<th>Strength</th>
<th>Fatigue</th>
<th>Weight</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>2d-1d</td>
<td>28-28</td>
<td>28</td>
<td>14</td>
<td>0.25</td>
<td>1.5</td>
<td>N/E</td>
<td>3.00</td>
<td>1.10</td>
</tr>
<tr>
<td>2d-1.5d</td>
<td>28-42</td>
<td>28</td>
<td>21</td>
<td>0.25</td>
<td>1.5</td>
<td>E/B</td>
<td>8.79</td>
<td>1.02</td>
</tr>
<tr>
<td>2d-2d</td>
<td>28-56</td>
<td>28</td>
<td>28</td>
<td>0.25</td>
<td>1.5</td>
<td>E/B</td>
<td>7.26</td>
<td>1.23</td>
</tr>
<tr>
<td>2d-2.5d</td>
<td>28-80</td>
<td>28</td>
<td>40</td>
<td>0.25</td>
<td>1.5</td>
<td>E/B</td>
<td>7.32</td>
<td>1.22</td>
</tr>
<tr>
<td>3d-1d</td>
<td>42-28</td>
<td>42</td>
<td>14</td>
<td>0.35</td>
<td>1.5</td>
<td>N/B</td>
<td>3.94</td>
<td>1.18</td>
</tr>
<tr>
<td>3d-1.5d</td>
<td>42-42</td>
<td>42</td>
<td>21</td>
<td>0.35</td>
<td>1.5</td>
<td>N/B</td>
<td>8.83</td>
<td>0.98</td>
</tr>
<tr>
<td>3d-2d</td>
<td>42-56</td>
<td>42</td>
<td>28</td>
<td>0.35</td>
<td>1.5</td>
<td>B</td>
<td>8.07</td>
<td>1.31</td>
</tr>
<tr>
<td>3d-2.5d</td>
<td>42-80</td>
<td>42</td>
<td>40</td>
<td>0.35</td>
<td>1.5</td>
<td>B</td>
<td>8.18</td>
<td>1.30</td>
</tr>
<tr>
<td>4d-1d</td>
<td>56-28</td>
<td>56</td>
<td>14</td>
<td>0.35</td>
<td>1.5</td>
<td>N/B</td>
<td>3.96</td>
<td>1.17</td>
</tr>
<tr>
<td>4d-1.5d</td>
<td>56-42</td>
<td>56</td>
<td>21</td>
<td>0.35</td>
<td>1.5</td>
<td>B</td>
<td>8.05</td>
<td>0.91</td>
</tr>
<tr>
<td>4d-2d</td>
<td>56-56</td>
<td>56</td>
<td>28</td>
<td>0.35</td>
<td>1.5</td>
<td>B</td>
<td>7.66</td>
<td>1.38</td>
</tr>
<tr>
<td>4d-2.5d</td>
<td>56-80</td>
<td>56</td>
<td>40</td>
<td>0.35</td>
<td>1.5</td>
<td>B</td>
<td>7.66</td>
<td>1.38</td>
</tr>
<tr>
<td>1d-1d</td>
<td>10-10-20</td>
<td>10</td>
<td>10</td>
<td>0.35</td>
<td>1.5</td>
<td>N/E</td>
<td>3.83</td>
<td>1.04</td>
</tr>
<tr>
<td>1d-1.5d</td>
<td>10-10-30</td>
<td>10</td>
<td>15</td>
<td>0.35</td>
<td>1.5</td>
<td>E</td>
<td>4.80</td>
<td>0.83</td>
</tr>
<tr>
<td>1d-2</td>
<td>10-10-40</td>
<td>10</td>
<td>20</td>
<td>0.35</td>
<td>1.5</td>
<td>E</td>
<td>4.35</td>
<td>0.91</td>
</tr>
<tr>
<td>1d-2.5d</td>
<td>10-10-50</td>
<td>10</td>
<td>25</td>
<td>0.35</td>
<td>1.5</td>
<td>E</td>
<td>4.48</td>
<td>0.89</td>
</tr>
<tr>
<td>2d-1d</td>
<td>10-20-20</td>
<td>20</td>
<td>10</td>
<td>0.35</td>
<td>1.5</td>
<td>N/E</td>
<td>3.18</td>
<td>1.03</td>
</tr>
<tr>
<td>2d-1.5d</td>
<td>10-20-30</td>
<td>20</td>
<td>15</td>
<td>0.35</td>
<td>1.5</td>
<td>N/E</td>
<td>8.14</td>
<td>0.86</td>
</tr>
<tr>
<td>2d-2d</td>
<td>10-20-40</td>
<td>20</td>
<td>20</td>
<td>0.35</td>
<td>1.5</td>
<td>E</td>
<td>6.32</td>
<td>1.11</td>
</tr>
<tr>
<td>2d-2.5d</td>
<td>10-20-50</td>
<td>20</td>
<td>25</td>
<td>0.35</td>
<td>1.5</td>
<td>E</td>
<td>5.42</td>
<td>1.29</td>
</tr>
<tr>
<td>3d-1d</td>
<td>10-30-20</td>
<td>30</td>
<td>10</td>
<td>0.35</td>
<td>1.5</td>
<td>N/B</td>
<td>3.09</td>
<td>0.84</td>
</tr>
<tr>
<td>3d-1.5d</td>
<td>10-30-30</td>
<td>30</td>
<td>15</td>
<td>0.35</td>
<td>1.5</td>
<td>N/B</td>
<td>5.35</td>
<td>0.95</td>
</tr>
<tr>
<td>3d-2d</td>
<td>10-30-40</td>
<td>30</td>
<td>20</td>
<td>0.35</td>
<td>1.5</td>
<td>B</td>
<td>4.78</td>
<td>1.32</td>
</tr>
<tr>
<td>3d-2.5d</td>
<td>10-30-50</td>
<td>30</td>
<td>25</td>
<td>0.35</td>
<td>1.5</td>
<td>B</td>
<td>4.48</td>
<td>1.41</td>
</tr>
<tr>
<td>4d-1d</td>
<td>10-40-20</td>
<td>40</td>
<td>10</td>
<td>0.35</td>
<td>1.5</td>
<td>N/B</td>
<td>3.33</td>
<td>0.78</td>
</tr>
<tr>
<td>4d-1.5d</td>
<td>10-40-30</td>
<td>40</td>
<td>15</td>
<td>0.35</td>
<td>1.5</td>
<td>N/B</td>
<td>5.89</td>
<td>0.86</td>
</tr>
<tr>
<td>4d-2d</td>
<td>10-40-40</td>
<td>40</td>
<td>20</td>
<td>0.35</td>
<td>1.5</td>
<td>B</td>
<td>4.70</td>
<td>1.34</td>
</tr>
<tr>
<td>4d-2.5d</td>
<td>10-40-50</td>
<td>40</td>
<td>25</td>
<td>0.35</td>
<td>1.5</td>
<td>B</td>
<td>4.36</td>
<td>1.44</td>
</tr>
<tr>
<td>1d-1d</td>
<td>20-20-20</td>
<td>20</td>
<td>20</td>
<td>0.35</td>
<td>1.5</td>
<td>N/E</td>
<td>9.54</td>
<td>0.83</td>
</tr>
<tr>
<td>1d-1.5d</td>
<td>20-20-30</td>
<td>20</td>
<td>30</td>
<td>0.35</td>
<td>1.5</td>
<td>E</td>
<td>9.16</td>
<td>0.87</td>
</tr>
<tr>
<td>1d-2d</td>
<td>20-20-40</td>
<td>20</td>
<td>40</td>
<td>0.35</td>
<td>1.5</td>
<td>E</td>
<td>7.98</td>
<td>0.99</td>
</tr>
<tr>
<td>1d-2.5d</td>
<td>20-20-100</td>
<td>20</td>
<td>50</td>
<td>0.35</td>
<td>1.5</td>
<td>E</td>
<td>7.74</td>
<td>1.02</td>
</tr>
<tr>
<td>2d-1d</td>
<td>20-40-20</td>
<td>40</td>
<td>20</td>
<td>0.35</td>
<td>1.5</td>
<td>N/E</td>
<td>5.08</td>
<td>1.28</td>
</tr>
<tr>
<td>2d-1.5d</td>
<td>20-40-30</td>
<td>40</td>
<td>30</td>
<td>0.35</td>
<td>1.5</td>
<td>N/E</td>
<td>14.99</td>
<td>0.93</td>
</tr>
<tr>
<td>2d-2d</td>
<td>20-40-40</td>
<td>40</td>
<td>40</td>
<td>0.35</td>
<td>1.5</td>
<td>E</td>
<td>11.18</td>
<td>1.25</td>
</tr>
<tr>
<td>2d-2.5d</td>
<td>20-40-100</td>
<td>40</td>
<td>50</td>
<td>0.35</td>
<td>1.5</td>
<td>E</td>
<td>11.53</td>
<td>1.21</td>
</tr>
<tr>
<td>3d-1d</td>
<td>20-60-20</td>
<td>60</td>
<td>20</td>
<td>0.35</td>
<td>1.5</td>
<td>N/B</td>
<td>4.85</td>
<td>1.07</td>
</tr>
<tr>
<td>3d-1.5d</td>
<td>20-60-30</td>
<td>60</td>
<td>30</td>
<td>0.35</td>
<td>1.5</td>
<td>N/B</td>
<td>13.73</td>
<td>0.74</td>
</tr>
<tr>
<td>3d-2d</td>
<td>20-60-40</td>
<td>60</td>
<td>40</td>
<td>0.35</td>
<td>1.5</td>
<td>B</td>
<td>10.15</td>
<td>1.24</td>
</tr>
<tr>
<td>3d-2.5d</td>
<td>20-60-100</td>
<td>60</td>
<td>50</td>
<td>0.35</td>
<td>1.5</td>
<td>B</td>
<td>10.36</td>
<td>1.22</td>
</tr>
<tr>
<td>4d-1d</td>
<td>20-80-40</td>
<td>80</td>
<td>20</td>
<td>0.35</td>
<td>1.5</td>
<td>N/B</td>
<td>5.04</td>
<td>1.03</td>
</tr>
<tr>
<td>4d-1.5d</td>
<td>20-80-60</td>
<td>80</td>
<td>30</td>
<td>0.35</td>
<td>1.5</td>
<td>N/B</td>
<td>13.95</td>
<td>0.73</td>
</tr>
<tr>
<td>4d-2d</td>
<td>20-80-80</td>
<td>80</td>
<td>40</td>
<td>0.35</td>
<td>1.5</td>
<td>B</td>
<td>10.17</td>
<td>1.24</td>
</tr>
</tbody>
</table>
Figure 4.12 Summary of comparison between ABAQUS simulation and analytical calculation results for bolt-hole elongation
Figure 4.13 End pull-out failure displacement comparison

Figure 4.14 Net-section failure displacement comparison
4.6 Summary of calculation procedure

To sum up, the procedure of calculating the bolt-hole elongation at the maximum load is as follows:

4.6.1 Circumferential strain

- Determine the failure mode of the connection by comparing the end distance, the edge distance and the bolt-hole diameter. The conditions are:

Net section failure mode:

\[ e_2 < \frac{(e_1 + d)}{2} \quad (4.13) \]
\[ e_2 < 1.75d \quad (4.14) \]
CHAPTER 4 PARAMETRIC STUDY FOR SINGLE BOLTED PLATES

End pull-out failure mode:

\[ e_1 \leq 2e_2 - d \]  \hspace{1cm} (4.15)
\[ e_1 \leq 2.5d \]  \hspace{1cm} (4.16)

Bearing failure mode:

\[ e_2 \geq 1.75d \]  \hspace{1cm} (4.17)
\[ e_1 \geq 2.5d \]  \hspace{1cm} (4.18)

- Determine whether it is a pure failure mode or transition between 2 failure modes.

Failure mode transition happens according to the following conditions.

Net-section and end pull-out failure mode transition:

\[ \frac{e_1 + 0.5d}{2} < e_2 < \frac{e_1 + d}{2} \]

Net-section and bearing failure mode transition:

\[ 1.25d < e_2 < 1.75d \]

End pull-out and bearing failure mode transition:

\[ 1.5d < e_1 < 2.5d \]

(a) If it is a pure failure mode, calculate the circumferential strain values at the different critical points by referring to Figure 4.5-Figure 4.7 respectively.

(b) If it is failure modes in transition, calculate the circumferential strain values at the critical points by referring to Figure 4.8-Figure 4.10 respectively.
4.6.2 Compressive strain

- The compressive strain is 1.0. This happens at $e_1 = 2d$. The compressive strain reduces to the value of steel ultimate tensile strain limit at $e_1 = 1.2d$. Interpolate between these two values for other $e_1$ values.
- Multiply the maximum compressive strain by a factor. This factor is 0 if $e_2 \leq 0.75d$. This factor is 1.0 if $e_2 \geq (e_1 + d)/2$. Interpolate if $e_2$ is between these two limits.
- Refer to Figure 4.11 for the compression strain distribution in front of the bolt hole.

Bolt hole elongation

- Calculate the total bolt-hole elongation with contributions from the tensile elongation around the bolt-hole circumference and the compressive pile up in front of the bolt.

4.7 Conclusions

This chapter has presented a comprehensive experimental, numerical and analytical study of thin-walled plate behaviour under shear in a single bolt, emphasizing on bolt-hole elongation. The following conclusions may be drawn:

1. Eurocode 3 and the Australian/New Zealand standard can be used to predict plate initial stiffness and strength.
2. To predict the maximum bolt-hole elongation, the circumferential strain distribution around the bolt hole may be considered to be linearly distributed between five critical points. Compressive strain also exists in front of the bolt.
3. This research has proposed a method to calculate the strains at these critical points according to the aforementioned three failure modes and three situations of failure mode transition.
4. Comparisons of the bolt-hole elongation between ABAQUS simulation results and analytical calculations using the proposed strain distributions show that the
proposed method gives very accurate results.
CHAPTER 5. PARAMETRIC STUDY AND ANALYTICAL MODEL FOR MULTIPLE BOLTED PLATES

5.1 Introduction

Chapter 4 has presented an analytical model to predict the load-deformation behaviour of bolted connection with a single bolt under shear, based on the results of an extensive series of numerical simulations using a validated simulation model built using ABAQUS. It has been concluded that the initial stiffness and load carrying capacity of such a connection can be predicted using the formulas provided in Eurocode 3[27] or Australia/New Zealand standards[17]; the author’s main contribution was to develop a method to calculate the maximum connection displacement at the connection strength. This displacement is based on circumferential strain distributions around the bolt hole and compressive strain in front of the bolt according to the connection failure modes. The assumed strain distributions were based on examination of the numerical parametric study results.

Realistic connections have more than one bolt and this chapter explains how the analytical approach may be extended to more practical cases of multiple holes.

5.2 Finite element modelling and validation

Again the commercial finite element modelling software ABAQUS was used. This section presents further evidence of validation of the author’s numerical simulation by comparing against the test results of Kim et al[24] for multiple bolt-hole plates.

5.2.1 Geometric simplification

Figure 5.1 shows the set-up. As in modelling of the single-hole plate tests (Chapter 3), the bolts were represented by rigid hollow cylinders during the entire simulation.
Due to symmetry, only half of the plate was modelled. Symmetrical boundary conditions (no plate in-plane movement, no rotation about the plate centre line), shown in Figure 5.2, were applied to the middle line of the test plate.

Figure 5.1 Kim et al.[24] test set-up

Symmetrical boundary

Figure 5.2 Half plate for simulation
5.2.2 Element type and mesh technique

ABAQUS element type C3D8R was used to simulate multi-hole plates as for single-hole plates.

Figure 5.3 shows 2 different meshes that are applied in the different areas of the plate: a fine mesh around the bolt-hole and a “biased” mesh for the rest of the plate. This “biased”[29] mesh allows the user to define the minimum and maximum element sizes for a part of the structure. The mesh size of the part will change gradually from the minimum to maximum size.

![Fine mesh](image)

![Biased mesh](image)

Figure 5.3 Different mesh sizes

Table 5.1 shows sensitivity of the simulation results to mesh size for one of the author’s single-hole test and one test of Kim et al[24]. A mesh size of ¼ of the plate
thickness is sufficient enough. This is used in the fine mesh. In the biased mesh, the maximum mesh size is 6 times the fine mesh size.

Table 5.1 Mesh sensitivity for single-hole plates

<table>
<thead>
<tr>
<th>Test SB2-4 of Kim et al[24]</th>
<th>Finite element size (width * length)</th>
<th>No. of Elements</th>
<th>Increase in mesh size</th>
<th>Simulation time (sec)</th>
<th>Test strength $P_{ue}$ (KN)</th>
<th>Simulated load $F_0$ (KN)</th>
<th>$P_s/P_{ue}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t/2 \times t/2$</td>
<td>7188</td>
<td>0%</td>
<td>1603</td>
<td>85.62</td>
<td>92.17</td>
<td>1.077</td>
<td></td>
</tr>
<tr>
<td>$t/3 \times t/3$</td>
<td>15015</td>
<td>109%</td>
<td>5006</td>
<td></td>
<td>90.95</td>
<td>1.062</td>
<td></td>
</tr>
<tr>
<td>$t/4 \times t/4$</td>
<td>25527</td>
<td>255%</td>
<td>8961</td>
<td></td>
<td>90.57</td>
<td>1.057</td>
<td></td>
</tr>
<tr>
<td>Author’s test D14-70-40 (Chapter 3)</td>
<td>Finite element size (width * length)</td>
<td>No. of Elements</td>
<td>Increase in mesh size</td>
<td>Simulation time (sec)</td>
<td>Test strength $P_{ue}$ (KN)</td>
<td>Simulated load $F_1$ (KN)</td>
<td>$P_s/P_{ue}$</td>
</tr>
<tr>
<td>$t/2 \times t/2$</td>
<td>5833</td>
<td>0%</td>
<td>633</td>
<td>13.65</td>
<td>13.99</td>
<td>1.025</td>
<td></td>
</tr>
<tr>
<td>$t/3 \times t/3$</td>
<td>9709</td>
<td>66%</td>
<td>3025</td>
<td></td>
<td>13.75</td>
<td>1.007</td>
<td></td>
</tr>
<tr>
<td>$t/4 \times t/4$</td>
<td>15325</td>
<td>163%</td>
<td>6221</td>
<td></td>
<td>13.53</td>
<td>0.991</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.2 and Figure 5.4 compare the author’s simulation results with the test results of Kim et al[24] for the multi-hole plate tests. These comparisons further confirm that the author’s simulation model is acceptable.

Table 5.2 Comparison between simulation results and test results from Kim et al[24]

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Thickness (mm)</th>
<th>End distance (mm)</th>
<th>Number of bolts</th>
<th>Test failure mode</th>
<th>Simulation failure mode</th>
<th>$P_{ue}$ (KN)</th>
<th>$F_0$ (KN)</th>
<th>$F_1$ (KN)</th>
<th>$F_0/P_{ue}$</th>
<th>$F_1/P_{ue}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SB1-4</td>
<td>1.46</td>
<td>60</td>
<td>2 (in direction of loading)</td>
<td>N (FIG 5.4a)</td>
<td>N (FIG 5.4a)</td>
<td>43.34</td>
<td>43.32</td>
<td>41.65</td>
<td>1.00</td>
<td>0.96</td>
</tr>
<tr>
<td>SB2-4</td>
<td>2.90</td>
<td>60</td>
<td>2 (as above)</td>
<td>N (FIG 5.4a)</td>
<td>N (FIG 5.4a)</td>
<td>85.62</td>
<td>86.81</td>
<td>90.57</td>
<td>1.01</td>
<td>1.06</td>
</tr>
<tr>
<td>SC2-3</td>
<td>2.90</td>
<td>30</td>
<td>4 (2x2)</td>
<td>B (FIG 5.4b)</td>
<td>B (FIG 5.4b)</td>
<td>161.59</td>
<td>173.92</td>
<td>176.8</td>
<td>1.08</td>
<td>1.09</td>
</tr>
<tr>
<td>SC2-4</td>
<td>2.90</td>
<td>60</td>
<td>4 (2x2)</td>
<td>B (FIG 5.4b)</td>
<td>B (FIG 5.4b)</td>
<td>162.32</td>
<td>152.79</td>
<td>159.7</td>
<td>0.94</td>
<td>0.98</td>
</tr>
</tbody>
</table>

Note:

$P_{ue}$: Maximum failure load from Kim et al.’s test

$F_0$: Maximum simulated failure load from Kim et al.[24]

$F_1$: Maximum simulated failure load from this study

Failure mode: $N$ for Net-section failure mode; $B$ for Bearing failure
5.3 Parametric study

The validated ABAQUS model has been used to conduct an extensive series of numerical parametric studies to generate a database of load-deformation behaviour for multiple-hole plates with different design parameters for the development of an analytical method. These parameters include the number of bolts in both directions, bolt spacing, end and edge distances, bolt diameter, plate thickness and ultimate
strain of steel. Table 5.3 lists the simulation cases. In total 88 simulations were performed.

Table 5.3 List of assessed parameters

<table>
<thead>
<tr>
<th>Bolt size (mm)</th>
<th>Bolt hole size d (mm)</th>
<th>Bolt number *</th>
<th>End distance e₁</th>
<th>Edge distance e₂</th>
<th>spacing p₁ (in the loading direction)</th>
<th>spacing p₂ (across the loading direction)</th>
<th>Thickness t (mm)</th>
<th>Ultimate strain of steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>14</td>
<td>2x1</td>
<td>1d</td>
<td>1d, 1.5d, 2d, 2.5d</td>
<td>3d</td>
<td>N/A</td>
<td>1.5, 3</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.5d</td>
<td>1d, 1.5d, 2d, 2.5d</td>
<td>3d</td>
<td>N/A</td>
<td>1.5</td>
<td>0.25, 0.35</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2d</td>
<td>1d, 1.5d, 2d, 2.5d</td>
<td>3d</td>
<td>N/A</td>
<td>1.5</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2.5d</td>
<td>1d, 1.5d, 2d, 2.5d</td>
<td>3d</td>
<td>N/A</td>
<td>1.5</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3d</td>
<td>1d, 1.5d, 2d, 2.5d</td>
<td>3d</td>
<td>N/A</td>
<td>1.5</td>
<td>0.35</td>
</tr>
<tr>
<td>12</td>
<td>14</td>
<td>2x1</td>
<td>1d</td>
<td>1d, 1.5d, 2d, 2.5d</td>
<td>6d</td>
<td>N/A</td>
<td>1.5</td>
<td>0.35</td>
</tr>
<tr>
<td>12</td>
<td>14</td>
<td>1x2</td>
<td>1d</td>
<td>1d, 1.5d, 2d, 2.5d</td>
<td>N/A</td>
<td>6d</td>
<td>1.5</td>
<td>0.35</td>
</tr>
<tr>
<td>12</td>
<td>14</td>
<td>3x1</td>
<td>1d</td>
<td>1d, 2d, 3d, 4d</td>
<td>6d</td>
<td>N/A</td>
<td>1.5</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1d</td>
<td>1d, 2d, 3d, 4d</td>
<td>6d</td>
<td>6d</td>
<td>1.5</td>
<td>0.35</td>
</tr>
<tr>
<td>12</td>
<td>14</td>
<td>2x1</td>
<td>1d</td>
<td>1d, 1.5d, 2d, 2.5d</td>
<td>N/A</td>
<td>3d</td>
<td>1.5</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.5d</td>
<td>1d, 1.5d, 2d, 2.5d</td>
<td>N/A</td>
<td>3d</td>
<td>1.5</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2d</td>
<td>1d, 1.5d, 2d, 2.5d</td>
<td>N/A</td>
<td>3d</td>
<td>1.5</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2.5d</td>
<td>1d, 1.5d, 2d, 2.5d</td>
<td>N/A</td>
<td>3d</td>
<td>1.5</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3d</td>
<td>1d, 1.5d, 2d, 2.5d</td>
<td>N/A</td>
<td>3d</td>
<td>1.5</td>
<td>0.35</td>
</tr>
<tr>
<td>12</td>
<td>14</td>
<td>2x2</td>
<td>1d</td>
<td>1d, 2d, 3d, 4d</td>
<td>3d</td>
<td>3d</td>
<td>1.5</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.5d</td>
<td>1d, 2d, 3d, 4d</td>
<td>3d</td>
<td>3d</td>
<td>1.5</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2d</td>
<td>1d, 2d, 3d, 4d</td>
<td>3d</td>
<td>3d</td>
<td>1.5</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2.5d</td>
<td>1d, 2d, 3d, 4d</td>
<td>3d</td>
<td>3d</td>
<td>1.5</td>
<td>0.35</td>
</tr>
<tr>
<td>8</td>
<td>10</td>
<td>2x1</td>
<td>1d</td>
<td>1d, 1.5d, 2d, 2.5d</td>
<td>3d</td>
<td>N/A</td>
<td>1.5</td>
<td>0.35</td>
</tr>
<tr>
<td>18</td>
<td>20</td>
<td>2x1</td>
<td>1d</td>
<td>1d, 1.5d, 2d, 2.5d</td>
<td>3d</td>
<td>N/A</td>
<td>1.5</td>
<td>0.35</td>
</tr>
</tbody>
</table>

*The first number indicates the number of bolts in the direction of loading and the second number is the number of bolts across the loading direction.

When simulating a plate with large end and edge distances, local buckling (curling) of the plate may happen at the hole position. In order to eliminate this effect and also to prevent plate deformation in the thickness direction, one thick plate is placed on each side of the bolted thin plate in the simulation model. These plates are 10 times thicker than the bolted plate and do not deform during the entire simulation. Figure 5.5 shows a typical mesh.
5.4 Development of an analytical model

As for a single bolt-hole plate, the load-deformation behaviour of a multiple bolt-hole plate in shear is assumed to be linear elastic-plastic. As shown in Figure 5.6 (Figure 4.1 in Chapter 4), its load-displacement curve is determined by 3 key parameters: initial stiffness, maximum load and deformation capacity.
5.4.1 Initial stiffness

Eurocode 3[7] provides a stiffness calculation formula for hot-rolled steel plate in bearing with bolts in one single row in the direction of loading, which is shown in Chapter 4 as equation (4.1):

\[ k = 24n_b k_b k_t f_u \]  \hspace{1cm} (5.1)

Where:

- \( n_b \) is the number of bolt row in the loading direction
- \( k_b \) is a factor that considers the effect of end distance and bolt row spacing and
- \( k_b = \min [k_{b1}, k_{b2}, 1.25] \)

with \( k_{b1} = 0.25e_1/d + 0.5 \) and \( k_{b2} = 0.25p_1/d + 0.375 \)

- \( k_t = 1.5t_j/d_{M16} \) is a reduction factor for steel plate thickness
- \( d_{M16} \): Nominal diameter of M16 bolt

For plate with \( m \times n \) bolt-holes in both directions (Figure 5.7), the initial stiffness can be calculated as shown below:

\[ k = \sum_{i=1}^{m} k_i = k_1 + k_2 + \cdots + k_n = mk_{row} \]  \hspace{1cm} (5.2)

Where, \( k_{row} \) is the initial stiffness of one row of bolts in the direction of loading, calculated using equation (5.1).

![Figure 5.7 Plate with multiple bolt-holes in both directions](image-url)
Table 5.4 Comparison of initial stiffness for plates with multiple bolt-holes in both directions

<table>
<thead>
<tr>
<th>End-edge distance (mm)</th>
<th>Bolt-hole diameter d (mm)</th>
<th>Vertical spacing (mm)</th>
<th>Horizontal spacing (mm)</th>
<th>( k_1 ) (N/mm)</th>
<th>( k_2 ) (N/mm)</th>
<th>( k_1/k_2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>2x1 bolt-holes</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14-14</td>
<td>14</td>
<td>N/A</td>
<td>42</td>
<td>19548</td>
<td>19353.6</td>
<td>1.01</td>
</tr>
<tr>
<td>14-21</td>
<td>14</td>
<td>N/A</td>
<td>42</td>
<td>21896</td>
<td>19353.6</td>
<td>1.13</td>
</tr>
<tr>
<td>14-28</td>
<td>14</td>
<td>N/A</td>
<td>42</td>
<td>20812</td>
<td>19353.6</td>
<td>1.08</td>
</tr>
<tr>
<td>14-35</td>
<td>14</td>
<td>N/A</td>
<td>42</td>
<td>21767</td>
<td>19353.6</td>
<td>1.12</td>
</tr>
<tr>
<td>21-14</td>
<td>14</td>
<td>N/A</td>
<td>42</td>
<td>29933</td>
<td>22579.2</td>
<td>1.32</td>
</tr>
<tr>
<td>21-21</td>
<td>14</td>
<td>N/A</td>
<td>42</td>
<td>30766</td>
<td>22579.2</td>
<td>1.36</td>
</tr>
<tr>
<td>21-28</td>
<td>14</td>
<td>N/A</td>
<td>42</td>
<td>29181</td>
<td>22579.2</td>
<td>1.29</td>
</tr>
<tr>
<td>21-35</td>
<td>14</td>
<td>N/A</td>
<td>42</td>
<td>29066</td>
<td>22579.2</td>
<td>1.29</td>
</tr>
<tr>
<td>28-14</td>
<td>14</td>
<td>N/A</td>
<td>42</td>
<td>31166</td>
<td>25804.8</td>
<td>1.21</td>
</tr>
<tr>
<td>28-21</td>
<td>14</td>
<td>N/A</td>
<td>42</td>
<td>32793</td>
<td>25804.8</td>
<td>1.27</td>
</tr>
<tr>
<td>28-28</td>
<td>14</td>
<td>N/A</td>
<td>42</td>
<td>32933</td>
<td>25804.8</td>
<td>1.28</td>
</tr>
<tr>
<td>28-35</td>
<td>14</td>
<td>N/A</td>
<td>42</td>
<td>32700</td>
<td>25804.8</td>
<td>1.27</td>
</tr>
<tr>
<td>35-14</td>
<td>14</td>
<td>N/A</td>
<td>42</td>
<td>31733</td>
<td>29030.4</td>
<td>1.09</td>
</tr>
<tr>
<td>35-21</td>
<td>14</td>
<td>N/A</td>
<td>42</td>
<td>31656</td>
<td>29030.4</td>
<td>1.09</td>
</tr>
<tr>
<td>35-28</td>
<td>14</td>
<td>N/A</td>
<td>42</td>
<td>31843</td>
<td>29030.4</td>
<td>1.10</td>
</tr>
<tr>
<td>35-35</td>
<td>14</td>
<td>N/A</td>
<td>42</td>
<td>33033</td>
<td>29030.4</td>
<td>1.14</td>
</tr>
<tr>
<td>42-14</td>
<td>14</td>
<td>N/A</td>
<td>42</td>
<td>31733</td>
<td>29030.4</td>
<td>1.09</td>
</tr>
<tr>
<td>42-21</td>
<td>14</td>
<td>N/A</td>
<td>42</td>
<td>31531</td>
<td>29030.4</td>
<td>1.09</td>
</tr>
<tr>
<td>42-28</td>
<td>14</td>
<td>N/A</td>
<td>42</td>
<td>31937</td>
<td>29030.4</td>
<td>1.10</td>
</tr>
<tr>
<td>42-35</td>
<td>14</td>
<td>N/A</td>
<td>42</td>
<td>32516</td>
<td>29030.4</td>
<td>1.12</td>
</tr>
<tr>
<td>14-14</td>
<td>14</td>
<td>N/A</td>
<td>84</td>
<td>16233</td>
<td>19353.6</td>
<td>0.84</td>
</tr>
<tr>
<td>14-21</td>
<td>14</td>
<td>N/A</td>
<td>84</td>
<td>23600</td>
<td>19353.6</td>
<td>1.22</td>
</tr>
<tr>
<td>14-28</td>
<td>14</td>
<td>N/A</td>
<td>84</td>
<td>20229</td>
<td>19353.6</td>
<td>1.05</td>
</tr>
<tr>
<td>14-35</td>
<td>14</td>
<td>N/A</td>
<td>84</td>
<td>20500</td>
<td>19353.6</td>
<td>1.06</td>
</tr>
<tr>
<td>21-14</td>
<td>14</td>
<td>N/A</td>
<td>84</td>
<td>21227</td>
<td>22579</td>
<td>0.94</td>
</tr>
<tr>
<td>21-21</td>
<td>14</td>
<td>N/A</td>
<td>84</td>
<td>26968</td>
<td>22579</td>
<td>1.19</td>
</tr>
<tr>
<td>21-28</td>
<td>14</td>
<td>N/A</td>
<td>84</td>
<td>27777</td>
<td>22579</td>
<td>1.23</td>
</tr>
<tr>
<td>21-35</td>
<td>14</td>
<td>N/A</td>
<td>84</td>
<td>27105</td>
<td>22579</td>
<td>1.20</td>
</tr>
<tr>
<td>28-14</td>
<td>14</td>
<td>N/A</td>
<td>84</td>
<td>25056</td>
<td>25804.8</td>
<td>0.97</td>
</tr>
<tr>
<td>28-21</td>
<td>14</td>
<td>N/A</td>
<td>84</td>
<td>31222</td>
<td>25804.8</td>
<td>1.21</td>
</tr>
</tbody>
</table>

1x2 bolt-holes
## PARAMETRIC STUDY FOR MULTIPLE BOLTED PLATES

<table>
<thead>
<tr>
<th>End-edge distance (mm)</th>
<th>Bolt-hole diameter d (mm)</th>
<th>Vertical spacing (mm)</th>
<th>Horizontal spacing (mm)</th>
<th>$K_1$(N/mm)</th>
<th>$K_2$(N/mm)</th>
<th>$k_1/k_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>14-14</td>
<td>14</td>
<td>84</td>
<td>N/A</td>
<td>26852</td>
<td>29030.4</td>
<td>0.92</td>
</tr>
<tr>
<td>14-28</td>
<td>14</td>
<td>84</td>
<td>N/A</td>
<td>31464</td>
<td>29030.4</td>
<td>1.08</td>
</tr>
<tr>
<td>14-42</td>
<td>14</td>
<td>84</td>
<td>N/A</td>
<td>33720</td>
<td>29030.4</td>
<td>1.12</td>
</tr>
<tr>
<td>14-56</td>
<td>14</td>
<td>84</td>
<td>N/A</td>
<td>34048</td>
<td>29030.4</td>
<td>1.17</td>
</tr>
</tbody>
</table>

Average difference 13.3%

Standard deviation 10.4%

$k_1$: initial stiffness from ABAQUS simulation

$k_2$: initial stiffness from Eurocode 3 calculation
Table 5.4 compares the FE simulation results with the calculation results using equation (5.2). Again the initial stiffness is determined by measuring the secant slope of the elastic part of the load-displacement curve at the position of 1 third of the ultimate load. In general the results from Eurocode 3 calculation give lower values compared with simulation results. The average difference between the two sets of results is 13.3% with a standard deviation of 10.4%. Considering the simplicity of the design calculation equations, it is proposed that the Eurocode 3 method can be extended to thin-walled plates.

To sum up, the Eurocode 3 formula for hot-rolled steel plates in bearing can be directly used for bolted plates in shear with multiple holes in any single direction or in both directions.

5.4.2 Load-carrying capacity

For plates with a single bolt, there are 3 possible different failure modes, depending on the end and edge distances: net-section fracture, end pull-out failure and bearing failure. For net-section fracture, the following formula can be used to calculate the maximum load:

\[ F_t = A_n \cdot f_u = (2e_2 - d) \cdot t \cdot f_u \]  
(5.3)

For end pull-out failure, the following formula provided by the Australian/New Zealand [17] and North American design standards [28] can be used to calculate the maximum load:

\[ F_s = t \cdot e_1 \cdot f_u \]  
(5.4)

For bearing failure, the following formula provided by Eurocode 3 [7] can be used to predict the maximum load:

\[ F_b = 2.5d \cdot t \cdot f_u \]  
(5.5)

Net-section fracture happens when

\[ F_t < F_s \] and \[ F_t < F_b \], giving:

\[ e_2 < (e_1 + d)/2 \]  
(5.6)
End pull-out happens when

\[ F_s < F_t \text{ and } F_s < F_b, \text{ leading to:} \]

\[ e_1 \leq 2e_2 - d \quad (5.8) \]

\[ e_1 \leq 2.5d \quad (5.9) \]

Bearing failure happens when

\[ F_b < F_s \text{ and } F_b < F_t, \text{ resulting in:} \]

\[ e_2 \geq 1.75d \quad (5.10) \]

\[ e_1 \geq 2.5d \quad (5.11) \]

The failure modes of plates with multiple bolt-holes are similar to plates with single bolt-hole, as explained in the following sections.

For a plate with multiple bolt-holes parallel and perpendicular to the loading direction (Figure 5.8), the design strength is the minimum of the following.

The failure load for net-section failure is:

\[ F_t = A_n \cdot f_u = (w - md) \cdot t \cdot f_u \quad (5.12) \]

Where
CHAPTER 5 
PARAMETRIC STUDY FOR MULTIPLE BOLTED PLATES

$m$ is the number of bolts in the direction perpendicular to loading;

$w$ is the plate width.

Except for the outer bolts (bolts 1 to $m$), bolt failure is either bearing failure or net-section failure because the bolt spacing in the loading direction is sufficiently large to prevent plate tearing failure between the bolts. The failure mode of the outer bolts is either bearing or end pull-out, depending on the end and edge distances. Net-section failure at the outer bolts will not happen. This can be demonstrated using two bolts in the direction of loading.

According to Figure 5.9:

\[
\begin{align*}
F &= F_1 + F_2 \\
F &= F_{S2} \\
F_1 &= F_{S1}
\end{align*}
\]

Since $F > F_{S1}$, so $F_{S2} > F_{S1}$

Therefore, the force in the cross-section at the inner bolt-hole position is always greater than the force in the cross-section at the outer bolt-hole position, which means that net-section failure will never happen at the outer bolt-hole position.
The bearing resistance of the bolt assembly is:

$$F_{b,Rd} = 2.5m \cdot n \cdot d \cdot t \cdot f_u$$

The end pull-out resistance of the bolt assembly is:

$$F_s = m \cdot t \cdot e_1 \cdot f_u + 2.5m(n - 1) \cdot d \cdot t \cdot f_u$$

Between bearing and end pull-out, bearing failure happens when $e_1 \geq 2.5d$ and end pull-out occurs when $e_1 < 2.5d$.

The conditions for the above three different failure modes are as below.

**i. Net-section failure**

Net-section failure happens when

$$F_t = (w - md) \cdot f_u < 2.5m \cdot n \cdot d \cdot t \cdot f_u \text{ for } e_1 \geq 2.5d$$

or
(w - md) \cdot t \cdot f_u < m(n - 1) \cdot 2.5d \cdot t \cdot f_u + mt \cdot e_1 \cdot f_u \text{ for } e_1 < 2.5d.

Since \( w = 2e_2 + (m - 1) \cdot p_2 \), the dimensional conditions are:

For \( e_1 < 2.5d \):

\[ e_2 < \frac{[me_1 - (m - 1)p_2 + m(2.5n - 1.5) \cdot d]}{2} \] (5.13)

For \( e_1 \geq 2.5d \):

\[ e_2 < \frac{[m \cdot (2.5n + 1) \cdot d - (m - 1) \cdot p_2]}{2} \] (5.14)

**ii ** Bearing failure & end pull-out failure

The condition for end pull-out failure is:

\[ e_1 < 2.5d \]

and

\[ e_2 \geq \frac{[m \cdot e_1 - (m - 1)p_2 + m(2.5n - 1.5) \cdot d]}{2} \] (5.15)

The condition for bearing failure is:

\[ e_1 \geq 2.5d \]

and

\[ e_2 \geq \frac{[m(2.5n + 1) \cdot d - (m - 1) \cdot p_2]}{2} \] (5.16)

Table 5.5 compares the calculated plate load-carrying capacity with FE simulation results. The average difference is 5.9% and the standard deviation is 5.9%, indicating that the calculation results are acceptable. From the comparison, it can be seen that the ultimate load capacity from calculation is generally smaller than the simulated results, indicating that the design calculation method is generally on the safe side.
### Table 5.5 Comparison of maximum load between simulation and calculation results for plates with multiple bolt-holes

<table>
<thead>
<tr>
<th>Bolt-hole configuration</th>
<th>End-edge distance (mm)</th>
<th>Bolt-hole diameter (mm)</th>
<th>Spacing (mm)</th>
<th>Bolt number</th>
<th>Failure mode</th>
<th>Simulation Results</th>
<th>Calculation Results</th>
<th>F2/F1</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 (2x2) bolt-holes</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>14-14</td>
<td>14</td>
<td>42</td>
<td>4</td>
<td>N</td>
<td>22.44</td>
<td>20.16</td>
<td>0.90</td>
</tr>
<tr>
<td></td>
<td>14-21</td>
<td>14</td>
<td>42</td>
<td>4</td>
<td>N</td>
<td>30.84</td>
<td>26.88</td>
<td>0.87</td>
</tr>
<tr>
<td></td>
<td>14-28</td>
<td>14</td>
<td>42</td>
<td>4</td>
<td>N</td>
<td>37.8</td>
<td>33.6</td>
<td>0.89</td>
</tr>
<tr>
<td></td>
<td>14-35</td>
<td>14</td>
<td>42</td>
<td>4</td>
<td>E</td>
<td>38.87</td>
<td>40.32</td>
<td>1.04</td>
</tr>
<tr>
<td></td>
<td>28-14</td>
<td>14</td>
<td>42</td>
<td>4</td>
<td>N</td>
<td>22.28</td>
<td>20.16</td>
<td>0.90</td>
</tr>
<tr>
<td></td>
<td>28-21</td>
<td>14</td>
<td>42</td>
<td>4</td>
<td>N</td>
<td>30.55</td>
<td>26.88</td>
<td>0.88</td>
</tr>
<tr>
<td></td>
<td>28-28</td>
<td>14</td>
<td>42</td>
<td>4</td>
<td>N</td>
<td>38.97</td>
<td>33.6</td>
<td>0.86</td>
</tr>
<tr>
<td></td>
<td>28-35</td>
<td>14</td>
<td>42</td>
<td>4</td>
<td>N</td>
<td>44.44</td>
<td>40.32</td>
<td>0.91</td>
</tr>
<tr>
<td>6 (2x3) bolt-holes</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>14-14</td>
<td>14</td>
<td>84</td>
<td>6</td>
<td>N</td>
<td>41.48</td>
<td>47.04</td>
<td>1.13</td>
</tr>
<tr>
<td></td>
<td>14-28</td>
<td>14</td>
<td>84</td>
<td>6</td>
<td>N</td>
<td>58.03</td>
<td>60.48</td>
<td>1.04</td>
</tr>
<tr>
<td></td>
<td>14-42</td>
<td>14</td>
<td>84</td>
<td>6</td>
<td>N</td>
<td>68.84</td>
<td>73.92</td>
<td>1.07</td>
</tr>
<tr>
<td></td>
<td>14-56</td>
<td>14</td>
<td>84</td>
<td>6</td>
<td>B</td>
<td>79.57</td>
<td>80.64</td>
<td>1.01</td>
</tr>
<tr>
<td>1x2 bolt-holes</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>14-21</td>
<td>14</td>
<td>42</td>
<td>2</td>
<td>N</td>
<td>14.44</td>
<td>13.44</td>
<td>0.93</td>
</tr>
<tr>
<td></td>
<td>14-28</td>
<td>14</td>
<td>42</td>
<td>2</td>
<td>N</td>
<td>20.63</td>
<td>20.16</td>
<td>0.98</td>
</tr>
<tr>
<td></td>
<td>14-35</td>
<td>14</td>
<td>42</td>
<td>2</td>
<td>E</td>
<td>20.26</td>
<td>23.52</td>
<td>1.16</td>
</tr>
<tr>
<td></td>
<td>21-21</td>
<td>14</td>
<td>42</td>
<td>2</td>
<td>N</td>
<td>14.25</td>
<td>13.44</td>
<td>0.94</td>
</tr>
<tr>
<td></td>
<td>21-28</td>
<td>14</td>
<td>42</td>
<td>2</td>
<td>N</td>
<td>20.64</td>
<td>20.16</td>
<td>0.98</td>
</tr>
<tr>
<td></td>
<td>21-35</td>
<td>14</td>
<td>42</td>
<td>2</td>
<td>B</td>
<td>25.49</td>
<td>26.88</td>
<td>1.05</td>
</tr>
<tr>
<td></td>
<td>28-21</td>
<td>14</td>
<td>42</td>
<td>2</td>
<td>N</td>
<td>14.17</td>
<td>13.44</td>
<td>0.95</td>
</tr>
<tr>
<td></td>
<td>28-28</td>
<td>14</td>
<td>42</td>
<td>2</td>
<td>N</td>
<td>20.55</td>
<td>20.16</td>
<td>0.98</td>
</tr>
<tr>
<td></td>
<td>28-35</td>
<td>14</td>
<td>42</td>
<td>2</td>
<td>N</td>
<td>27.63</td>
<td>26.88</td>
<td>0.97</td>
</tr>
<tr>
<td></td>
<td>35-21</td>
<td>14</td>
<td>42</td>
<td>2</td>
<td>N</td>
<td>14.29</td>
<td>13.44</td>
<td>0.94</td>
</tr>
<tr>
<td></td>
<td>35-28</td>
<td>14</td>
<td>42</td>
<td>2</td>
<td>N</td>
<td>21.77</td>
<td>20.16</td>
<td>0.93</td>
</tr>
<tr>
<td></td>
<td>35-35</td>
<td>14</td>
<td>42</td>
<td>2</td>
<td>N</td>
<td>27.86</td>
<td>26.88</td>
<td>0.96</td>
</tr>
<tr>
<td></td>
<td>42-21</td>
<td>14</td>
<td>42</td>
<td>2</td>
<td>N</td>
<td>14.33</td>
<td>13.44</td>
<td>0.94</td>
</tr>
<tr>
<td></td>
<td>42-28</td>
<td>14</td>
<td>42</td>
<td>2</td>
<td>N</td>
<td>21.7</td>
<td>20.16</td>
<td>0.93</td>
</tr>
<tr>
<td></td>
<td>42-35</td>
<td>14</td>
<td>42</td>
<td>2</td>
<td>N</td>
<td>28.6</td>
<td>26.88</td>
<td>0.94</td>
</tr>
<tr>
<td></td>
<td>14-21</td>
<td>14</td>
<td>84</td>
<td>2</td>
<td>N</td>
<td>14.47</td>
<td>13.44</td>
<td>0.93</td>
</tr>
<tr>
<td></td>
<td>14-28</td>
<td>14</td>
<td>84</td>
<td>2</td>
<td>N</td>
<td>20.37</td>
<td>20.16</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>14-35</td>
<td>14</td>
<td>84</td>
<td>2</td>
<td>E</td>
<td>24.15</td>
<td>23.52</td>
<td>0.97</td>
</tr>
<tr>
<td>1x3 bolt-holes</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>14-28</td>
<td>14</td>
<td>84</td>
<td>3</td>
<td>N</td>
<td>21.71</td>
<td>20.16</td>
<td>0.93</td>
</tr>
</tbody>
</table>
### 5.4.3 Displacement

It can be seen from Figure 5.10(a) and Figure 5.10(b) that the displacement of the plate is the elongation of the first set of inner bolt-holes. Similar to the deformation of a plate with single bolt-hole, the elongation of a plate with multi bolt-holes can be calculated from the circumferential strain distribution around the inner bolt-holes plus any compressive pile up in front of the bolts.

<table>
<thead>
<tr>
<th>14-42</th>
<th>14</th>
<th>84</th>
<th>3</th>
<th>N</th>
<th>33</th>
<th>33.6</th>
<th>1.02</th>
</tr>
</thead>
<tbody>
<tr>
<td>14-56</td>
<td>14</td>
<td>84</td>
<td>3</td>
<td>B</td>
<td>42.4</td>
<td>40.32</td>
<td>0.95</td>
</tr>
</tbody>
</table>

### 2x1 bolt-holes

<table>
<thead>
<tr>
<th>14-21</th>
<th>14</th>
<th>42</th>
<th>2</th>
<th>E</th>
<th>13.61</th>
<th>13.44</th>
<th>0.99</th>
</tr>
</thead>
<tbody>
<tr>
<td>14-28</td>
<td>14</td>
<td>42</td>
<td>2</td>
<td>E</td>
<td>14.01</td>
<td>13.44</td>
<td>0.96</td>
</tr>
<tr>
<td>14-35</td>
<td>14</td>
<td>42</td>
<td>2</td>
<td>E</td>
<td>14.11</td>
<td>13.44</td>
<td>0.95</td>
</tr>
<tr>
<td>21-21</td>
<td>14</td>
<td>42</td>
<td>2</td>
<td>E</td>
<td>21.55</td>
<td>20.16</td>
<td>0.94</td>
</tr>
<tr>
<td>21-28</td>
<td>14</td>
<td>42</td>
<td>2</td>
<td>E</td>
<td>22.1</td>
<td>20.16</td>
<td>0.91</td>
</tr>
<tr>
<td>21-35</td>
<td>14</td>
<td>42</td>
<td>2</td>
<td>E</td>
<td>22.75</td>
<td>20.16</td>
<td>0.89</td>
</tr>
<tr>
<td>28-21</td>
<td>14</td>
<td>42</td>
<td>2</td>
<td>E</td>
<td>27.61</td>
<td>26.88</td>
<td>0.97</td>
</tr>
<tr>
<td>28-28</td>
<td>14</td>
<td>42</td>
<td>2</td>
<td>E</td>
<td>27.48</td>
<td>26.88</td>
<td>0.98</td>
</tr>
<tr>
<td>28-35</td>
<td>14</td>
<td>42</td>
<td>2</td>
<td>E</td>
<td>27.68</td>
<td>26.88</td>
<td>0.97</td>
</tr>
<tr>
<td>35-21</td>
<td>14</td>
<td>42</td>
<td>2</td>
<td>B</td>
<td>28.38</td>
<td>28.8</td>
<td>1.01</td>
</tr>
<tr>
<td>35-28</td>
<td>14</td>
<td>42</td>
<td>2</td>
<td>B</td>
<td>29.86</td>
<td>28.8</td>
<td>0.96</td>
</tr>
<tr>
<td>35-35</td>
<td>14</td>
<td>42</td>
<td>2</td>
<td>B</td>
<td>29.63</td>
<td>28.8</td>
<td>0.97</td>
</tr>
<tr>
<td>42-21</td>
<td>14</td>
<td>42</td>
<td>2</td>
<td>B</td>
<td>28.4</td>
<td>28.8</td>
<td>1.01</td>
</tr>
<tr>
<td>42-28</td>
<td>14</td>
<td>42</td>
<td>2</td>
<td>B</td>
<td>30.63</td>
<td>28.8</td>
<td>0.94</td>
</tr>
<tr>
<td>42-35</td>
<td>14</td>
<td>42</td>
<td>2</td>
<td>B</td>
<td>30.92</td>
<td>28.8</td>
<td>0.93</td>
</tr>
</tbody>
</table>

Average difference 5.9%

Standard deviation 5.9%

- F1: Maximum failure load from ABAQUS simulation
- F2: Maximum failure load from calculation
- N: net-section failure
- E: end pull-out failure
- B: bearing failure
Circumferential strain distribution

After detailed assessment of strain distributions around the first set of inner bolt holes for the parametric study cases, it was found that the circumferential strain distribution in plates with multiple bolt-holes is similar to that with single bolt hole. In addition to the three pure failure modes (net-section, bearing, end pull-out), the authors’ previous research on single bolt-hole plate discovered that it is also necessary to consider the three transitions from one failure mode to another. The same approach will be taken for plates with multiple bolt-holes. As for plates with single bolt hole, the bolt-hole diameter is divided into four equal parts (Figure 5.10 c) and the strain distribution is assumed to be linear within each segment.
1) **Net section failure**

For net section failure, it is assumed that the strain at point C is equal to the ultimate tensile strain of steel. The strain at points A, B, D and E is zero. Figure 5.11 shows the assumed strain distribution around the bolt hole.
2) End pull-out failure

It should be noticed that end pull-out happens at the outer bolt-holes. However, the displacement of the plate is calculated as the elongation of the first set of inner bolt-holes. These two positions coincide when there is only one set of bolts in the loading direction. In this case, the author’s method (Chapter 4) for plates with single bolt-hole can be directly used. However, when there are more than one set of bolts in the loading direction, it is necessary to consider the interaction between the first set of inner bolts and the outer bolts.

Refer to Figure 5.12, the displacement at the 1st set of inner bolts consists of 2 parts: tensile elongation of the bolt-hole circumference and compressive pilling up in front of the bolt. The maximum compressive strain at the bolt/plate contact point is assumed to be 1.0, The compressive strain decreases further away from the bolt and is assumed to be 0 at a distance 1d from the bolt/plate contact, as shown in Figure 5.13. Therefore, the maximum compressive displacement is: $D_c = \frac{1}{2} \cdot \varepsilon_c \cdot d = \frac{1}{2} d$. 

Figure 5.11 Assumed circumferential strain distribution for net-section failure
Figure 5.12 Two components of total displacement

Figure 5.13: Compressive strain distribution along plate length
As can be seen from upper figure in Figure 5.14, the tensile deformation at the 1st set of inner bolts (Bolt 2 in Figure 5.14) does not cause any deformation at the outer bolts (Bolt 1) because the distances between the bolts in the loading direction can be maintained without movement of the plate at the outer bolt position. However, when compressive deformation at the 1st set of inner bolts (Bolt 2 in Figure 5.14) occurs, deformations at bolts after the 1st set of inner bolts have to happen, i.e. the compressive pile-up deformation of the inner bolts is the sum of the compressive pile-up and tensile circumferential deformation of the outer bolts. The required amount of deformation at each hole is different and decreases further away from the 1st set of inner bolts. In fact, when there are three (n=3) or more (n>3) sets of bolts in
the loading direction, the required amount of deformation at the outer bolts is reduced to such a low lever that end pull-out will not occur. But if there are two sets of bolts in the loading direction and if the end distance is small \((1d < e_1 < 1.3d)\), it is possible for end pull-out of the outer bolts to happen if the compressive deformation \((\frac{1}{2}d)\) at the 1st set of inner bolts is greater than the achievable displacement at the outer bolts for end pull-out. The achievable displacement for end pull-out of the other bolts can be calculated as for plates with single bolt hole. This can be calculated by assuming the following strain distributions (refer to Figure 5.15): zero strain at positions C, D and E; \(\varepsilon_B = \varepsilon_t + \mu \cdot \varepsilon_r\), where \(\varepsilon_r\) is the ultimate tensile strain of steel, \(\mu\) is Poisson’s ratio (0.3) and \(\varepsilon_r\) is the radial compressive strain due to bearing. As mentioned before, it is assumed that \(\varepsilon_r = 1.0\).

In this case, the achievable displacement for end pull-out of the outer bolts should be added to the tensile elongation of the 1st set of inner bolt-holes to give the total displacement of the connection assembly.
3) **Bearing failure**

When bearing failure happens, it is assumed that the strains at point C, D and E are zero. The strain at point A is \( \varepsilon_B = \varepsilon_t + \mu \cdot \varepsilon_r \) owing to combined tension and compression in front of the bolt. For example, in Figure 5.16, the strain at point A is \( 0.35 + 0.3 \times 1.0 = 0.65 \). The strain distribution between A and C is linear so the strain at point B is half of that at point A. Figure 5.16 shows the complete assumed circumferential strain distribution around the bolt hole under bearing failure.

![Figure 5.16 Assumed circumferential strain distribution for bearing failure](image)

4) **Failure modes in transition**

Based on the above discussions for end pull-out failure of the outer bolts, it is necessary to separate the considerations into one set of bolts in the loading direction \((n=1)\), two sets of bolts in the loading direction \((n=2)\) and three or more sets of bolts in the loading direction \((n\geq3)\). For \(n=1\), the authors’ previous method (reference) on plates with single bolt can be used. This will not be repeated here.
a. Plate with more than 2 bolt-holes in loading direction \((n \geq 3)\)

In this case, there is only one failure mode transition: between net-section failure mode and bearing failure mode. From equations (5.13) and (5.15), it can be seen that when \(e_1 < 2.5d\), edge distance \(e_2 = [m \cdot e_1 - (m - 1)p_2 + m(2.5n - 1.5) \cdot d]/2\) marks the separation between net-section failure and bearing failure. It is assumed that when \(e_2 \leq 1d\), the circumferential strain around the bolt-hole follows pure net-section failure circumferential strain distribution (Figure 5.17). When \(e_2 \geq [m \cdot e_1 - (m - 1)p_2 + m(2.5n - 1.5) \cdot d]/2\), the tensile strain around the bolt-hole follows bearing failure strain distribution (Figure 5.17). When \(e_2\) is between the range of \(1d\) and \([m \cdot e_1 - (m - 1)p_2 + m(2.5n - 1.5) \cdot d]/2\), linear interpolation can be applied. Similarly, from equations (14) and (16), it can be seen that when \(e_1 \geq 2.5d\), \(e_2 = [m \cdot (2.5n + 1) \cdot d - (m - 1)p_2]/2\) is the critical point to separate net-section failure from bearing failure. It is assumed that when \(e_2 \leq 1d\), the circumferential strain around the bolt-hole follows net-section circumferential strain distribution (Figure 5.17). When \(e_2 \geq [m \cdot (2.5n + 1) \cdot d - (m - 1)p_2]/2\), the circumferential strain around the bolt-hole follows bearing failure circumferential strain distribution. When \(e_2\) is between \(1d\) and \([m \cdot (2.5n + 1) \cdot d - (m - 1)p_2]/2\), linear interpolation is applied.

Figure 5.17 shows the transition in circumferential strain distribution at different critical points with increasing \(e_2\). In some cases, it is possible that the value \([m \cdot e_1 - (m - 1)p_2 + m(2.5n - 1.5) \cdot d]/2\) (for \(e_1 < 2.5d\)) or \([m \cdot (2.5n + 1) \cdot d - (m - 1)p_2]/2\) for \((e_1 \geq 2.5d)\) is negative or smaller than \(1d\). This means that bearing failure dominates and the circumferential strain around the bolt-hole should follow bearing failure circumferential strain distribution.
Figure 5.17 Assumed strain values for plate with multiple bolt-holes in both horizontal & vertical directions, \( n \geq 3 \).

b. **Plate with 2 bolt-holes in loading direction**

In this case, the bearing failure and end pull-out failure should be linked. Therefore, for plates with 2 bolt-holes in the loading direction, the failure mode transition is between net-section and bearing or net-section and end pull-out.

Putting \( n = 2 \) into equations (5.13) and (5.14) gives:

For \( e_1 < 2.5d \)

\[
    e_2 < \frac{[3.5m \cdot d + me_1 - (m - 1)p_2]}{2} \tag{5.17}
\]

For \( e_1 \geq 2.5d \),

\[
    e_2 < \frac{[6m \cdot d - (m - 1)p_2]}{2} \tag{5.18}
\]

This means that for the end distance \( e_1 < 2.5d \), the edge distance \( e_2 = \frac{[3.5m \cdot d + me_1 - (m - 1)p_2]}{2} \) marks the separation of net-section and bearing/end pull-out.
failure; for the end distance $e_1 \geq 2.5d$, the edge distance $e_2 = [6m \cdot d - (m - 1) p_2]/2$ marks the separation of net-section and bearing failure. It is assumed that when $e_2 \leq 1d$, the strain distribution is according to net-section failure. When $e_2 \geq [3.5m \cdot d + me_1 - (m - 1) p_2]/2$ (for $e_1 < 2.5d$) or $e_2 \geq [6m \cdot d - (m - 1) p_2]/2$ (for $e_1 \geq 2.5d$), the strain distribution is according to bearing/end pull-out failure. During the transition period, linear interpolation can be used. Figure 5.18 shows the assumed change of strain values depending on the edge distance $e_2$.

![Figure 5.18 Assumed strain values at different critical points for transition from net-section to bearing/end pull-out failure](image)

Figure 5.18 Assumed strain values at different critical points for transition from net-section to bearing/end pull-out failure

$X_1 = 1d$

when $e_1 < 2.5d$, $X_2 = [3.5md + me_1 - (m - 1)p_2]/2$ but $X_2 \geq 1.5d$

when $e_1 \geq 2.5d$, $X_2 = [6md - (m - 1)p_2]/2$ but $X_2 \geq 1.5d$
Compressive strain

In order to calculate the bolt hole elongation due to compressive pile-up, it is assumed that the compressive strain changes from the maximum value at the bolt/plate contact point to zero at a distance of one bolt diameter away (or the actual edge of the plate if less), as shown in Figure 5.13.

The same plate geometry conditions used to determine the different plate pure and failure modes transitions for circumferential strain distributions should be used to determine the compressive strain distributions.

For plates with only one bolt in the loading direction, the authors’ method for plates with single-bolt [30] can be used. If there are two bolt-holes in the loading direction and end pull-out happens, the compressive displacement of the 1st set of inner bolts should be replaced by the end pull-out displacement of the outer bolts if the latter is smaller. The compressive displacement of the 1st set of inner bolts can be calculated following the same procedure below for plates with 3 or more bolts in the loading direction.

For plates with 3 or more bolts in the loading direction, end pull-out failure will not happen. If pure bearing failure occurs, the maximum compressive strain is assumed to be 1.0 as in the authors’ previous study for plates with a single bolt. The compressive strain reaches maximum value when

\[
\bar{e}_2 \geq \min\{[m e_1 - (m - 1)p_2 + m(2.5n - 1.5) \cdot d ]/2, 1.75d\}
\]

according to equation (5.15). When \(e_2 \leq 0.75d\) (based on the authors’ research for plates with a single bolt for consistency), the compressive strain is equal to zero. When the edge distance falls between these two values, linear interpolation can be used.

As mentioned before, it is possible that the value of \(e_2 = [m e_1 - (m - 1)p_2 + m(2.5n - 1.5) \cdot d ]/2\) is negative or smaller than 1d. This means that plate bearing failure controls and the compressive strain should be assumed to reach the maximum value 1.0.

Table 5.6 and Figure 5.19 compare plate displacements between the FE simulated results and the calculated results. It can be seen that the simulated and calculated plate displacements agree well, with an average difference of 14.3% and 9.4%
standard deviation. Considering the complexity of structural behaviour at the ultimate load and the simplicity of the proposed deformation calculation method, the above comparison suggests that the proposed calculation method is acceptable.

Table 5.6 Displacement comparison between ABAQUS simulations & calculation results

<table>
<thead>
<tr>
<th>End-edge distance (mm)</th>
<th>Bolt-hole diameter d (mm)</th>
<th>p₁ (mm)</th>
<th>p₂ (mm)</th>
<th>D₁</th>
<th>D₂</th>
<th>D₂/D₁</th>
</tr>
</thead>
<tbody>
<tr>
<td>14-14</td>
<td>14</td>
<td>42</td>
<td>N/A</td>
<td>3.53</td>
<td>3.11</td>
<td>0.88</td>
</tr>
<tr>
<td>14-21</td>
<td>14</td>
<td>42</td>
<td>N/A</td>
<td>5.85</td>
<td>5.50</td>
<td>0.94</td>
</tr>
<tr>
<td>14-28</td>
<td>14</td>
<td>42</td>
<td>N/A</td>
<td>8.84</td>
<td>8.66</td>
<td>1.00</td>
</tr>
<tr>
<td>14-35</td>
<td>14</td>
<td>42</td>
<td>N/A</td>
<td>7.32</td>
<td>10.58</td>
<td>1.51</td>
</tr>
<tr>
<td>21-14</td>
<td>14</td>
<td>42</td>
<td>N/A</td>
<td>3.37</td>
<td>2.90</td>
<td>0.86</td>
</tr>
<tr>
<td>21-21</td>
<td>14</td>
<td>42</td>
<td>N/A</td>
<td>4.75</td>
<td>4.85</td>
<td>1.02</td>
</tr>
<tr>
<td>21-28</td>
<td>14</td>
<td>42</td>
<td>N/A</td>
<td>6.52</td>
<td>7.72</td>
<td>1.18</td>
</tr>
<tr>
<td>21-35</td>
<td>14</td>
<td>42</td>
<td>N/A</td>
<td>7.85</td>
<td>10.58</td>
<td>1.05</td>
</tr>
<tr>
<td>28-14</td>
<td>14</td>
<td>42</td>
<td>N/A</td>
<td>3.40</td>
<td>2.84</td>
<td>0.83</td>
</tr>
<tr>
<td>28-21</td>
<td>14</td>
<td>42</td>
<td>N/A</td>
<td>4.37</td>
<td>4.36</td>
<td>1.00</td>
</tr>
<tr>
<td>28-28</td>
<td>14</td>
<td>42</td>
<td>N/A</td>
<td>5.73</td>
<td>6.89</td>
<td>1.20</td>
</tr>
<tr>
<td>28-35</td>
<td>14</td>
<td>42</td>
<td>N/A</td>
<td>8.38</td>
<td>9.38</td>
<td>0.86</td>
</tr>
<tr>
<td>35-14</td>
<td>14</td>
<td>42</td>
<td>N/A</td>
<td>3.10</td>
<td>2.71</td>
<td>0.87</td>
</tr>
<tr>
<td>35-21</td>
<td>14</td>
<td>42</td>
<td>N/A</td>
<td>4.66</td>
<td>3.20</td>
<td>0.69</td>
</tr>
<tr>
<td>35-28</td>
<td>14</td>
<td>42</td>
<td>N/A</td>
<td>8.45</td>
<td>6.20</td>
<td>0.73</td>
</tr>
<tr>
<td>35-35</td>
<td>14</td>
<td>42</td>
<td>N/A</td>
<td>9.34</td>
<td>8.36</td>
<td>0.89</td>
</tr>
<tr>
<td>42-14</td>
<td>14</td>
<td>42</td>
<td>N/A</td>
<td>2.94</td>
<td>2.71</td>
<td>0.92</td>
</tr>
<tr>
<td>42-21</td>
<td>14</td>
<td>42</td>
<td>N/A</td>
<td>4.74</td>
<td>3.20</td>
<td>0.68</td>
</tr>
<tr>
<td>42-28</td>
<td>14</td>
<td>42</td>
<td>N/A</td>
<td>8.00</td>
<td>6.20</td>
<td>0.77</td>
</tr>
<tr>
<td>42-35</td>
<td>14</td>
<td>42</td>
<td>N/A</td>
<td>10.83</td>
<td>8.36</td>
<td>0.77</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>1X2 bolt-holes</th>
<th>Bolt-hole diameter d (mm)</th>
<th>p₁ (mm)</th>
<th>p₂ (mm)</th>
<th>D₁</th>
<th>D₂</th>
<th>D₂/D₁</th>
</tr>
</thead>
<tbody>
<tr>
<td>14-14</td>
<td>14</td>
<td>42</td>
<td>N/A</td>
<td>4.99</td>
<td>5.21</td>
<td>1.04</td>
</tr>
<tr>
<td>14-21</td>
<td>14</td>
<td>42</td>
<td>N/A</td>
<td>5.44</td>
<td>5.21</td>
<td>0.96</td>
</tr>
<tr>
<td>14-28</td>
<td>14</td>
<td>42</td>
<td>N/A</td>
<td>5.26</td>
<td>5.21</td>
<td>0.99</td>
</tr>
<tr>
<td>14-35</td>
<td>14</td>
<td>42</td>
<td>N/A</td>
<td>5.37</td>
<td>5.21</td>
<td>0.97</td>
</tr>
<tr>
<td>21-14</td>
<td>14</td>
<td>42</td>
<td>N/A</td>
<td>4.54</td>
<td>2.76</td>
<td>0.61</td>
</tr>
<tr>
<td>21-21</td>
<td>14</td>
<td>42</td>
<td>N/A</td>
<td>7.00</td>
<td>8.74</td>
<td>1.25</td>
</tr>
<tr>
<td>21-28</td>
<td>14</td>
<td>42</td>
<td>N/A</td>
<td>6.91</td>
<td>8.74</td>
<td>1.26</td>
</tr>
<tr>
<td>21-35</td>
<td>14</td>
<td>42</td>
<td>N/A</td>
<td>6.93</td>
<td>8.74</td>
<td>1.26</td>
</tr>
<tr>
<td>28-14</td>
<td>14</td>
<td>42</td>
<td>N/A</td>
<td>4.32</td>
<td>4.24</td>
<td>0.98</td>
</tr>
<tr>
<td>28-21</td>
<td>14</td>
<td>42</td>
<td>N/A</td>
<td>11.81</td>
<td>11.53</td>
<td>0.98</td>
</tr>
<tr>
<td>28-28</td>
<td>14</td>
<td>42</td>
<td>N/A</td>
<td>10.43</td>
<td>11.53</td>
<td>1.11</td>
</tr>
<tr>
<td>28-35</td>
<td>14</td>
<td>42</td>
<td>N/A</td>
<td>9.91</td>
<td>11.53</td>
<td>1.16</td>
</tr>
<tr>
<td>35-14</td>
<td>14</td>
<td>42</td>
<td>N/A</td>
<td>5.16</td>
<td>4.24</td>
<td>0.82</td>
</tr>
<tr>
<td>35-21</td>
<td>14</td>
<td>42</td>
<td>N/A</td>
<td>7.51</td>
<td>8.29</td>
<td>1.10</td>
</tr>
<tr>
<td>35-28</td>
<td>14</td>
<td>42</td>
<td>N/A</td>
<td>9.20</td>
<td>10.58</td>
<td>1.15</td>
</tr>
<tr>
<td>35-35</td>
<td>14</td>
<td>42</td>
<td>N/A</td>
<td>8.70</td>
<td>10.58</td>
<td>1.22</td>
</tr>
<tr>
<td>42-14</td>
<td>14</td>
<td>42</td>
<td>N/A</td>
<td>5.00</td>
<td>4.24</td>
<td>0.85</td>
</tr>
<tr>
<td>42-21</td>
<td>14</td>
<td>42</td>
<td>N/A</td>
<td>7.50</td>
<td>8.29</td>
<td>1.11</td>
</tr>
<tr>
<td>42-28</td>
<td>14</td>
<td>42</td>
<td>N/A</td>
<td>8.56</td>
<td>10.58</td>
<td>1.24</td>
</tr>
<tr>
<td>42-35</td>
<td>14</td>
<td>42</td>
<td>N/A</td>
<td>8.47</td>
<td>10.58</td>
<td>1.25</td>
</tr>
</tbody>
</table>
CHAPTER 5  PARAMETRIC STUDY FOR MULTIPLE BOLTED PLATES

<p>| | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>14-14</td>
<td>14</td>
<td>42</td>
<td>42</td>
<td>3.83</td>
<td>3.67</td>
</tr>
<tr>
<td>14-21</td>
<td>14</td>
<td>42</td>
<td>42</td>
<td>6.81</td>
<td>7.56</td>
</tr>
<tr>
<td>14-28</td>
<td>14</td>
<td>42</td>
<td>42</td>
<td>9.78</td>
<td>9.77</td>
</tr>
<tr>
<td>14-35</td>
<td>14</td>
<td>42</td>
<td>42</td>
<td>8.67</td>
<td>10.15</td>
</tr>
<tr>
<td>21-14</td>
<td>14</td>
<td>42</td>
<td>42</td>
<td>3.92</td>
<td>3.67</td>
</tr>
<tr>
<td>21-21</td>
<td>14</td>
<td>42</td>
<td>42</td>
<td>6.02</td>
<td>7.53</td>
</tr>
<tr>
<td>21-28</td>
<td>14</td>
<td>42</td>
<td>42</td>
<td>9.12</td>
<td>9.58</td>
</tr>
<tr>
<td>21-35</td>
<td>14</td>
<td>42</td>
<td>42</td>
<td>8.71</td>
<td>9.94</td>
</tr>
<tr>
<td>28-14</td>
<td>14</td>
<td>42</td>
<td>42</td>
<td>3.25</td>
<td>3.67</td>
</tr>
<tr>
<td>28-21</td>
<td>14</td>
<td>42</td>
<td>42</td>
<td>6.19</td>
<td>7.42</td>
</tr>
<tr>
<td>28-28</td>
<td>14</td>
<td>42</td>
<td>42</td>
<td>10.65</td>
<td>9.47</td>
</tr>
<tr>
<td>28-35</td>
<td>14</td>
<td>42</td>
<td>42</td>
<td>10.09</td>
<td>9.77</td>
</tr>
<tr>
<td>35-14</td>
<td>14</td>
<td>42</td>
<td>42</td>
<td>3.21</td>
<td>3.67</td>
</tr>
<tr>
<td>35-21</td>
<td>14</td>
<td>42</td>
<td>42</td>
<td>5.79</td>
<td>7.42</td>
</tr>
<tr>
<td>35-28</td>
<td>14</td>
<td>42</td>
<td>42</td>
<td>8.15</td>
<td>9.39</td>
</tr>
<tr>
<td>35-35</td>
<td>14</td>
<td>42</td>
<td>42</td>
<td>7.90</td>
<td>9.64</td>
</tr>
</tbody>
</table>

2x3 bolt-holes

<p>| | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>14-14</td>
<td>14</td>
<td>84</td>
<td>84</td>
<td>4.56</td>
<td>3.67</td>
</tr>
<tr>
<td>14-28</td>
<td>14</td>
<td>84</td>
<td>84</td>
<td>7.54</td>
<td>6.46</td>
</tr>
<tr>
<td>14-42</td>
<td>14</td>
<td>84</td>
<td>84</td>
<td>7.81</td>
<td>8.51</td>
</tr>
<tr>
<td>14-56</td>
<td>14</td>
<td>84</td>
<td>84</td>
<td>9.64</td>
<td>10.57</td>
</tr>
</tbody>
</table>

\[ D_1: \text{Displacement at maximum load from ABAQUS simulation} \]
\[ D_2: \text{Displacement at maximum load from calculation} \]

Figure 5.19 Simulated displacement VS calculated maximum plate displacement
To sum up, the procedure for calculating the connection elongation at the maximum load is as follows:

### i  Circumferential strain

Determine the failure mode of the connection by comparing the end distance, edge distance, bolt-hole diameter and spacing.

#### 1) Plate with more than 2 bolt-holes in the loading direction

For plate with more than 2 bolt-holes in the loading direction, the failure conditions are summarized as below:
CHAPTER 5  PARAMETRIC STUDY FOR MULTIPLE BOLTED PLATES

For failure mode transition (net-section/bearing), refer to Figure 5.17 for circumferential strain calculation.

2) **Plate with 2 bolt-holes in the loading direction**

For plate with 2 bolt-holes in the loading direction, the failure condition is summarized as below:

- **End pull-out failure, strain distribution in Figure 5.15**
  
  \[1d < e_1 < 1.3d\]
  
  \[e_2 \geq \frac{[3.5m \cdot d + me_1 - (m - 1)p_2]}{2}\]

- **Net-section failure, strain distribution in Figure 5.11**

  \[1.3d \leq e_1 < 2.5d\]
  
  \[e_2 \geq \frac{[3.5m \cdot d + me_1 - (m - 1)p_2]}{2}\]

  \[e_1 \geq 2.5d\]
  
  \[e_2 \geq \frac{[6m \cdot d - (m - 1)p_2]}{2}\]

- **Bearing failure, strain distribution in Figure 5.16**

  \[1.3d \leq e_1 < 2.5d\]
  
  \[e_2 \geq \frac{[3.5m \cdot d + me_1 - (m - 1)p_2]}{2}\]

  \[e_1 \geq 2.5d\]
  
  \[e_2 \geq \frac{[6m \cdot d - (m - 1)p_2]}{2}\]

For failure mode transition (net-section/end pull-out, net-section/bearing), refer to Figure 5.18 for circumferential strain calculation.
ii Compressive strain

(1) See Figure 5.13 for region of compression strain in front of the bolt hole.

(2) Compression strain = 0 if $e_2 \leq 0.75d$.

(3) Compression strain = 1.0 if $e_2 \geq \min[(me_1 - (m - 1)p_2 + m(2.5n - 1.5d)2, 1.75d)]$.

(4) Interpolation between (2) and (3) above.

iii Bolt hole elongation

Once the tensile and compressive strain distributions are determined, the connection displacement is the sum of the tensile elongation around the 1st set of inner bolts and the compressive pile up in front of the 1st set of inner bolts. In the special case when end pull-out failure happens in plates with 2 bolt-holes in the loading direction, the compressive displacement of the 1st set of inner bolts should be replaced by the end pull-out displacement of the outer bolts if the latter is smaller.

5.5 Conclusions

This chapter has presented a comprehensive numerical and analytical study of the behaviour of thin-walled plate with multiple bolts under shear, emphasizing on plate displacement, i.e. the elongation of the 1st set of inner bolt-holes (furthest away from the plate end). The following conclusions may be drawn:

- The general finite element package ABAQUS was an accurate and effective tool in simulating detailed plate behaviour with multiple bolts in shear.
- Eurocode 3 and the Australian/New Zealand standard can be used to predict plate initial stiffness and strength.
- The plate displacement is controlled by elongation of the 1st set of bolt holes. To predict the maximum plate displacement, the circumferential strain distribution around the bolt hole may be considered to be linearly distributed between five critical points. Compressive strain also exists in front of the 1st set of inner bolts.
- A method has been proposed to calculate the strains at these critical points according to three failure modes (net section failure, bearing failure, end pull-out failure).
out) and transition from one to another. The calculation procedure is summarized in section 5.4.

- Comparisons between the calculation results and ABAQUS simulation results gave an average difference of 14.3% and standard deviation of 9.4%. The analytical results are considered accurate.
6.1 Introduction

This chapter assesses the applicability of the findings of this research at ambient temperature to elevated temperatures that are generated under fire condition. For bearing connection that has uniform temperature in all the connection components, it is expected that the ambient temperature approach should be entirely applicable if the ambient temperature mechanical properties of steel are replaced by those at elevated temperatures. This chapter assesses this premise based on a series of numerical parametric studies. The same ABAQUS model is used and validation of the model for high temperature applications is by comparison against the test results of HIRASHIMA et al[31].

6.2 Brief description of the tests of HIRASHIMA et al[31]

HIRASHIMA’s[31] fire tests were conducted on friction type high tension bolted hot-rolled steel connections. Figure 6.1 shows the set-up and dimensions of the test connections.
In total, 21 steady state tests were conducted at temperatures ranging from 20°C to 650°C. Table 6.1 gives detail of these tests.

<table>
<thead>
<tr>
<th>Test temperature (°C)</th>
<th>20</th>
<th>100</th>
<th>200</th>
<th>300</th>
<th>400</th>
<th>500</th>
<th>550</th>
<th>600</th>
<th>650</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of tests</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Bolt diameter d (mm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>22</td>
</tr>
<tr>
<td>End distance (mm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>60</td>
</tr>
<tr>
<td>Edge distance (mm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>50</td>
</tr>
<tr>
<td>Thickness (mm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>25</td>
</tr>
<tr>
<td>Ultimate strain</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.3</td>
</tr>
</tbody>
</table>
6.2.1 Elevated temperature material properties

Steel plates

HIRASHIMA et al did not carry out any coupon test to decide the steel mechanical properties. The steel grade used in the tests was known as carbon steel grade SM490A with a nominal yield stress at ambient temperature 400 N/mm².

The detailed material properties of SM490A were taken from the Japanese guide book for fire-resistant performance of structural materials[32]. They are given in Table 6.2.

Steel mechanical properties change at elevated temperatures. The mechanical properties of steel in this high temperature research are modified by applying the strength and stiffness reduction factors in Eurocode 3 Part 1.2[33], as shown in Table 6.3.

The engineering stress-strain curves at elevated temperatures are constructed following the method in Eurocode 3 Part 1.2[33], as shown in Figure 6.2. The resulting engineering stress-strain curves for SM490A at different elevated temperatures are shown in Figure 6.3. For ABAQUS simulations, the engineering stress-strain curve has to be converted to the true stress-strain curve using equation (6.1) and (6.2).

\[
\sigma_t = \sigma_n (1 + \varepsilon_t) \tag{6.1}
\]

\[
\varepsilon_t = \ln (1 + \varepsilon_n) \tag{6.2}
\]

Table 6.2 Mechanical properties of SM490A[32]

<table>
<thead>
<tr>
<th>Steel grade</th>
<th>Young’s modulus (N/mm²)</th>
<th>0.2% proof stress (N/mm²)</th>
<th>Ultimate stress (N/mm²)</th>
<th>Limiting strain for yield stress (%)</th>
<th>Ultimate strain (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM490A</td>
<td>210000</td>
<td>400</td>
<td>540</td>
<td>0.3</td>
<td>0.35</td>
</tr>
</tbody>
</table>
It should be pointed out that in Eurocode 3 Part 1.2, the limiting strain at the ultimate stress and the ultimate strain limits are set as 0.15 and 0.2 respectively, whilst those in the tests of HIRASHIMA et al [1] are 0.3 and 0.35 respectively.

In Eurocode 3 Part 1.2, the transition from the proportional stress to the yield stress is described by an elliptic curve. The implementation of this relationship in ABAQUS simulation is much more complex than assuming a linear transition but with little influence on simulation results. Therefore, a linear transition was adopted, which gives the stress-strain relationship shown in Figure 6.3.

Figure 6.2 Stress-strain relationship for steel at elevated temperatures allowing strain hardening from Eurocode 3[33]
High Temperature Behaviour

Figure 6.3 Stress-strain curves of SM490A at elevated temperatures according Eurocode 3[33]

\[\text{stress (N/mm}^2\text{)}\]

\[\text{strain}\]

In previous chapters that are focused on thin-walled steel connections under bearing, the bolt diameter to plate thickness ratio is $12/1.5=8$. Because of this high value, there was very little deformation in the bolts compared to the connected steel plates. Therefore, to reduce the number of finite elements and numerical simulation time, the bolts were modelled as rigid hollow shell elements that had no deformation during the entire simulation.

However, in the tests of HIRASHIMA et al., the bolt diameter/plate thickness ratio is very small ($22/25<1$). The bolts may be more flexible and weaker compared to the connected plates. In a number of tests, large bolt deformation and fracture were observed. Clearly, it is not suitable to use the same hollow rigid non-deformable tube to simulate the bolts in the fire tests and bolt deformation should be included.

Faithful modelling of detailed behaviour of bolts can be rather complex, particularly for friction type high tension bolts in shear. For example, Gray and McCarthy
devoted considerable effort to modelling bearing behaviour of high tension bolts in shear\[34, 35\]. Here the bolt is represented by 2 beam elements and 2 rigid surfaces, as shown in Figure 6.4 (b). The rigid surfaces represent the contact surfaces of the bolt and are coupled to the beam elements. A pre-tension section is placed in the middle of the 2 beam elements to represent the bolt torque. In their research, the 2 plates were modelled using shell element S4R, as shown in Figure 6.4 (a).

![Figure 6.4 Bolt in shear FE model by Gary and McCarthy][34]

The simulation results of this model indicate that this bolt model is able to simulate accurately the deformation of the friction grip bolt under pre-tension. However, this bolt model requires detailed information such as bolt pre-tension, friction factor of specific contact surfaces. Furthermore, in their research, because their emphasis was on bolt behaviour, the plates are modelled using shell element. In the author’s research, the focus is on the plate behaviour and accurate strain distribution is required around the bolt-hole in the plate. In order to do so, the plates in this research should be modelled using 3D elements. This would necessitate a much more complex bolt model to be developed. Because the focus of this research is plate deformation rather than bolt deformation, it was decided to use a simpler bolt model by using the same element type C3D8R as for the plates. Whilst it was not possible to simulate slip between the plates, as will be shown later, this model was able to predict bolt failure in shear, as shown in Figure 6.5. Furthermore, later discussions on deformation in this chapter will only focus on plate bearing behaviour.
Grade 10.9 bolts were used in HIRASHIMA et al.’s tests. They conducted high temperature tensile tests to obtain the bolt stress-strain curves at elevated temperatures. The test results and the recorded stress-strain curves are reproduced in Table 6.4 and Figure 6.6. These properties were directly imported to the present ABAQUS model.
Table 6.3 Reduction factors for carbon steel at elevated temperature according to Eurocode 3[33]

<table>
<thead>
<tr>
<th>Steel Temperature $\theta_c$</th>
<th>Reduction factors at temperature $\theta_c$ relative to the value of $f_y$ or $E_a$ at $20^\circ C$</th>
<th>Reduction factor (relative to $f_y$) for effective yield strength $k_{y,0} = f_{y,0}/f_y$</th>
<th>Reduction factor (relative to $f_y$) for proportional limit $k_{y,0} = f_{y,0}/f_y$</th>
<th>Reduction factor (relative to $E_a$) for the slope of the linear elastic range $k_{y,0} = E_{y,0}/E_a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$20^\circ C$</td>
<td>1,000</td>
<td>1,000</td>
<td>1,000</td>
<td>1,000</td>
</tr>
<tr>
<td>$100^\circ C$</td>
<td>1,000</td>
<td>1,000</td>
<td>0,900</td>
<td>1,000</td>
</tr>
<tr>
<td>$200^\circ C$</td>
<td>1,000</td>
<td>0,807</td>
<td>0,800</td>
<td>0,700</td>
</tr>
<tr>
<td>$300^\circ C$</td>
<td>1,000</td>
<td>0,613</td>
<td>0,600</td>
<td>0,510</td>
</tr>
<tr>
<td>$400^\circ C$</td>
<td>1,000</td>
<td>0,420</td>
<td>0,310</td>
<td>0,340</td>
</tr>
<tr>
<td>$500^\circ C$</td>
<td>0,780</td>
<td>0,260</td>
<td>0,130</td>
<td>0,130</td>
</tr>
<tr>
<td>$600^\circ C$</td>
<td>0,470</td>
<td>0,180</td>
<td>0,090</td>
<td>0,080</td>
</tr>
<tr>
<td>$700^\circ C$</td>
<td>0,230</td>
<td>0,075</td>
<td>0,045</td>
<td>0,045</td>
</tr>
<tr>
<td>$800^\circ C$</td>
<td>0,110</td>
<td>0,050</td>
<td>0,040</td>
<td>0,040</td>
</tr>
<tr>
<td>$900^\circ C$</td>
<td>0,060</td>
<td>0,0375</td>
<td>0,0250</td>
<td>0,0250</td>
</tr>
<tr>
<td>$1000^\circ C$</td>
<td>0,040</td>
<td>0,0250</td>
<td>0,0125</td>
<td>0,0125</td>
</tr>
<tr>
<td>$1100^\circ C$</td>
<td>0,020</td>
<td>0,0125</td>
<td>0,0000</td>
<td>0,0000</td>
</tr>
<tr>
<td>$1200^\circ C$</td>
<td>0,000</td>
<td>0,0000</td>
<td>0,0000</td>
<td>0,0000</td>
</tr>
</tbody>
</table>

NOTE: For intermediate values of the steel temperature, linear interpolation may be used.

Table 6.4 Results of High-Temperature Tensile Tests of Bolts [31]

<table>
<thead>
<tr>
<th>Test Series</th>
<th>Test Temperatures [$^\circ C$]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>20</td>
</tr>
<tr>
<td>0.1% Proof Stress [N/mm$^2$]</td>
<td>No.1</td>
</tr>
<tr>
<td></td>
<td>No.2</td>
</tr>
<tr>
<td>0.2% Proof Stress [N/mm$^2$]</td>
<td>No.1</td>
</tr>
<tr>
<td></td>
<td>No.2</td>
</tr>
<tr>
<td>Tensile Strength [N/mm$^2$]</td>
<td>No.1</td>
</tr>
<tr>
<td></td>
<td>No.2</td>
</tr>
<tr>
<td>Elongation [%]</td>
<td>No.1</td>
</tr>
<tr>
<td></td>
<td>No.2</td>
</tr>
<tr>
<td>Reduction of Area [%]</td>
<td>No.1</td>
</tr>
<tr>
<td></td>
<td>No.2</td>
</tr>
</tbody>
</table>
6.2.2 Mesh sensitivity

The ambient temperature simulation results (Chapter 4&5) suggest that the best mesh size for optimal simulation accuracy and computation efficiency is ¼ plate thickness. However, due to much bigger plate thickness used in the tests of HIRASHIMA et al, it is no longer appropriate to retain ¼ plate thickness as the mesh size. After trial and error, the best mesh size was found to be 1/20\textsuperscript{th} the connected plate thickness at places such as the bolt-hole area. For other areas of the plate, the biased meshing technique is used. The maximum element size was about 6 times the fine mesh size. The mesh size of bolt was bigger than that of the steel plate in the fine mesh region. This is because the bolt surface was set as the master surface in contact with the plate bolt-hole.

Figure 6.7 gives an example of the FE model for the steel plate and bolt.
6.2.3 Initial boundary conditions

In HIRASHIMA et al.’s tests, gaps existed in the direction parallel to the loading direction between the bolt and plate at the beginning of the test and slip occurred. Figure 6.8 shows the recorded load-displacement curves that clearly indicate that slip happened in all tests.
Due to unavailability of load-slip data, it was not possible to model the initial load-slip relationship. In this research, only the load-displacement behaviour after contact is simulated. To do so, the plate and the bolt are set in contact from the beginning of loading, as can be seen in Figure 6.9, so that there is no slip displacement.
6.2.4 Comparison between FE modelling and test results

HIRASHIMA et al.’s tests were conducted at 8 different temperatures from 20°C to 650°C. Two or three duplicate tests were performed under each temperature.

Figure 6.10-Figure 6.13 compares the FE simulation curves with the experimental results. The simulation curves are shifted along the horizontal axis to enable comparison for the maximum load. It can be seen that overall the agreement of load capacity between the simulation and test results is good, validating the simple bolt model in predicting bolt failure in shear. As mentioned in section 6.2.1 on bolts, slip and bolt deformation cannot be accurately simulated due to simplicity of the bolt model. As a result, differences in the overall displacements at maximum load between the simulation and test results are quite high. Nevertheless, the slopes to the load-displacement curves (representing stiffness) of the simulation and test results are very close at low temperature (less than 500°C). The difference becomes particular larger at higher temperatures (over 500°C), possibly as a result of using a stiffer steel stress-strain model. But it is not possible to confirm this because the test report does not contain any high temperature material test information.

The bearing behaviour of the plate in shear is the focus of this research, rather than the bearing behaviour of bolt in shear. Therefore, no further attempt was made to improve the current bolt model.
Figure 6.10 Comparison of load-displacement curve at 20°C and 300°C

NOTE:
Solid lines: Test results
Dotted lines: FE simulation results

Figure 6.11 Comparison of load-displacement curve at 200°C and 400°C

NOTE:
Solid lines: Test results
Dotted lines: FE simulation results
NOTE:
Solid lines: Test results
Dotted lines: FE simulation results

Figure 6.12 Comparison of load-displacement curve at 500°C and 600°C

NOTE:
Solid lines: Test results
Dotted lines: FE simulation results

Figure 6.13 Comparison of load-displacement curve at 550°C and 650°C
Table 6.5 compares the maximum loads and the corresponding displacements between the FE simulation and HIRASHIMA’s test results (initial and friction slip displacements removed). Overall, the simulation results are very good for the initial stiffness, the maximum load and the plate displacement (without bolt slips) at the maximum load.

Table 6.5 Comparison between HIRASHIMA’s test & FE simulation results

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>20</th>
<th>200</th>
<th>300</th>
<th>400</th>
<th>500</th>
<th>550</th>
<th>600</th>
<th>650</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1 (mm)</td>
<td>6.2</td>
<td>6.1</td>
<td>8.0</td>
<td>5.5</td>
<td>6.1</td>
<td>6.2</td>
<td>6.1</td>
<td>6.0</td>
</tr>
<tr>
<td>D2 (mm)</td>
<td>5.67</td>
<td>5.49</td>
<td>5.45</td>
<td>4.86</td>
<td>5.58</td>
<td>5.76</td>
<td>5.55</td>
<td>5.44</td>
</tr>
<tr>
<td>D2/D1 (mm)</td>
<td>0.91</td>
<td>0.9</td>
<td>0.68</td>
<td>0.88</td>
<td>0.91</td>
<td>0.93</td>
<td>0.91</td>
<td>0.91</td>
</tr>
<tr>
<td>F1 (KN)</td>
<td>491</td>
<td>484</td>
<td>463</td>
<td>357</td>
<td>212</td>
<td>146</td>
<td>99</td>
<td>64</td>
</tr>
<tr>
<td>F2 (KN)</td>
<td>449</td>
<td>476</td>
<td>466</td>
<td>397</td>
<td>232</td>
<td>182</td>
<td>123</td>
<td>73</td>
</tr>
<tr>
<td>F2/F1</td>
<td>0.91</td>
<td>0.98</td>
<td>1.01</td>
<td>1.11</td>
<td>1.09</td>
<td>1.25</td>
<td>1.24</td>
<td>1.14</td>
</tr>
</tbody>
</table>

Note:
D1: Recorded Displacement (slip displacement removed)
D2: FE simulation displacement
F1: Test Maximum load
F2: FE simulation maximum load

6.3 Parametric study using FE modelling

Using the same ABAQUS model that has been validated against the test results of HIRASHIMA et al., a series of 26 numerical parametric simulations have been performed. Table 6.6 lists details of the parametric study cases. These parametric studies are selected to investigate how the change of each individual parameter will affect the failure mode of the plate and therefore the load-displacement behaviour of the plate. In each set, only one parameter was changed while the others remained fixed to see whether the change of this parameter in the controlled range would cause change of the plate failure mode.
Table 6.6 Details of numerical parametric study cases

<table>
<thead>
<tr>
<th>Set-1</th>
<th>Bolt-hole size d 14mm</th>
<th>Bolt number 4</th>
<th>End distance 1d</th>
<th>Edge distance 1d</th>
<th>Thickness 1.5mm</th>
<th>Spacing 3d</th>
<th>Ultimate strain 0.35</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixed parameters</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Changed parameter</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Model name</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Set-2</td>
<td>Bolt-hole size d 14mm</td>
<td>Bolt number 4</td>
<td>End distance 3d</td>
<td>Temperature 500</td>
<td>Thickness 1.5mm</td>
<td>Spacing 3d</td>
<td>Ultimate strain 0.35</td>
</tr>
<tr>
<td>Fixed parameters</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Changed parameter</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Model name</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Set-3</td>
<td>Bolt-hole size d 14mm</td>
<td>Bolt number 4</td>
<td>Edge distance 4d</td>
<td>Temperature 300</td>
<td>Thickness 1.5mm</td>
<td>Spacing 3d</td>
<td>Ultimate strain 0.35</td>
</tr>
<tr>
<td>Fixed parameters</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Changed parameter</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Model name</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Set-4</td>
<td>Bolt-hole size d 14mm</td>
<td>Bolt number 4</td>
<td>End distance 1.5 d</td>
<td>Edge distance 4d</td>
<td>Temperature 300</td>
<td>Spacing 3d</td>
<td>Ultimate strain 0.35</td>
</tr>
<tr>
<td>Fixed parameters</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Changed parameter</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Model name</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Set-5</td>
<td>Bolt-hole size d 14mm</td>
<td>Bolt number 4</td>
<td>End distance 1d</td>
<td>Temperature 300</td>
<td>Thickness 1.5mm</td>
<td>Spacing 6d</td>
<td>Ultimate strain 0.35</td>
</tr>
<tr>
<td>Fixed parameters</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Changed parameter</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Model name</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Set-6</td>
<td>Bolt-hole size d 14mm</td>
<td>Bolt number 6 14mm</td>
<td>End distance 1d</td>
<td>Temperature 300</td>
<td>Thickness 1.5mm</td>
<td>Spacing 3d</td>
<td>Ultimate strain 0.35</td>
</tr>
<tr>
<td>Fixed parameters</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Changed parameter</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Model name</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Set-7</td>
<td>Temperature 500</td>
<td>Bolt number 4</td>
<td>End distance 1d</td>
<td>Edge distance 4d</td>
<td>Thickness 1.5mm</td>
<td>Spacing 3d</td>
<td>Ultimate strain 0.35</td>
</tr>
<tr>
<td>Fixed parameters</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Changed parameter</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Model name</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Set-8</td>
<td>Temperature 300</td>
<td>Bolt number 4</td>
<td>End distance 2d</td>
<td>Edge distance 4d</td>
<td>Thickness 1.5mm</td>
<td>Spacing 3d</td>
<td>Bolt-hole size d 14mm</td>
</tr>
<tr>
<td>Fixed parameters</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Changed parameter</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Model name</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Set-1**
- **Fixed parameters**
  - Bolt-hole size: 14mm
  - Bolt number: 4
  - End distance: 1d
  - Edge distance: 1d
  - Thickness: 1.5mm
  - Spacing: 3d
  - Ultimate strain: 0.35

**Set-2**
- **Fixed parameters**
  - Bolt-hole size: 14mm
  - Bolt number: 4
  - End distance: 3d
  - Temperature: 500°C
  - Thickness: 1.5mm
  - Spacing: 3d
  - Ultimate strain: 0.35

**Set-3**
- **Fixed parameters**
  - Bolt-hole size: 14mm
  - Bolt number: 4
  - Edge distance: 4d
  - Temperature: 300°C
  - Thickness: 1.5mm
  - Spacing: 3d
  - Ultimate strain: 0.35

**Set-4**
- **Fixed parameters**
  - Bolt-hole size: 14mm
  - Bolt number: 4
  - End distance: 1.5d
  - Edge distance: 4d
  - Temperature: 300°C
  - Thickness: 1.5mm
  - Spacing: 3d
  - Ultimate strain: 0.35

**Set-5**
- **Fixed parameters**
  - Bolt-hole size: 14mm
  - Bolt number: 4
  - End distance: 1d
  - Edge distance: 4d
  - Temperature: 300°C
  - Thickness: 1.5mm
  - Spacing: 6d
  - Ultimate strain: 0.35

**Set-6**
- **Fixed parameters**
  - Bolt-hole size: 14mm
  - Bolt number: 6
  - End distance: 1d
  - Temperature: 300°C
  - Thickness: 1.5mm
  - Spacing: 3d
  - Ultimate strain: 0.35

**Set-7**
- **Fixed parameters**
  - Temperature: 500°C
  - Bolt number: 4
  - End distance: 1d
  - Edge distance: 4d
  - Thickness: 1.5mm
  - Spacing: 3d
  - Bolt-hole size: 14mm

**Set-8**
- **Fixed parameters**
  - Temperature: 300°C
  - Bolt number: 4
  - End distance: 2d
  - Edge distance: 4d
  - Thickness: 1.5mm
  - Spacing: 3d
  - Ultimate strain: 0.25, 0.35

**Model names**
- **Set-1** (20°C), **Set-1-2** (200°C), **Set-1-3** (300°C), **Set-1-4** (400°C), **Set-1-5** (500°C), **Set-1-6** (600°C), **Set-1-7** (700°C)
- **Set-2** (edge distance 1d), **Set-2-2** (edge distance 2d), **Set-2-3** (edge distance 4.5d)
- **Set-3** (end distance 1d), **Set-3-2** (end distance 1.5d), **Set-3-3** (end distance 2d)
- **Set-4** (thickness 1.5mm), **Set-4-2** (thickness 3mm)
- **Set-5** (bolt-hole diameter 10mm, 20mm)
- **Set-6** (edge distance 1d, 2d, 3d, 4d)
- **Set-7** (bolt-hole diameter 10mm, 20mm)
- **Set-8** (Ultimate strain 0.25, 0.35)
Figure 6.14-Figure 6.21 show the simulated load-displacement results for the 8 sets of parametric study cases. The simulation results reveal that keeping all parameters the same, the change of temperature only influences the maximum load of the model; the difference of displacements under different temperatures is noticeably small.

Figure 6.14 Simulated load-displacement relationships for set-1 models
Figure 6.15 Simulated load-displacement relationships for set-2 models

Figure 6.16 Simulated load-displacement relationships for set-3 models
Figure 6.17 Simulated load-displacement relationships for set-4 models

Figure 6.18 Simulated load-displacement relationships for set-5 models
Figure 6.19 Simulated load-displacement relationships for set-6 models

Figure 6.20 Simulated load-displacement relationships for set-7 models
6.3.1 Comparison between simulation and proposed calculation results
As for the normal temperature research presented in Chapters 4 and 5, the comparisons will be made for the three key values of connection load-deflection curve (Figure 6.22): initial stiffness, strength and deformation capacity.

Figure 6.21 Simulated load-displacement relationships for set-8 models

Figure 6.22 Three key values of connection load-displacement curve
6.3.2 Initial stiffness

This chapter will investigate direct application of the ambient temperature calculation methods for the three key quantities of bearing connection behaviour, but replacing the ambient temperature steel mechanical properties with those at elevated temperatures.

The stiffness calculation equation is equation (4.1) and is repeated as equation (6.3) below:

\[ k = 24n_b \cdot k_b \cdot k_t \cdot d \cdot f_u \]  \hspace{1cm} (6.3)

For elevated temperature applications, the ultimate stress \( f_u \) should use that at elevated temperatures, obtained by multiplying the ambient temperature value by the reduction factor given by Eurocode 3 Part 1.2 (repeated as Table 6.3).

Table 6.7 and Figure 6.23 compare the numerical simulation and calculation results. The average difference is 4% with a standard deviation of 10%, which indicates very good accuracy for the calculation method.

Table 6.7 Comparison for initial stiffness between FE simulation and analytical calculation results at elevated temperatures

<table>
<thead>
<tr>
<th>Model name</th>
<th>End distance (mm)</th>
<th>Edge distance (mm)</th>
<th>Bolt-hole diameter (mm)</th>
<th>Bolt number</th>
<th>Temperature (°C)</th>
<th>Thickness (mm)</th>
<th>Spacing</th>
<th>( k_1 ) (N/mm)</th>
<th>( k_2 ) (N/mm)</th>
<th>( k_1/k_2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Set-1-1</td>
<td>14 (1d)</td>
<td>14 (1d)</td>
<td>14</td>
<td>2X2</td>
<td>20</td>
<td>1.5</td>
<td>42 (3d)</td>
<td>43915</td>
<td>38707</td>
<td>1.13</td>
</tr>
<tr>
<td>Set-1-2</td>
<td>14 (1d)</td>
<td>14 (1d)</td>
<td>14</td>
<td>2X2</td>
<td>200</td>
<td>1.5</td>
<td>42 (3d)</td>
<td>39675</td>
<td>38707</td>
<td>1.02</td>
</tr>
<tr>
<td>Set-1-3</td>
<td>14 (1d)</td>
<td>14 (1d)</td>
<td>14</td>
<td>2X2</td>
<td>300</td>
<td>1.5</td>
<td>42 (3d)</td>
<td>32409</td>
<td>38707</td>
<td>0.84</td>
</tr>
<tr>
<td>Set-1-4</td>
<td>14 (1d)</td>
<td>14 (1d)</td>
<td>14</td>
<td>2X2</td>
<td>400</td>
<td>1.5</td>
<td>42 (3d)</td>
<td>36290</td>
<td>38707</td>
<td>0.94</td>
</tr>
<tr>
<td>Set-1-5</td>
<td>14 (1d)</td>
<td>14 (1d)</td>
<td>14</td>
<td>2X2</td>
<td>500</td>
<td>1.5</td>
<td>42 (3d)</td>
<td>32286</td>
<td>30192</td>
<td>1.07</td>
</tr>
<tr>
<td>Set-1-6</td>
<td>14 (1d)</td>
<td>14 (1d)</td>
<td>14</td>
<td>2X2</td>
<td>600</td>
<td>1.5</td>
<td>42 (3d)</td>
<td>17354</td>
<td>18192</td>
<td>0.95</td>
</tr>
<tr>
<td>Set-1-7</td>
<td>14 (1d)</td>
<td>14 (1d)</td>
<td>14</td>
<td>2X2</td>
<td>700</td>
<td>1.5</td>
<td>42 (3d)</td>
<td>7432</td>
<td>8903</td>
<td>0.83</td>
</tr>
<tr>
<td>Set-2-1</td>
<td>42 (3d)</td>
<td>14 (1d)</td>
<td>14</td>
<td>2X2</td>
<td>500</td>
<td>1.5</td>
<td>42 (3d)</td>
<td>38758</td>
<td>45287</td>
<td>0.86</td>
</tr>
<tr>
<td>Set-2-2</td>
<td>42 (3d)</td>
<td>28 (2d)</td>
<td>14</td>
<td>2X2</td>
<td>500</td>
<td>1.5</td>
<td>42 (3d)</td>
<td>41326</td>
<td>45287</td>
<td>0.91</td>
</tr>
<tr>
<td>Set-2-3</td>
<td>42 (3d)</td>
<td>63 (4.5d)</td>
<td>14</td>
<td>2X2</td>
<td>500</td>
<td>1.5</td>
<td>42 (3d)</td>
<td>41493</td>
<td>45287</td>
<td>0.92</td>
</tr>
<tr>
<td>Set-3-1</td>
<td>14 (1d)</td>
<td>56 (4d)</td>
<td>14</td>
<td>2X2</td>
<td>300</td>
<td>1.5</td>
<td>42 (3d)</td>
<td>37493</td>
<td>38707</td>
<td>0.97</td>
</tr>
<tr>
<td>Set-3-2</td>
<td>21(1.5d)</td>
<td>56 (4d)</td>
<td>14</td>
<td>2X2</td>
<td>300</td>
<td>1.5</td>
<td>42 (3d)</td>
<td>44667</td>
<td>45158</td>
<td>0.99</td>
</tr>
<tr>
<td>Set-3-3</td>
<td>28 (2d)</td>
<td>56 (4d)</td>
<td>14</td>
<td>2X2</td>
<td>300</td>
<td>1.5</td>
<td>42 (3d)</td>
<td>48023</td>
<td>51610</td>
<td>0.93</td>
</tr>
<tr>
<td>Set-4-1</td>
<td>21(1.5d)</td>
<td>56 (4d)</td>
<td>14</td>
<td>2X2</td>
<td>300</td>
<td>1.5</td>
<td>42 (3d)</td>
<td>44667</td>
<td>45158</td>
<td>0.99</td>
</tr>
<tr>
<td>Set-4-2</td>
<td>21(1.5d)</td>
<td>56 (4d)</td>
<td>14</td>
<td>2X2</td>
<td>300</td>
<td>3</td>
<td>42 (3d)</td>
<td>86007</td>
<td>90317</td>
<td>0.95</td>
</tr>
<tr>
<td>Set-5-1</td>
<td>10 (1d)</td>
<td>40 (4d)</td>
<td>10</td>
<td>2X2</td>
<td>300</td>
<td>1.5</td>
<td>42 (3d)</td>
<td>29351</td>
<td>25805</td>
<td>1.14</td>
</tr>
<tr>
<td>Set-5-2</td>
<td>20 (1d)</td>
<td>80 (4d)</td>
<td>20</td>
<td>2X2</td>
<td>300</td>
<td>1.5</td>
<td>42 (3d)</td>
<td>48236</td>
<td>58061</td>
<td>0.83</td>
</tr>
<tr>
<td>Set-6-1</td>
<td>14 (1d)</td>
<td>14 (1d)</td>
<td>14</td>
<td>2X3</td>
<td>300</td>
<td>1.5</td>
<td>84 (6d)</td>
<td>56218</td>
<td>58061</td>
<td>0.97</td>
</tr>
<tr>
<td>Set-6-2</td>
<td>14 (1d)</td>
<td>28 (2d)</td>
<td>14</td>
<td>2X3</td>
<td>300</td>
<td>1.5</td>
<td>84 (6d)</td>
<td>59115</td>
<td>58061</td>
<td>1.02</td>
</tr>
</tbody>
</table>
### Load carrying capacity

The ambient temperature calculation method, details of which are presented in Chapter 5, is summarized as follows.

For plates with a single bolt, there are 3 possible different failure modes, depending on the end and edge distances: net-section fracture, end pull-out failure and bearing failure.
For net-section fracture, the following formula can be used to calculate the maximum load:

\[ F_t = A_n \cdot f_u = (2e_2 - d) \cdot t \cdot f_u \quad (6.4) \]

For end pull-out failure, the following formula provided by the Australian/New Zealand [17] and North American design standards [28] can be used to calculate the maximum load:

\[ F_s = t \cdot e_1 \cdot f_u \quad (6.5) \]

For bearing failure, the following formula provided by Eurocode 3 [27] can be used to predict the maximum load:

\[ F_b = 2.5d \cdot t \cdot f_u \quad (6.6) \]

For plate with multiple bolt-holes as shown in Figure 6.24, equations (6.4)-(6.6) can be transformed to:

Net section failure:

\[ F_t = A_n \cdot f_u = (w - md) \cdot t \cdot f_u = 2e_2 + (m - 1)p_2 - m \cdot d \quad (6.7) \]

End pull-out failure:

\[ F_s = m \cdot t \cdot e_1 \cdot f_u + 2.5m(n - 1) \cdot d \cdot t \cdot f_u \quad (6.8) \]

Bearing failure:

\[ F_{b,Rd} = 2.5m \cdot n \cdot d \cdot t \cdot f_u \quad (6.9) \]
CHAPTER 6  HIGH TEMPERATURE BEHAVIOUR

The conditions for the above three different failure modes are as below:

\textit{i} \hspace{1em} \textbf{Net-section failure}

Net-section failure happens when

\[ F_t = (w - md) \cdot f_u < 2.5m \cdot n \cdot d \cdot t \cdot f_u \text{ for } e_1 \geq 2.5d \]

Or

\[ (w - md) \cdot t \cdot f_u < m(n - 1) \cdot 2.5d \cdot t \cdot f_u + mt \cdot e_1 \cdot f_u \text{ for } e_1 < 2.5d \]

Since \( w = 2e_2 + (m - 1) \cdot p_2 \), the dimensional conditions are:

For \( e_1 < 2.5d \):

\[ e_2 < [m e_1 - (m - 1)p_2 + m(2.5n - 1.5) \cdot d]/2 \] \hspace{1em} (6.10)

For \( e_1 \geq 2.5d \):

\[ e_2 < [m \cdot (2.5n + 1) \cdot d - (m - 1)p_2]/2 \] \hspace{1em} (6.11)

\textit{ii} \hspace{1em} \textbf{Bearing failure and end pull-out failure}

The condition for end pull-out failure is:

\[ 1d < e_1 < 1.3d \text{ and } n = 2 \]
The condition for bearing failure is:

1) \[ e_1 \geq 2.5d \text{ and } n > 2 \]

Or \[ e_1 \geq 2.5d \text{ and } n = 1 \]

\[ e_2 \geq [m \cdot e_1 - (m - 1)p_2 + m(2.5n - 1.5) \cdot d]/2 \]  

(6.12)

2) \[ 1.3d \leq e_1 < 2.5d \text{ and } n = 2 \]

Or \[ e_1 < 2.5d \text{ and } n > 2 \]

\[ e_2 \geq [m \cdot e_1 - (m - 1)p_2 + m(2.5n - 1.5) \cdot d]/2 \]  

(6.13)

(6.14)

To use the above equations for elevated temperature applications, all one needs to do is to replace the steel ultimate strength at ambient temperature \( f_u \) by that at elevated temperatures.

Table 6.8 Comparison of load carrying capacity between FE simulation and analytical calculation results at elevated temperatures

<table>
<thead>
<tr>
<th>Model name</th>
<th>End distance (mm)</th>
<th>Edge distance (mm)</th>
<th>Bolt-hole diameter (mm)</th>
<th>Bolt number</th>
<th>Temperature (°C)</th>
<th>Thickness (mm)</th>
<th>Spacing (mm)</th>
<th>( F_1 ) (KN)</th>
<th>( F_2 ) (KN)</th>
<th>( F_2/F_1 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Set-1-1</td>
<td>14 (1d)</td>
<td>14 (1d)</td>
<td>14</td>
<td>2X2</td>
<td>20</td>
<td>1.5</td>
<td>42 (3d)</td>
<td>23.03</td>
<td>20.16</td>
<td>0.88</td>
</tr>
<tr>
<td>Set-1-2</td>
<td>14 (1d)</td>
<td>14 (1d)</td>
<td>14</td>
<td>2X2</td>
<td>200</td>
<td>1.5</td>
<td>42 (3d)</td>
<td>22.02</td>
<td>20.16</td>
<td>0.92</td>
</tr>
<tr>
<td>Set-1-3</td>
<td>14 (1d)</td>
<td>14 (1d)</td>
<td>14</td>
<td>2X2</td>
<td>300</td>
<td>1.5</td>
<td>42 (3d)</td>
<td>21.65</td>
<td>20.16</td>
<td>0.93</td>
</tr>
<tr>
<td>Set-1-4</td>
<td>14 (1d)</td>
<td>14 (1d)</td>
<td>14</td>
<td>2X2</td>
<td>400</td>
<td>1.5</td>
<td>42 (3d)</td>
<td>20.80</td>
<td>20.16</td>
<td>0.97</td>
</tr>
<tr>
<td>Set-1-5</td>
<td>14 (1d)</td>
<td>14 (1d)</td>
<td>14</td>
<td>2X2</td>
<td>500</td>
<td>1.5</td>
<td>42 (3d)</td>
<td>16.37</td>
<td>15.73</td>
<td>0.96</td>
</tr>
<tr>
<td>Set-1-6</td>
<td>14 (1d)</td>
<td>14 (1d)</td>
<td>14</td>
<td>2X2</td>
<td>600</td>
<td>1.5</td>
<td>42 (3d)</td>
<td>9.67</td>
<td>9.48</td>
<td>0.98</td>
</tr>
<tr>
<td>Set-1-7</td>
<td>14 (1d)</td>
<td>14 (1d)</td>
<td>14</td>
<td>2X2</td>
<td>700</td>
<td>1.5</td>
<td>42 (3d)</td>
<td>4.75</td>
<td>4.64</td>
<td>0.98</td>
</tr>
<tr>
<td>Set-2-1</td>
<td>42 (3d)</td>
<td>14 (1d)</td>
<td>14</td>
<td>2X2</td>
<td>500</td>
<td>1.5</td>
<td>42 (3d)</td>
<td>16.49</td>
<td>15.72</td>
<td>0.95</td>
</tr>
<tr>
<td>Set-2-2</td>
<td>42 (3d)</td>
<td>28 (2d)</td>
<td>14</td>
<td>2X2</td>
<td>500</td>
<td>1.5</td>
<td>42 (3d)</td>
<td>29.08</td>
<td>26.21</td>
<td>0.90</td>
</tr>
<tr>
<td>Set-2-3</td>
<td>42 (3d)</td>
<td>63 (4.5d)</td>
<td>14</td>
<td>2X2</td>
<td>500</td>
<td>1.5</td>
<td>42 (3d)</td>
<td>48.76</td>
<td>52.40</td>
<td>1.07</td>
</tr>
<tr>
<td>Set-3-1</td>
<td>14 (1d)</td>
<td>56 (4d)</td>
<td>14</td>
<td>2X2</td>
<td>300</td>
<td>1.5</td>
<td>42 (3d)</td>
<td>49.46</td>
<td>47.40</td>
<td>0.96</td>
</tr>
<tr>
<td>Set-3-2</td>
<td>21 (1.5d)</td>
<td>56 (4d)</td>
<td>14</td>
<td>2X2</td>
<td>300</td>
<td>1.5</td>
<td>42 (3d)</td>
<td>46.86</td>
<td>53.80</td>
<td>1.14</td>
</tr>
<tr>
<td>Set-3-3</td>
<td>28 (2d)</td>
<td>56 (4d)</td>
<td>14</td>
<td>2X2</td>
<td>300</td>
<td>1.5</td>
<td>42 (3d)</td>
<td>53.60</td>
<td>60.48</td>
<td>1.11</td>
</tr>
<tr>
<td>Set-4-1</td>
<td>21 (1.5d)</td>
<td>56 (4d)</td>
<td>14</td>
<td>2X2</td>
<td>300</td>
<td>1.5</td>
<td>42 (3d)</td>
<td>46.86</td>
<td>53.80</td>
<td>1.14</td>
</tr>
<tr>
<td>Set-4-2</td>
<td>21 (1.5)</td>
<td>56 (4d)</td>
<td>14</td>
<td>2X2</td>
<td>300</td>
<td>3</td>
<td>42 (3d)</td>
<td>95.09</td>
<td>107.60</td>
<td>1.13</td>
</tr>
<tr>
<td>Set-5-1</td>
<td>10 (1d)</td>
<td>40 (4d)</td>
<td>10</td>
<td>2X2</td>
<td>300</td>
<td>1.5</td>
<td>42 (3d)</td>
<td>29.68</td>
<td>33.60</td>
<td>1.13</td>
</tr>
<tr>
<td>Set-5-2</td>
<td>20 (1d)</td>
<td>80 (4d)</td>
<td>20</td>
<td>2X2</td>
<td>300</td>
<td>1.5</td>
<td>42 (3d)</td>
<td>64.38</td>
<td>67.20</td>
<td>1.04</td>
</tr>
<tr>
<td>Set-6-1</td>
<td>14 (1d)</td>
<td>14 (1d)</td>
<td>14</td>
<td>2X3</td>
<td>300</td>
<td>1.5</td>
<td>84 (6d)</td>
<td>38.46</td>
<td>40.32</td>
<td>1.05</td>
</tr>
<tr>
<td>Set-6-2</td>
<td>14 (1d)</td>
<td>28 (2d)</td>
<td>14</td>
<td>2X3</td>
<td>300</td>
<td>1.5</td>
<td>84 (6d)</td>
<td>54.39</td>
<td>53.76</td>
<td>0.99</td>
</tr>
<tr>
<td>Set-6-3</td>
<td>14 (1d)</td>
<td>42 (3d)</td>
<td>14</td>
<td>2X3</td>
<td>300</td>
<td>1.5</td>
<td>84 (6d)</td>
<td>64.05</td>
<td>67.20</td>
<td>1.05</td>
</tr>
</tbody>
</table>
Table 6.8 and Figure 6.25 compare the simulated and calculated load carrying capacities. The average difference between the two sets of results is 7% with a standard deviation of 8%. Again the results are accurate enough for design applications at elevated temperatures.

To further confirm accuracy of the proposed calculation method, Table 6.9 compares the simulated failure modes and those predicted using the conditions in equations (6.10)-(6.14). In every case, the failure mode has been correctly predicted. Examples comparing failure modes are demonstrated in Figure 6.26-Figure 6.28.
Table 6.9 Comparison of predicted failure modes & simulated failure modes

<table>
<thead>
<tr>
<th>Model name</th>
<th>End distance (mm)</th>
<th>Edge distance (mm)</th>
<th>Bolt-hole diameter (mm)</th>
<th>Bolt number</th>
<th>Temperature (°C)</th>
<th>Thickness (mm)</th>
<th>Spacing (mm)</th>
<th>M₁</th>
<th>M₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Set-1-1</td>
<td>14 (1d)</td>
<td>14 (1d)</td>
<td>14</td>
<td>2X2</td>
<td>20</td>
<td>1.5</td>
<td>42 (3d)</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>Set-1-2</td>
<td>14 (1d)</td>
<td>14 (1d)</td>
<td>14</td>
<td>2X2</td>
<td>200</td>
<td>1.5</td>
<td>42 (3d)</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>Set-1-3</td>
<td>14 (1d)</td>
<td>14 (1d)</td>
<td>14</td>
<td>2X2</td>
<td>300</td>
<td>1.5</td>
<td>42 (3d)</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>Set-1-4</td>
<td>14 (1d)</td>
<td>14 (1d)</td>
<td>14</td>
<td>2X2</td>
<td>400</td>
<td>1.5</td>
<td>42 (3d)</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>Set-1-5</td>
<td>14 (1d)</td>
<td>14 (1d)</td>
<td>14</td>
<td>2X2</td>
<td>500</td>
<td>1.5</td>
<td>42 (3d)</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>Set-1-6</td>
<td>14 (1d)</td>
<td>14 (1d)</td>
<td>14</td>
<td>2X2</td>
<td>600</td>
<td>1.5</td>
<td>42 (3d)</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>Set-1-7</td>
<td>14 (1d)</td>
<td>14 (1d)</td>
<td>14</td>
<td>2X2</td>
<td>700</td>
<td>1.5</td>
<td>42 (3d)</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>Set-2-1</td>
<td>42 (3d)</td>
<td>14 (1d)</td>
<td>14</td>
<td>2X2</td>
<td>500</td>
<td>1.5</td>
<td>42 (3d)</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>Set-2-2</td>
<td>42 (3d)</td>
<td>28 (2d)</td>
<td>14</td>
<td>2X2</td>
<td>500</td>
<td>1.5</td>
<td>42 (3d)</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>Set-2-3</td>
<td>42 (3d)</td>
<td>63 (4.5d)</td>
<td>14</td>
<td>2X2</td>
<td>500</td>
<td>1.5</td>
<td>42 (3d)</td>
<td>B</td>
<td>B</td>
</tr>
<tr>
<td>Set-3-1</td>
<td>14 (1d)</td>
<td>56 (4d)</td>
<td>14</td>
<td>2X2</td>
<td>300</td>
<td>1.5</td>
<td>42 (3d)</td>
<td>E</td>
<td>E</td>
</tr>
<tr>
<td>Set-3-2</td>
<td>21 (1.5d)</td>
<td>56 (4d)</td>
<td>14</td>
<td>2X2</td>
<td>300</td>
<td>1.5</td>
<td>42 (3d)</td>
<td>B</td>
<td>B</td>
</tr>
<tr>
<td>Set-3-3</td>
<td>28 (2d)</td>
<td>56 (4d)</td>
<td>14</td>
<td>2X2</td>
<td>300</td>
<td>1.5</td>
<td>42 (3d)</td>
<td>B</td>
<td>B</td>
</tr>
<tr>
<td>Set-4-1</td>
<td>21 (1.5d)</td>
<td>56 (4d)</td>
<td>14</td>
<td>2X2</td>
<td>300</td>
<td>3</td>
<td>42 (3d)</td>
<td>B</td>
<td>B</td>
</tr>
<tr>
<td>Set-4-2</td>
<td>21 (1.5d)</td>
<td>56 (4d)</td>
<td>14</td>
<td>2X2</td>
<td>300</td>
<td>1.5</td>
<td>42 (3d)</td>
<td>E</td>
<td>E</td>
</tr>
<tr>
<td>Set-5-1</td>
<td>10 (1d)</td>
<td>40 (4d)</td>
<td>10</td>
<td>2X2</td>
<td>300</td>
<td>1.5</td>
<td>42 (3d)</td>
<td>E</td>
<td>E</td>
</tr>
<tr>
<td>Set-5-2</td>
<td>20 (1d)</td>
<td>80 (4d)</td>
<td>20</td>
<td>2X2</td>
<td>300</td>
<td>1.5</td>
<td>42 (3d)</td>
<td>B</td>
<td>B</td>
</tr>
<tr>
<td>Set-6-1</td>
<td>14 (1d)</td>
<td>14 (1d)</td>
<td>14</td>
<td>2X3</td>
<td>300</td>
<td>1.5</td>
<td>84 (6d)</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>Set-6-2</td>
<td>14 (1d)</td>
<td>28 (2d)</td>
<td>14</td>
<td>2X3</td>
<td>300</td>
<td>1.5</td>
<td>84 (6d)</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>Set-6-3</td>
<td>14 (1d)</td>
<td>42 (3d)</td>
<td>14</td>
<td>2X3</td>
<td>300</td>
<td>1.5</td>
<td>84 (6d)</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>Set-6-4</td>
<td>14 (1d)</td>
<td>56 (4d)</td>
<td>14</td>
<td>2X3</td>
<td>300</td>
<td>1.5</td>
<td>84 (6d)</td>
<td>B</td>
<td>B</td>
</tr>
<tr>
<td>Set-7-1</td>
<td>20 (2d)</td>
<td>40 (4d)</td>
<td>10</td>
<td>2X2</td>
<td>500</td>
<td>1.5</td>
<td>42 (3d)</td>
<td>B</td>
<td>B</td>
</tr>
<tr>
<td>Set-7-2</td>
<td>40 (2d)</td>
<td>80 (4d)</td>
<td>20</td>
<td>2X2</td>
<td>500</td>
<td>1.5</td>
<td>42 (3d)</td>
<td>B</td>
<td>B</td>
</tr>
<tr>
<td>Set-8-1</td>
<td>28 (2d)</td>
<td>56 (4d)</td>
<td>14</td>
<td>2X2</td>
<td>300</td>
<td>1.5</td>
<td>42 (3d)</td>
<td>B</td>
<td>B</td>
</tr>
<tr>
<td>Set-8-2</td>
<td>28 (2d)</td>
<td>56 (4d)</td>
<td>14</td>
<td>2X2</td>
<td>300</td>
<td>1.5</td>
<td>42 (3d)</td>
<td>B</td>
<td>B</td>
</tr>
</tbody>
</table>

M₁: Failure mode from ABAQUS simulation
M₂: Failure mode from calculation
N: Net-section failure
S: End pull-out failure
B: Bearing failure
Example for predicting model set-1-1:

For $e_1 < 2.5d$,

$$e_2 = 1d < \frac{[m e_1 - (m-1)p_2 + m(2.5n-1.5)d]}{2} = 3d \quad (6.10)$$

Therefore it is net-section failure.

Figure 6.26 Example of net-section failure comparison

Example for predicting model set-3-1:

For $n=2$ and $e_1 < 2.5d$,

$$e_2 = 4d > \frac{[m e_1 - (m-1)p_2 + m(2.5n-1.5)d]}{2} = 3d \quad (6.12)$$

Therefore it is end pull-out failure.

Figure 6.27 Example of end pull-out failure comparison
6.3.4 Displacement at ultimate load

Details of displacement calculation are provided in Appendix section of this thesis. The method is based on finding the elongation of the 1st inner bolt hole in the direction of loading if the failure modes are bearing and net section (Figure 6.26), or the end pull-out of the outer bolt hole (the last bolt hole in the loading direction) if the failure mode is end pull-out. In addition, compression pile-up is added if this occurs. Furthermore, to avoid step changes in the connection deformation – plate geometry dimension relationship, failure mode transitions have been introduced.

To apply the ambient temperature method to elevated temperatures, one needs to use the appropriate strain limit at the ultimate stress. For the numerical parametric study cases, the strain limit was 0.3.

Example for predicting model set-6-4:

\[ e_2 = 4d \geq \frac{[m e_{1 = \text{(m-1)}p_2 + m(2.5n-1.5)d}]}{2} = 4d \]  

(6.14)

Therefore it is bearing failure.

Figure 6.28 Example for bearing failure comparison
Figure 6.29 Displacement of plate with multiple bolt-holes
Table 6.10 Comparison for displacement at maximum load between FE simulation and the proposed calculation method at elevated temperatures

<table>
<thead>
<tr>
<th>Model name</th>
<th>End distance (mm)</th>
<th>Edge distance (mm)</th>
<th>Bolt-hole diameter (mm)</th>
<th>Bolt number</th>
<th>Temperature (°C)</th>
<th>Thickness (mm)</th>
<th>Spacing (mm)</th>
<th>D1 (mm)</th>
<th>D2 (mm)</th>
<th>D2/D1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Set-1-1</td>
<td>14 (1d)</td>
<td>14 (1d)</td>
<td>14</td>
<td>2X2</td>
<td>20</td>
<td>1.5</td>
<td>42 (3d)</td>
<td>3.97</td>
<td>3.67</td>
<td>0.93</td>
</tr>
<tr>
<td>Set-1-2</td>
<td>14 (1d)</td>
<td>14 (1d)</td>
<td>14</td>
<td>2X2</td>
<td>200</td>
<td>1.5</td>
<td>42 (3d)</td>
<td>4.02</td>
<td>3.67</td>
<td>0.91</td>
</tr>
<tr>
<td>Set-1-3</td>
<td>14 (1d)</td>
<td>14 (1d)</td>
<td>14</td>
<td>2X2</td>
<td>300</td>
<td>1.5</td>
<td>42 (3d)</td>
<td>4.46</td>
<td>3.67</td>
<td>0.82</td>
</tr>
<tr>
<td>Set-1-4</td>
<td>14 (1d)</td>
<td>14 (1d)</td>
<td>14</td>
<td>2X2</td>
<td>400</td>
<td>1.5</td>
<td>42 (3d)</td>
<td>4.55</td>
<td>3.67</td>
<td>0.81</td>
</tr>
<tr>
<td>Set-1-5</td>
<td>14 (1d)</td>
<td>14 (1d)</td>
<td>14</td>
<td>2X2</td>
<td>500</td>
<td>1.5</td>
<td>42 (3d)</td>
<td>4.53</td>
<td>3.67</td>
<td>0.81</td>
</tr>
<tr>
<td>Set-1-6</td>
<td>14 (1d)</td>
<td>14 (1d)</td>
<td>14</td>
<td>2X2</td>
<td>600</td>
<td>1.5</td>
<td>42 (3d)</td>
<td>4.55</td>
<td>3.67</td>
<td>0.81</td>
</tr>
<tr>
<td>Set-1-7</td>
<td>14 (1d)</td>
<td>14 (1d)</td>
<td>14</td>
<td>2X2</td>
<td>700</td>
<td>1.5</td>
<td>42 (3d)</td>
<td>4.77</td>
<td>3.67</td>
<td>0.77</td>
</tr>
<tr>
<td>Set-2-1</td>
<td>42 (3d)</td>
<td>14 (1d)</td>
<td>14</td>
<td>2X2</td>
<td>500</td>
<td>1.5</td>
<td>42 (3d)</td>
<td>4.31</td>
<td>3.67</td>
<td>0.85</td>
</tr>
<tr>
<td>Set-2-2</td>
<td>42 (3d)</td>
<td>28 (2d)</td>
<td>14</td>
<td>2X2</td>
<td>500</td>
<td>1.5</td>
<td>42 (3d)</td>
<td>7.32</td>
<td>9.47</td>
<td>1.29</td>
</tr>
<tr>
<td>Set-2-3</td>
<td>42 (3d)</td>
<td>63 (4.5d)</td>
<td>14</td>
<td>2X2</td>
<td>500</td>
<td>1.5</td>
<td>42 (3d)</td>
<td>9.45</td>
<td>10.57</td>
<td>1.22</td>
</tr>
<tr>
<td>Set-3-1</td>
<td>14 (1d)</td>
<td>56 (4d)</td>
<td>14</td>
<td>2X2</td>
<td>300</td>
<td>1.5</td>
<td>42 (3d)</td>
<td>8.48</td>
<td>10.57</td>
<td>1.25</td>
</tr>
<tr>
<td>Set-3-2</td>
<td>21 (1.5d)</td>
<td>56 (4d)</td>
<td>14</td>
<td>2X2</td>
<td>300</td>
<td>1.5</td>
<td>42 (3d)</td>
<td>9.17</td>
<td>10.57</td>
<td>1.15</td>
</tr>
<tr>
<td>Set-3-3</td>
<td>28 (2d)</td>
<td>56 (4d)</td>
<td>14</td>
<td>2X2</td>
<td>300</td>
<td>1.5</td>
<td>42 (3d)</td>
<td>9.81</td>
<td>10.57</td>
<td>1.08</td>
</tr>
<tr>
<td>Set-4-1</td>
<td>21 (1.5d)</td>
<td>56 (4d)</td>
<td>14</td>
<td>2X2</td>
<td>300</td>
<td>1.5</td>
<td>42 (3d)</td>
<td>9.17</td>
<td>10.57</td>
<td>1.15</td>
</tr>
<tr>
<td>Set-4-2</td>
<td>21 (1.5)</td>
<td>56 (4d)</td>
<td>14</td>
<td>2X2</td>
<td>300</td>
<td>3</td>
<td>42 (3d)</td>
<td>8.79</td>
<td>10.57</td>
<td>1.20</td>
</tr>
<tr>
<td>Set-5-1</td>
<td>10 (1d)</td>
<td>40 (4d)</td>
<td>10</td>
<td>2X2</td>
<td>300</td>
<td>1.5</td>
<td>42 (3d)</td>
<td>5.49</td>
<td>6.25</td>
<td>1.14</td>
</tr>
<tr>
<td>Set-5-2</td>
<td>20 (1d)</td>
<td>80 (4d)</td>
<td>20</td>
<td>2X2</td>
<td>300</td>
<td>1.5</td>
<td>42 (3d)</td>
<td>12.66</td>
<td>12.53</td>
<td>0.99</td>
</tr>
<tr>
<td>Set-6-1</td>
<td>14 (1d)</td>
<td>14 (1d)</td>
<td>14</td>
<td>2X3</td>
<td>300</td>
<td>1.5</td>
<td>84 (6d)</td>
<td>4.80</td>
<td>3.67</td>
<td>0.76</td>
</tr>
<tr>
<td>Set-6-2</td>
<td>14 (1d)</td>
<td>28 (2d)</td>
<td>14</td>
<td>2X3</td>
<td>300</td>
<td>1.5</td>
<td>84 (6d)</td>
<td>8.16</td>
<td>8.84</td>
<td>1.08</td>
</tr>
<tr>
<td>Set-6-3</td>
<td>14 (1d)</td>
<td>42 (3d)</td>
<td>14</td>
<td>2X3</td>
<td>300</td>
<td>1.5</td>
<td>84 (6d)</td>
<td>9.10</td>
<td>9.72</td>
<td>1.07</td>
</tr>
<tr>
<td>Set-6-4</td>
<td>14 (1d)</td>
<td>56 (4d)</td>
<td>14</td>
<td>2X3</td>
<td>300</td>
<td>1.5</td>
<td>84 (6d)</td>
<td>10.49</td>
<td>10.57</td>
<td>1.01</td>
</tr>
<tr>
<td>Set-7-1</td>
<td>20 (2d)</td>
<td>40 (4d)</td>
<td>10</td>
<td>2X2</td>
<td>500</td>
<td>1.5</td>
<td>42 (3d)</td>
<td>5.78</td>
<td>6.25</td>
<td>1.08</td>
</tr>
<tr>
<td>Set-7-2</td>
<td>40 (2d)</td>
<td>80 (4d)</td>
<td>20</td>
<td>2X2</td>
<td>500</td>
<td>1.5</td>
<td>42 (3d)</td>
<td>12.23</td>
<td>12.53</td>
<td>1.02</td>
</tr>
<tr>
<td>Set-8-1</td>
<td>28 (2d)</td>
<td>56 (4d)</td>
<td>14</td>
<td>2X2</td>
<td>300</td>
<td>1.5</td>
<td>42 (3d)</td>
<td>8.89</td>
<td>10.02</td>
<td>1.13</td>
</tr>
<tr>
<td>Set-8-2</td>
<td>28 (2d)</td>
<td>56 (4d)</td>
<td>14</td>
<td>2X2</td>
<td>300</td>
<td>1.5</td>
<td>42 (3d)</td>
<td>9.81</td>
<td>10.57</td>
<td>1.08</td>
</tr>
</tbody>
</table>

D1: Displacement from ABAQUS simulation  
D2: Displacement from calculation
Table 6.10 and Figure 6.30 compare the simulated and calculated plate displacements. From it can be seen that when end distance is small (1d), the displacement from calculation tends to be smaller than simulated result. When end distance is bigger than 1d, the proposed method tends to overestimate the displacement of the structure. The average difference between these results is 14% with a standard deviation of 16%. Considering the complexity of plate in shear under elevated temperatures, this level of accuracy is considered acceptable for design purpose.

6.4 Comparison between analytical and simulated load-displacement curves

After the 3 critical quantities in Figure 6.22 have been determined, the load-displacement curve of the plate in bearing can be established. Figure 6.31 shows the
generic simplified load-displacement curve. Figure 6.32-Figure 6.40 compare the analytical load-displacement curves with the FE simulation results for all the 8 sets of parametrical study cases. In Figure 6.31, $F_u$ is the ultimate strength of the connection, calculated according to section 6.3.3. $F_p$ is obtained by replacing the maximum stress of steel 1/2 of the maximum stress of steel.

Figure 6.31 Proposed load-displacement curve for plate in bearing
Figure 6.32 Comparison of predicted and simulated load-displacements for set-1-1 to set-1-3

Figure 6.33 Comparison of predicted and simulated load-displacements for set-1-4 to set-1-7
Figure 6.34 Comparison of predicted and simulated load-displacements for set-2 models

Figure 6.35 Comparison of predicted and simulated load-displacements for set-3 models
Figure 6.36 Comparison of predicted and simulated load-displacements for set-4 models

Figure 6.37 Comparison of predicted and simulated load-displacements for set-5 models
Figure 6.38 Comparison of predicted and simulated load-displacements for set-6 models

Figure 6.39 Comparison of predicted and simulated load-displacements for set-7 models
Figure 6.40 Comparison of predicted and simulated load-displacements for set-8 models

From the figures shown above, it can be seen that the proposed load-displacement curves give very good prediction compared to the simulation results; the 3 major factors, initial stiffness, ultimate load and displacement at ultimate load are well predicted.

6.5 Summary

This chapter has assessed application of the proposed analytical load-displacement curve for ambient temperature to elevated temperature conditions. From the results of this chapter, the following conclusions can be drawn:

- The simple bolt model in this research is not suitable for simulating the bearing behaviour of friction grip bolts. However, the ABAQUS model of this research is sufficiently accurate for simulating the bearing behaviour of thin-walled plates. In addition, the simple bolt model of this research is able to simulate bolt failure.

- The ambient temperature method to predict the bearing plate load-deformation behaviour can be directly applied to elevated temperatures, provided the ambient temperature material mechanical properties are replaced those at elevated temperatures.

- The averages and standard deviations for the differences between the calculated and numerical simulation results for the three key load-deformation values (initial stiffness, load carrying capacity and plate displacement at the ultimate strength) are 4% and 10%, 7% and 8%, and 14% and 16% respectively. This level of accuracy is considered acceptable.

- The proposed simplified load-displacement curve gives close agreement with the simulation load-displacement curves.
CHAPTER 7. CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

7.1 Summary of completed work

Although many research studies have been carried out on bearing behaviour of bolted plate in shear, there are a few gap areas left untouched.

- Most researches only consider the behaviour of single bolted plate in shear. There is very little information for multiple bolted plates.
- Most researches focus on predicting failure modes, plate strength and initial stiffness, the ductility of the plate has received little investigation.
- Most researches focus on ambient temperature behaviour instead of elevated temperature behaviour.
- Most researches are for hot-rolled structures, very few researches are concerned with cold-formed thin-walled structures.

This research has filled the above-mentioned gaps. This research has made the following investigations:

- To obtain necessary experimental information, a series of single bolted plate in bearing tests have been conducted.
- By using the commercial finite element modelling software ABAQUS, a 3D FE model for bearing behaviour of plate in shear has established. The ABAQUS model was verified by comparing the simulation results with obtained test results.
- A parametric study for bearing behaviour of single bolted plate in shear at ambient temperature has been carried using the verified ABAQUS model. After the parametric study, an analytical model has been proposed to predict bearing behaviour of single bolted plate in shear at ambient temperature. Calculation methods for the three major factors, initial stiffness, strength and deformation at maximum load position have been explained.
• After the single bolted plate study, a parametric study for bearing behaviour of multiple bolted plates in shear at ambient temperature has been carried out using the verified ABAQUS model. An analytical model has been proposed to predict bearing behaviour of multiple bolted plates in shear at ambient temperature. Calculation methods for the three major factors, initial stiffness, strength and deformation at maximum load position have been explained.

7.2 Conclusions

Based on the completed work, the following conclusions can be drawn:

• The conducted single bolted plates in shear tests have successfully identified different failure modes. Three different failure modes were found: net-section fracture, end pull-out and bearing failure. These three failure modes may change due to different combinations of the following parameters: end distance, edge distance and bolt-hole diameter.

• The FE model using the commercial package ABAQUS is sufficiently accurate in predicting the bearing behaviour of thin-walled bolted plate. Although the FE model in Chapter 6 failed to deliver accurate prediction for the bearing behaviour of friction grip bolt in shear, the bearing behaviour of the plates was accurately simulated. Bolt failure was also predicted.

• It is found that the Eurocode 3 and the Australian/New Zealand design standards can be used to predict initial stiffness and ultimate strength of the bearing behaviour of thin-walled bolted plate in shear at both ambient and elevated temperatures. However, in some circumstances the predicted initial stiffness consistently overestimates test and FE simulation results. It is recommended that a constant multiplication factor is applied to the design equation. In general, the predicted ultimate strength is slightly smaller than the results obtained from test and simulation. The design equations are acceptable.
• The displacement caused by the bearing behaviour of thin-walled bolted plate in shear can be predicted using the proposed method in this thesis. The displacement consists of 2 parts: part 1 for calculating the bolt-hole elongation based on piecewise linear distribution of circumferential strains around the bolt-hole; part 2 for calculating the compressive pile-up in front of the bolt.

• Table 7.1 and Table 7.2 summarize the proposed calculation methods for the three major factors of initial stiffness, maximum load and displacement at the maximum load for single bolt and multiple bolts respectively.

• The above method can also be used for elevated temperatures, provided the ambient temperature properties of steel are replaced by the elevated temperature properties.

Table 7.1 Proposed calculation method for single bolted plate in bearing behaviour

<table>
<thead>
<tr>
<th>Initial stiffness</th>
<th>$k = 24n_uk_kb_df_u$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum load</td>
<td>Net-section failure:</td>
</tr>
<tr>
<td></td>
<td>$F = (2e_2 - d) \cdot t \cdot f_u$</td>
</tr>
<tr>
<td></td>
<td>End pull-out failure:</td>
</tr>
<tr>
<td></td>
<td>$F = t \cdot e_1 \cdot f_u$</td>
</tr>
<tr>
<td></td>
<td>Bearing failure:</td>
</tr>
<tr>
<td></td>
<td>$F = 2.5d \cdot t \cdot f_u$</td>
</tr>
<tr>
<td>Displacement at</td>
<td>1. Calculate circumferential strains at the critical points, decide circumferential strain distribution around the bolt-hole edge. The strain distributions are presented in Figure 7.1-Figure 7.3. For transition from one failure mode to another, the strain distributions are presented in Figure 7.4-Figure 7.6.</td>
</tr>
<tr>
<td>maximum load</td>
<td>2. Calculate circumferential displacement $D_T$ according to the circumferential strain distributions above.</td>
</tr>
<tr>
<td></td>
<td>3. Calculate compressive strain at bolt plate contact point. The compressive strain distribution is shown in Figure 7.7.</td>
</tr>
</tbody>
</table>
Calculate compressive pill-up displacement $D_C$.
4. The total displacement is $D = D_I + D_C$

Figure 7.1 Assumed circumferential strain distribution for net-section failure

Figure 7.2 Assumed circumferential strain distribution for end pull-out failure
Figure 7.3 Assumed circumferential strain distribution for bearing failure

Figure 7.4 Strains at different critical points during transition from net section failure to end pull-out failure
Figure 7.5 Strain values at different critical points during transition from net-section to bearing failure

Figure 7.6 Assumed strain values at different critical points for transition from end pull-out to bearing failure
CONCLUSION

Figure 7.7 Compressive strain distribution along plate length

Table 7.2 Proposed calculation method for multiple bolted plate in bearing behaviour

<table>
<thead>
<tr>
<th>Displacement at maximum load</th>
<th>Initial stiffness</th>
<th>Maximum load</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Calculate circumferential strains at the critical points; decide circumferential strain distributions around the bolt-hole edge. The strain distributions are presented in Figure 7.1-Figure 7.3. For transition from one failure mode to another, the strain distributions are presented in Figure 7.8-Figure 7.9. 2. Calculate circumferential displacement $D_T$ according to the circumferential strain distribution. 3. Calculate compressive strain at bolt plate contact point, The compressive strain distribution is shown in Figure 7.7. Calculate compressive pill-up displacement $D_C$. 4. The total displacement is $D=D_T+D_C$</td>
<td>$k = mk_{row} = 24mn_bk_tdf_u$</td>
<td>Net-section failure: $F_t = A_n \cdot f_u = (w - md) \cdot t \cdot f_u$</td>
</tr>
<tr>
<td>End pull-out failure: $F_s = m \cdot t \cdot e_1 \cdot f_u + 2.5m(n - 1) \cdot d \cdot t \cdot f_u$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bearing failure: $F_{b,Rd} = 2.5m \cdot n \cdot d \cdot t \cdot f_u$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 7.8 Assumed strain values for plate with multiple bolt-holes in both horizontal & vertical directions, n≥3.
7.3 Recommendations for future study

The following further research studies may be carried out to improve knowledge in this area:

- Further experimental research studies should be carried out at elevated temperatures.

- As mentioned in the Introduction chapter, in this research, the local buckling effect was ignored by restraining the deformation of the plates in the thickness direction. This is similar to the fin plate in fin plate connections or the beam web behaviour in double web cleat connections. However, there are
situations where there is no restraint to the thin plates in bearing (for example beam web in fin plate connections) Experimental study and finite element investigations should be further carried out to investigate the effects local buckling effect on plate bearing behaviour.

- For friction grip bolts, a better bolt model should be implemented so that bolt slip can be simulated.

- The proposed plate bearing load-displacement model should be incorporated into thin-walled joints to investigate the behaviour of different types of complete joint.
CALCULATION EXAMPLE FOR SINGLE BOLTED PLATE IN SHEAR DISPLACEMENT

End distance: \( e_1 = 1.25d \), Edge distance: \( e_2 = 1d \), bolt hole diameter \( d = 14\text{mm} \)

Plate thickness: 1.5mm, ultimate tensile stress of steel = 320 N/mm\(^2\), Poisson’s ratio = 0.3, ultimate tensile strain of steel = 0.35.

1. **Circumferential strains**

End pull-out load: \( t \cdot e_1 \cdot f_u = 1.5 \times (1.25 \times 14) \times 320 = 8.4\text{kn} \)

Net-section load: \( t \cdot (2e_2 - d) \cdot f_u = 1.5 \times (2 - 1) \times 14 \times 320 = 6.7\text{kn} \)

Bearing failure load: \( 2.5d \cdot t \cdot f_u = 2.5 \times 14 \times 1.5 \times 320 = 16.8\text{kn} \)

Therefore, the failure mode is net section failure.

Furthermore, since \( (e_1 + 0.5d)/2 < e_2 < (e_1 + d)/2 \), i.e. \( 0.875d < e_2 < 1.125d \), the failure mode is net-section/end pull-out transition.

For pure end pull-out failure mode (when \( e_2 = 1.125d \)):

The circumferential strains are:

\( \varepsilon_{AO} = 0.35, \varepsilon_{BO} = 0.65, \varepsilon_{CO} = 0 \)

For pure net-section failure mode (when \( e_2 = 0.875d \)):
The circumferential strains are:

\[ \varepsilon_{AO} = 0, \varepsilon_{BO} = 0, \varepsilon_{CO} = 0.35 \]

Interpolation for the circumferential strains at \( e_2=1d \):

\[ \varepsilon_C = 0.35 - \frac{0.35 - 0}{1.125d - 0.875d} \times (1d - 0.875d) = 0.18 \]

\[ \varepsilon_B = 0 + \frac{0.65 - 0}{1.125d - 0.875d} \times (1d - 0.875d) = 0.33 \]

\[ \varepsilon_A = 0 + \frac{0.35 - 0}{1.125d - 0.875d} \times (1d - 0.875d) = 0.18 \]

Figure APX-1 shows the circumferential strain distribution around the bolt hole.

Figure APX-1 Circumferential strain distribution around bolt hole

The total bolt-hole elongation due to circumferential strain can be calculated as:
2. Compressive strain

Since the failure mode is net-section, two linear interpolations are necessary.

First, calculate the maximum compressive strain.

At \( e_1 = 1.2d \), the maximum compressive strain is:

\[
\varepsilon_{AC} = 0.35
\]

At \( e_1 = 2d \), maximum compressive strain is:

\[
\varepsilon_{AC} = 1.0
\]

Therefore, maximum compressive strain at \( e_1 = 1.25d \) is:

\[
\varepsilon_{AC} = 0.35 + \frac{1 - 0.35}{2d - 1.2d} \cdot (1.25d - 1.2d) = 0.39
\]

Second, find the multiplication factor for edge distance \( e_2 \):

The lower bound is defined by:

\[
e_2 = 0.75d \quad , \quad \varepsilon_{AC} = 0
\]

The upper bound is defined by:

\[
e_2 = (1.25d + d)/2 = 1.125d \quad , \quad \varepsilon_{AC} = 0.39
\]

Interpolation for \( e_2 = 1d \):
$\varepsilon_{AC} = 0 + \frac{0.39}{1.125d - 0.75d} \cdot (1d - 0.75d) = 0.26$

Figure APX-2 shows the compressive strain distribution along the plate length in front of the bolt.

The plate pile up due to compressive strain is:

$$D_c = \varepsilon_{AC} \cdot \frac{1}{2} \cdot (1.25d - 0.5d) = 0.26 \times \frac{1}{2} \times 0.75 \times 14 = 1.37mm$$

The total bolt hole elongation is

$$D = D_r + D_c = 3.80 + 1.37 = 5.17mm$$
APPENDIX B. CALCULATION EXAMPLE FOR MULTIPLE BOLTED PLATE IN SHEAR

End distance: $e_1=1d$, Edge distance: $e_2=1d$, bolt hole diameter $d=14\text{mm}$, bolt-hole number 6 ($m=2$, $n=3$), spacing $p_1=6d$, $p_2=6d$

Plate thickness: $1.5\text{mm}$, ultimate tensile stress of steel = $320 \text{N/mm}^2$, Poisson’s ratio = 0.3, ultimate tensile strain of steel = 0.35.

![Figure APX-3 Plate with 6 bolt-holes](image)

1. Calculation of initial stiffness

Using the initial stiffness formula provided by Eurocode 3 to calculate a single bolt row in loading direction:

$$k_1 = 24n_bk_i d f_u$$

$$n_b = 3$$

$$k_b = \min[(0.25 \cdot 1 \cdot d / d + 0.5), (0.25 \cdot 6 \cdot d / d + 0.375), 1.25] = 0.75$$
APPENDIX B

\[ k_i = \min[1.5 \cdot \frac{t_f}{d_{\text{M16}}}, 2.5] = 0.14 \]

\[ k_1 = 24 \times 3 \times 0.75 \times 0.14 \times 12 \times 320 = 29030.4 \]

There are 2 bolt rows perpendicular to the loading direction, therefore the initial stiffness is:

\[ K = 2k_1 = 2 \times 29030.4 = 58060.8 (N/mm) \]

(Abaqus simulation result = 56201 N/mm)

2. Calculation of maximum load bearing capacity

Since the bolt number is more than 2 in the loading direction, end pull-out failure will not happen.

Net-section failure load is:

\[ F_i = A_u \cdot f_u = (2e_2 + p_2 - 2d) \cdot t \cdot f_u = 2 \times 14 + 6 \times 14 - 2 \times 14) \times 1.5 \times 320 = 40.32 (KN) \]

Bearing failure load is:

\[ F_b = 2F_i + 2F_2 + 2F_3 = 2t \cdot e_1 \cdot f_u + 2 \cdot 2.5 \cdot d \cdot t \cdot f_u + 2 \cdot 2.5 \cdot d \cdot t \cdot f_u \]

\[ = 2 \times 1.5 \times 14 \times 320 + 2 \times 2.5 \times 14 \times 1.5 \times 320 + 2 \times 2.5 \times 14 \times 1.5 \times 320 = 80.6 (KN) \]

\[ F_i < F_b \], therefore it is net-section failure. The failure load is 40.32 KN.

(Abaqus simulation result = 41.48 KN)
3. Calculation of displacement at maximum load

For circumferential strain, the lower bound of edge distance is $e_{2l} = ld$. The upper bound of edge distance is

$$e_{2u} = (2.5n - 1.5)d + e_1 - p_2 / 2 = (2.5 \times 3 - 1.5)d + d - 3d = 4d$$

$e_2 = e_{2l}$, therefore it is net-section/bearing in transition.

![Figure APX-4 Critical points on inner bolt-hole](image)

- Circumferential strains

For pure net-section failure mode:

The circumferential strains are:

$$\varepsilon_{AO} = 0, \varepsilon_{BO} = 0, \varepsilon_{CO} = 0.35$$

Figure APX-5 shows the circumferential strain distribution around the bolt hole.

The total bolt-hole elongation due to circumferential strain can be calculated as:

$$D_T = \frac{1}{2} \cdot 2 \cdot \frac{\pi R}{4} \cdot \varepsilon_{CO} = 3.14 \times 7 \times 4 \times 0.35 = 1.92 (mm)$$
**Compressive strain**

For compressive strain, at the lower bound of edge distance 0.75d, the compressive strain is 0. At upper bound of edge distance $e_{2u} = \min(4d, 1.75d) = 1.75d$, the compressive strain is 1.0.

Since $e_{2l} < e_2 < e_{2u}$, the compression strain is obtained by interpolation:

$$
\varepsilon_c = \frac{1}{1.75d - 0.75d} \cdot 0.25d = 0.25
$$

Figure APX-6 shows the compressive strain distribution along the plate length in front of the bolt.

Therefore, the compressive displacement is:

$$
D_c = \frac{1}{2} \cdot d \cdot \varepsilon_c = 0.5 \times 14 \times 0.25 = 1.75 (mm)
$$

The total displacement of the plate is:
APPENDIX B

\[ D = D_l + D_c = 1.92 + 1.75 = 3.67 \text{ (mm)} \]

(ABAQUS simulation result = 4.56mm)

Figure APX-6 Compressive strain distribution
APPENDIX C. STRESS-STRAIN CURVES OF THE TENSILE COUPON TESTS

Figure APX-7 Stress-strain curve for test S1

Figure APX-8 Stress-strain curve for test S2
Figure APX 9 Stress-strain curve for test S3

Figure APX 10 Stress-strain curve for test S4
Figure APX 11 Stress-strain curve for test S5

Figure APX 12 Stress-strain curve for test S6
PUBLICATIONS


He, Y.C. and Y.C. Wang, *Load-deflection behaviour of thin-walled plates with multiple bolts in shearing*, Thin-Walled Structures, accepted
1. Spyrou, S., Development of a component-based model of steel beam-to-column joints at elevated temperatures, 2002, University of Sheffield.
8. Block, F.M., Development of a Component-Based Finite Element for Steel Beam-to-Column Connections at Elevated Temperatures, 2006, University of Sheffield.
17. AS/NZS, Cold-formed steel structures—AS/NZS 46001996, Sydney, NSW, Australia.