**Michigan
Technological
University**

Michigan Technological University
Digital Commons @ Michigan Tech

Dissertations, Master's Theses and Master's Reports

2016

A NOCSAE DROP TEST/ 3D-FEM STUDY ON THE RELATIONSHIP BETWEEN KINEMATIC RESPONSE OF THE HEAD, HEAD IMPACT CONTACT PRESSURE (HICP) AND KINETIC RESPONSE OF THE BRAIN TO DELINEATE THE RISK OF TRAUMATIC BRAIN INJURIES (TBI).

Raghavendra Krishna Tej Bhamidipati
Michigan Technological University, rbhamidi@mtu.edu

Copyright 2016 Raghavendra Krishna Tej Bhamidipati

Recommended Citation

Bhamidipati, Raghavendra Krishna Tej, "A NOCSAE DROP TEST/ 3D-FEM STUDY ON THE RELATIONSHIP BETWEEN KINEMATIC RESPONSE OF THE HEAD, HEAD IMPACT CONTACT PRESSURE (HICP) AND KINETIC RESPONSE OF THE BRAIN TO DELINEATE THE RISK OF TRAUMATIC BRAIN INJURIES (TBI).", Open Access Master's Thesis, Michigan Technological University, 2016.
<https://doi.org/10.37099/mtu.dc.etdr/73>

Follow this and additional works at: <https://digitalcommons.mtu.edu/etdr>

Part of the [Biomechanical Engineering Commons](#), and the [Computer-Aided Engineering and Design Commons](#)

A NOCSAE DROP TEST/ 3D-FEM STUDY ON THE RELATIONSHIP BETWEEN
KINEMATIC RESPONSE OF THE HEAD, HEAD IMPACT CONTACT PRESSURE
(HICP) AND KINETIC RESPONSE OF THE BRAIN TO DELINEATE THE RISK OF
TRAUMATIC BRAIN INJURIES (TBI).

By

Raghavendra Krishna Tej Bhamidipati

A THESIS

Submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

In Mechanical Engineering

MICHIGAN TECHNOLOGICAL UNIVERSITY

2016

© 2016 Raghavendra KrishnaTej Bhamidipati

This thesis has been approved in partial fulfillment of the requirements for the Degree of
MASTER OF SCIENCE in Mechanical Engineering

Department of Mechanical Engineering – Engineering Mechanics

Thesis Advisor: *Dr. Gopal Jayaraman*

Committee Member: *Dr. V.C. Rao Komaravolu*

Committee Member: *Dr. Ibrahim Miskioglu*

Committee Member: *Dr. Allan A. Struthers*

Department Chair: *Dr. William Predebon*

People say that God can't be everywhere,

So

He created "Mother"

To

My Mother

Table of Contents

List of Figures.....	x
List of Tables	xxiv
Abbreviations Used	xxvi
Acknowledgements	xxvii
Abstract.....	xxviii
Chapter 1 INTRODUCTION	1
1.1 Introduction.....	1
1.2 Demography of Head Injuries.....	3
1.3 Wayne State Tolerance Curve:	4
1.4 Objective & Strategy.....	5
Chapter 2 BRAIN INJURIES.....	7
2.1 Focal Injuries	7
2.1.1 Contusion	8
2.1.2 Epidural Hematoma	8
2.1.3 Subdural Hematoma.....	8
2.2 Diffuse Injuries	8
2.2.1 Concussion.....	8
2.2.2 Diffuse Axonal Injury	9
Chapter 3 EXPERIMENTS, RESULTS & DISCUSSIONS.....	10
3.1 Experimental Procedure:.....	10
3.2 NOCSAE Drop Tests:.....	10

3.2.1 Setup:	10
3.2.2 Head Linear Acceleration Curve	11
3.2.2.1 Frontal	13
3.2.2.2 45° to Frontal:	15
3.2.2.3 Lateral:	16
3.2.2.4 Posterior	17
3.2.3 Measurement of Area of Impact	20
3.2.4 Calculation of Impact Force and HICP.....	22
3.2.5 Discussion	24
3.3 Pressure Film and Topaq Analyzer	25
3.3.1 Pressure Films	25
3.3.2 Selection of Pressure Films.....	26
3.3.3 Topaq Analyzer.....	26
3.3.4 Setup	27
3.3.5 Results.....	27
3.3.6 Discussions	27
3.4 Comparison of Results and Discussions	29
3.4.1 Comparison of HICP between Pressure films and Accelerometers.....	29
3.4.2 HICP Plots	32
3.4.2.1 Drop Height Vs. Maximum Linear Acceleration	32
3.4.2.2 Drop Heights Vs. Maximum HICP	33
3.4.2.3 Drop Height Vs. Maximum HICP Vs Maximum Linear Acceleration	34

Chapter 4 HICP VS STRESS DISTRIBUTION IN BRAIN BY FINITE

ELEMENT ANALYSIS	36
4.1 Introduction.....	36
4.2 FE model of Human Head	36
4.2.1 Material Properties.....	37
4.3 HICP Input Curves.....	39
4.4 Boundary Conditions	41
4.5 Output Settings and Time step.....	43
4.6 Results & Discussions.....	43
4.6.1 Frontal.....	44
4.6.1.1 Drop Height of 2 feet	44
4.6.1.2 Drop Height of 3 feet	46
4.6.1.3 Drop Height of 4 feet	48
4.6.1.4 Drop Height of 5 feet	50
4.6.1.5 Discussion	54
4.6.2 45° to Frontal.....	57
4.6.2.1 Drop Height of 2 feet	57
4.6.2.2 Drop Height of 3 feet	59
4.6.2.3 Drop Height of 4 feet	60
4.6.2.4 Drop Height of 5 feet	62
4.6.2.5 Discussion	64
4.6.3 Lateral	67
4.6.3.1 Drop Height of 2 feet	67

4.6.3.2 Drop Height of 3 feet	70
4.6.3.3 Drop Height of 4 feet	72
4.6.3.4 Drop Height of 5 feet	74
4.6.2.5 Discussion	77
4.6.4 Posterior	80
4.6.4.1 Drop height of 2 feet	80
4.6.3.2 Drop Height of 3 feet	82
4.6.4.3 Drop Height of 4 feet	84
4.6.3.4 Drop Height of 5 feet	86
4.6.4.5 Discussion	88
4.6.5 Overall Results Discussion	91
 Chapter 5 CORRELATION BETWEEN HEAD ACCELERATION AND BRAIN	
STRESS DISTRIBUTIONS.....	94
5.1 Introduction.....	94
5.2 Determination of TBI Tolerance drop height using Maximum Shear stress	94
5.3 Determination of TBI Tolerance drop height using Linear Accelerations	98
5.4 TBI Criteria.....	99
5.4.1 Frontal region of Impact	100
5.4.2 45° to Frontal region of impact	102
5.4.3 Lateral region of impact.....	104
5.4.4 Posterior region of impact.....	106
5.5 Formula Proposition.....	110
 Chapter 6 CONCLUSIONS AND RECOMMENDATIONS	113

6.1 Conclusions	113
6.2 Recommendations	116
Appendix A	118
A1 Frontal	118
A1.1 Pressure film deformations	118
A1.2 Topaq analyzer Outputs	119
A2 45° to Frontal	120
A2.1 Pressure film deformations	120
A2.2 Topaq analyzer Outputs	121
A3 Lateral	122
A3.1 Pressure film deformations	122
A3.2 Topaq analyzer Outputs	123
A4 Posterior	124
A4.1 Pressure film deformations	124
A4.2 Topaq analyzer Outputs	125
Appendix B	127
B1 Frontal	127
B1.1 Drop Height of 2 feet	127
B1.2 Drop Height of 3 feet	128
B1.3 Drop Height of 4 feet	129
B1.4 Drop Height of 5 feet	130
B2 45° to Frontal	131
B2.1 Drop Height of 2 feet	131

B2.2 Drop Height of 3 feet	132
B2.3 Drop Height of 4 feet	133
B2.4 Drop Height of 5 feet	134
B3 Lateral.....	135
B3.1 Drop Height of 2 feet	135
B3.2 Drop Height of 3 feet	136
B3.3 Drop Height of 4 feet	137
B3.4 Drop Height of 5 feet	139
B4 Posterior	140
B4.1 Drop Height of 2 feet	140
B4.2 Drop Height of 3 feet	141
B4.3 Drop Height of 4 feet	142
B4.4 Drop Height of 5 feet	143
Appendix C	144
Appendix D	155
References	158

List of Figures

Figure 1.1 Wayne State Tolerance Curve	5
Figure 3.1 NOCSAE Drop Test Instrumentation at Michigan Tech	11
Figure 3.2 Linear Acceleration Plot obtained from the Siglab Unit	12
Figure 3.3 Headform with its X,Y,Z Axes.....	13
Figure 3.4 Linear Acceleration curve for Frontal 2 feet drop.....	13
Figure 3.5 Linear Acceleration curve for Frontal 3 feet drop.....	14
Figure 3.6 Linear Acceleration curve for Frontal 4 feet drop.....	14
Figure 3.7 Linear Acceleration curve for Frontal 5 feet drop.....	14
Figure 3.8 Linear Acceleration curve for 45° to Frontal 2 feet drop	15
Figure 3.9 Linear Acceleration curve for 45° to Frontal 3 feet drop	15
Figure 3.10 Linear Acceleration curve for 45° to Frontal 4 feet drop	15
Figure 3.11 Linear Acceleration curve for 45° to Frontal 5 feet drop	16
Figure 3.12 Linear Acceleration curve for Lateral 2 feet drop	16
Figure 3.13 Linear Acceleration curve for Lateral 3 feet drop	16
Figure 3.14 Linear Acceleration curve for Lateral 4 feet drop	17
Figure 3.15 Linear Acceleration curve for Lateral 5 feet drop	17
Figure 3.16 Linear Acceleration curve for Posterior 2 feet drop.....	17
Figure 3.17 Linear Acceleration curve for Posterior 3 feet drop.....	18
Figure 3.18 Linear Acceleration curve for Posterior 4 feet drop.....	18
Figure 3.19 Linear Acceleration curve for Posterior 5 feet drop.....	18
Figure 3.20 Head form with chalk applied for Area measurement.....	20
Figure 3.21 Projected Area of Impact on the Anvil.....	21
Figure 3.22 Explanation of working of a Pressure Film and C.S View of a Film.....	25
Figure 3.23 Maximum Linear Acceleration Vs Drop Height	32
Figure 3.24 HICP Vs Drop Height	33
Figure 3.25 Plot of Drop height Vs HICP Vs Linear Acceleration for Frontal region of Impact	34

Figure 3.26 Plot of Drop height Vs HICP Vs Linear Acceleration for 45 to Frontal region of Impact	34
Figure 3.27 Plot of Drop Height Vs HICP Vs Linear Acceleration for Lateral region of Impact	35
Figure 3.28 Plot of Drop Height Vs HICP Vs Linear Acceleration for Lateral region of Impact	35
Figure 4.1 Meshed 3D form Model with Impact Areas Marked on it	37
Figure 4.2 FE Model for Frontal Impact.....	38
Figure 4.3 FE Model for 45 to Frontal Impact.....	38
Figure 4.4 FE Model for Lateral Impact.....	39
Figure 4.5 FE Model for Posterior Impact.....	39
Figure 4.6 Impact Pressure Curves for Impact in Frontal Region	40
Figure 4.7 Impact Pressure Curves for Impact in 45 to Frontal Region	40
Figure 4.8 Impact Pressure Curves for Impact in Lateral Region	41
Figure 4.9 Impact Pressure Curves for Impact in Posterior Region	41
Figure 4.10 Unit Spring elements connecting skull to the Ground point	42
Figure 4.11 von Mises stress Frontal 2 feet	44
Figure 4.12 Normal stress Sx Frontal 2 feet	44
Figure 4.13 Normal stress Sy Frontal 2 feet	44
Figure 4.14 Normal stress Sz Frontal 2 feet	44
Figure 4.15 Normal stress Sx Frontal 2 feet	44
Figure 4.16 Normal stress Sy Frontal 2 feet	44
Figure 4.17 Shear stress Sxy Frontal 2 feet	55
Figure 4.18 Shear stress Sxy Frontal 2 feet	45
Figure 4.19 Shear stress Syz Frontal 2 feet.....	45
Figure 4.20 Shear stress Syz Frontal 2 feet.....	45
Figure 4.21 Shear stress Syz Frontal 2 feet.....	45
Figure 4.22 Shear stress Sxz Frontal 2 feet.....	45
Figure 4.23 Shear stress Sxz Frontal 2 feet.....	46
Figure 4.24 Shear stress Sxz Frontal 2 feet.....	46

Figure 4.25 Normal stress S_x Frontal 3 feet	46
Figure 4.26 Normal stress S_x Frontal 3 feet	46
Figure 4.27 Normal stress S_y Frontal 3 feet	46
Figure 4.28 Normal stress S_y Frontal 3 feet	46
Figure 4.29 Normal stress S_z Frontal 3 feet	47
Figure 4.30 von Mises stress Frontal 3 feet	47
Figure 4.31 Shear stress S_{xy} Frontal 3 feet	57
Figure 4.32 Shear stress S_{xy} Frontal 3 feet	47
Figure 4.33 Shear stress S_{yz} Frontal 3 feet.....	47
Figure 4.34 Shear stress S_{yz} Frontal 3 feet.....	47
Figure 4.35 Shear stress S_{zx} Frontal 3 feet.....	48
Figure 4.36 Shear stress S_{zx} Frontal 3 feet.....	48
Figure 4.37 von Mises stress Frontal 4 feet	48
Figure 4.38 Normal stress S_x Frontal 4 feet	48
Figure 4.39 Normal stress S_x Frontal 4 feet	48
Figure 4.40 Normal stress S_x Frontal 4 feet	48
Figure 4.41 Normal stress S_y Frontal 4 feet	49
Figure 4.42 Normal stress S_y Frontal 4 feet	49
Figure 4.43 Normal stress S_z Frontal 4 feet	49
Figure 4.44 Shear stress S_{xy} Frontal 4 feet	59
Figure 4.45 Shear stress S_{xy} Frontal 4 feet	49
Figure 4.46 Shear stress S_{xy} Frontal 4 feet	49
Figure 4.47 Shear stress S_{yz} Frontal 4 feet.....	50
Figure 4.48 Shear stress S_{yz} Frontal 4 feet.....	50
Figure 4.49 Shear stress S_{zx} Frontal 4 feet.....	50
Figure 4.50 Shear stress S_{zx} Frontal 4 feet.....	50
Figure 4.51 von Mises stress Frontal 5 feet	50
Figure 4.52 Normal stress S_x Frontal 5 feet	50
Figure 4.53 Normal stress S_x Frontal 5 feet	51
Figure 4.54 Normal stress S_x Frontal 5 feet	51

Figure 4.55 Normal stress S_y Frontal 5 feet	51
Figure 4.56 Normal stress S_y Frontal 5 feet	51
Figure 4.57 Normal stress S_z Frontal 5 feet	51
Figure 4.58 Shear stress S_{xy} Frontal 5 feet	51
Figure 4.59 Shear stress S_{xy} Frontal 5 feet	52
Figure 4.60 Shear stress S_{xy} Frontal 5 feet	52
Figure 4.61 Shear stress S_{xy} Frontal 5 feet	52
Figure 4.62 Shear stress S_{yz} Frontal 5 feet.....	52
Figure 4.63 Shear stress S_{yz} Frontal 5 feet.....	52
Figure 4.64 Shear stress S_{yz} Frontal 5 feet.....	52
Figure 4.65 Shear stress S_{zx} Frontal 5 feet.....	53
Figure 4.66 Shear stress S_{zx} Frontal 5 feet.....	53
Figure 4.67 Comparison of Pressure on brain and HICP during Frontal Impact	55
Figure 4.68 Maximum Principal stress (Tension) and von Mises Stress on brain obtained from FE Simulation of Frontal Impacts	55
Figure 4.69 Stress Variation on brain with respect to drop height during Frontal Impact	56
Figure 4.70 Normal stress S_x 45° to Frontal 2 feet.....	57
Figure 4.71 Normal stress S_x 45° to Frontal 2 feet.....	57
Figure 4.72 Normal stress S_y 45° to Frontal 2 feet.....	57
Figure 4.73 Normal stress S_y 45° to Frontal 2 feet.....	57
Figure 4.74 Normal stress S_z 45° to Frontal 2 feet.....	57
Figure 4.75 von Mises stress 45° to Frontal 2 feet.....	57
Figure 4.76 Shear stress S_{xy} 45° to Frontal 2 feet.....	58
Figure 4.77 Shear stress S_{xy} 45° to Frontal 2 feet.....	58
Figure 4.78 Shear stress S_{yz} 45° to Frontal 2 feet	58
Figure 4.79 Shear stress S_{yz} 45° to Frontal 2 feet.	58
Figure 4.80 Shear stress S_{zx} 45° to Frontal 2 feet	58
Figure 4.81 Shear stress S_{zx} 45° to Frontal 2 feet	58
Figure 4.82 Normal stress S_x 45° to Frontal 3 feet.....	59
Figure 4.83 Normal stress S_x 45° to Frontal 3 feet.....	59

Figure 4.84 Shear stress S_{xy} 45° to Frontal 3 feet	59
Figure 4.85 Shear stress S_{xy} 45° to Frontal 3 feet	59
Figure 4.86 Normal stress S_y 45° to Frontal 3 feet	59
Figure 4.87 von Mises stress 45° to Frontal 3 feet	59
Figure 4.88 Shear stress S_{yz} 45° to Frontal 3 feet	60
Figure 4.89 Normal stress S_z 45° to Frontal 3 feet	60
Figure 4.90 Normal stress S_z 45° to Frontal 3 feet	60
Figure 4.91 Shear stress S_{zx} 45° to Frontal 3 feet	60
Figure 4.92 Normal stress S_x 45° to Frontal 4 feet	60
Figure 4.93 Normal stress S_y 45° to Frontal 4 feet	60
Figure 4.94 Shear stress S_{xy} 45° to Frontal 4 feet	61
Figure 4.95 Shear stress S_{xy} 45° to Frontal 4 feet	61
Figure 4.96 Normal stress S_y 45° to Frontal 4 feet	61
Figure 4.97 Shear stress S_{yz} 45° to Frontal 4 feet	61
Figure 4.98 Shear stress S_{yz} 45° to Frontal 4 feet	61
Figure 4.99 Normal stress S_z 45° to Frontal 4 feet	61
Figure 4.100 Shear stress S_{zx} 45° to Frontal 4 feet	62
Figure 4.101 von Mises stress 45° to Frontal 4 feet	62
Figure 4.102 Normal stress S_x 45° to Frontal 5 feet	62
Figure 4.103 Normal stress S_x 45° to Frontal 5 feet	62
Figure 4.104 Shear stress S_{xy} 45° to Frontal 5 feet	62
Figure 4.105 Shear stress S_{xy} 45° to Frontal 5 feet	62
Figure 4.106 Normal stress S_y 45° to Frontal 5 feet	63
Figure 4.107 Shear stress S_{yz} 45° to Frontal 5 feet	63
Figure 4.108 Shear stress S_{yz} 45° to Frontal 5 feet	63
Figure 4.109 Normal stress S_z 45° to Frontal 5 feet	63
Figure 4.110 Shear stress S_{zx} 45° to Frontal 5 feet	63
Figure 4.111 von Mises stress 45° to Frontal 5 feet	63
Figure 4.112 Comparison of Pressure on brain and HICP during 45° to Frontal Impact ..	65

Figure 4.113 Maximum Principal stress (Tension) and von Mises Stress on brain obtained from FE Simulation of 45° to Frontal Impacts	65
Figure 4.114 Stress Variation on brain with respect to drop height during 45° to Frontal Impact	66
Figure 4.115 von Mises stress Lateral 2 feet	67
Figure 4.116 Normal stress Sx Lateral 2 feet	67
Figure 4.117 Normal stress Sx Lateral 2 feet	67
Figure 4.118 Normal stress Sx Lateral 2 feet	67
Figure 4.119 Normal stress Sy Lateral 2 feet	67
Figure 4.120 Normal stress Sy Lateral 2 feet	67
Figure 4.121 Normal stress Sz Lateral 2 feet.....	68
Figure 4.122 Normal stress Sz Lateral 2 feet.....	68
Figure 4.123 Normal stress Sz Lateral 2 feet.....	68
Figure 4.124 Shear stress Sxy Lateral 2 feet.....	68
Figure 4.125 Shear stress Sxy Lateral 2 feet.....	68
Figure 4.126 Shear stress Sxy Lateral 2 feet.....	68
Figure 4.127 Shear stress Syz Lateral 2 feet.....	69
Figure 4.128 Shear stress Syz Lateral 2 feet.....	69
Figure 4.129 Shear stress Sxz Lateral 2 feet.....	69
Figure 4.130 Shear stress Sxz Lateral 2 feet.....	69
Figure 4.131 Shear stress Sxz Lateral 2 feet.....	69
Figure 4.132 Shear stress Sxz Lateral 2 feet.....	69
Figure 4.133 Normal stress Sx Lateral 3 feet	70
Figure 4.134 Normal stress Sx Lateral 3 feet	70
Figure 4.135 Normal stress Sx Lateral 3 feet	70
Figure 4.136 Normal stress Sy Lateral 3 feet	70
Figure 4.137 Normal stress Sz Lateral 3 feet.....	70
Figure 4.138 Normal stress Sz Lateral 3 feet.....	70
Figure 4.139 Shear stress Sxy Lateral 3 feet.....	71
Figure 4.140 Shear stress Sxy Lateral 3 feet.....	71

Figure 4.141 Shear stress S_{xy} Lateral 3 feet.....	71
Figure 4.142 Shear stress S_{xy} Lateral 3 feet.....	71
Figure 4.143 Shear stress S_{yz} Lateral 3 feet.....	71
Figure 4.144 Shear stress S_{yz} Lateral 3 feet.....	71
Figure 4.145 Shear stress S_{zx} Lateral 3 feet.....	72
Figure 4.146 von Mises stress Lateral 3 feet	72
Figure 4.147 Normal stress S_x Lateral 4 feet	72
Figure 4.148 Normal stress S_x Lateral 4 feet	72
Figure 4.149 Normal stress S_x Lateral 4 feet	72
Figure 4.150 Normal stress S_y Lateral 4 feet	72
Figure 4.151 von Mises stress Lateral 4 feet	73
Figure 4.152 Normal stress S_z Lateral 4 feet.....	73
Figure 4.153 Shear stress S_{xy} Lateral 4 feet.....	73
Figure 4.154 Shear stress S_{xy} Lateral 4 feet.....	73
Figure 4.155 Shear stress S_{yz} Lateral 4 feet.....	73
Figure 4.156 Shear stress S_{yz} Lateral 4 feet.....	73
Figure 4.157 Shear stress S_{zx} Lateral 4 feet.....	74
Figure 4.158 Shear stress S_{zx} Lateral 4 feet.....	74
Figure 4.159 Normal stress S_x Lateral 5 feet	74
Figure 4.160 Normal stress S_x Lateral 5 feet	74
Figure 4.161 Normal stress S_x Lateral 5 feet	74
Figure 4.162 Normal stress S_y Lateral 5 feet	74
Figure 4.163 Normal stress S_y Lateral 5 feet	75
Figure 4.164 Normal stress S_z Lateral 5 feet.....	75
Figure 4.165 Normal stress S_z Lateral 5 feet.....	75
Figure 4.166 Shear stress S_{xy} Lateral 5 feet.....	75
Figure 4.167 Shear stress S_{xy} Lateral 5 feet.....	75
Figure 4.168 Shear stress S_{yz} Lateral 5 feet.....	75
Figure 4.169 Shear stress S_{yz} Lateral 5 feet.....	76
Figure 4.170 Shear stress S_{zx} Lateral 5 feet.....	76

Figure 4.171 Shear stress S_{zx} Lateral 5 feet	76
Figure 4.172 von Mises stress Lateral 5 feet	76
Figure 4.173 Comparison of Pressure on brain and HICP during Lateral Impact.....	78
Figure 4.174 Maximum Principal stress (Tension) and von Mises Stress on brain obtained from FE Simulation of Lateral Impacts	78
Figure 4.175 Stress Variation on brain with respect to drop height during Lateral Impact	79
Figure 4.176 Normal stress S_x Posterior 2 feet	80
Figure 4.177 Normal stress S_x Posterior 2 feet	80
Figure 4.178 von Mises stress Posterior 2 feet	80
Figure 4.179 Normal stress S_y Posterior 2 feet	80
Figure 4.180 Normal stress S_z Posterior 2 feet.....	80
Figure 4.181 Shear stress S_{xy} Posterior 2 feet	80
Figure 4.182 Shear stress S_{xy} Posterior 2 feet	81
Figure 4.183 Shear stress S_{xy} Posterior 2 feet	81
Figure 4.184 Shear stress S_{yz} Posterior 2 feet.....	81
Figure 4.185 Shear stress S_{yz} Posterior 2 feet.....	81
Figure 4.186 Shear stress S_{zx} Posterior 2 feet.....	81
Figure 4.187 Shear stress S_{zx} Posterior 2 feet.....	81
Figure 4.188 Normal stress S_x Posterior 3 feet	82
Figure 4.189 Normal stress S_x Posterior 3 feet	82
Figure 4.190 Normal stress S_y Posterior 3 feet	82
Figure 4.191 Normal stress S_y Posterior 3 feet	82
Figure 4.192 Normal stress S_z Posterior 3 feet.....	82
Figure 4.193 von Mises stress Posterior 3 feet	82
Figure 4.194 Shear stress S_{xy} Posterior 3 feet	83
Figure 4.195 Shear stress S_{xy} Posterior 3 feet	83
Figure 4.196 Shear stress S_{yz} Posterior 3 feet.....	83
Figure 4.197 Shear stress S_{yz} Posterior 3 feet.....	83
Figure 4.198 Shear stress S_{zx} Posterior 3 feet.....	83

Figure 4.199 Shear stress S_{zx} Posterior 3 feet.....	83
Figure 4.200 Normal stress S_x Posterior 4 feet	84
Figure 4.201 Normal stress S_x Posterior 4 feet	84
Figure 4.202 Normal stress S_y Posterior 4 feet	84
Figure 4.203 Normal stress S_y Posterior 4 feet	84
Figure 4.204 Normal stress S_z Posterior 4 feet.....	84
Figure 4.205 Shear stress S_{xy} Posterior 4 feet	84
Figure 4.206 Shear stress S_{xy} Posterior 4 feet	85
Figure 4.207 von Mises stress Posterior 4 feet	85
Figure 4.208 Shear stress S_{yz} Posterior 4 feet.....	85
Figure 4.209 Shear stress S_{zx} Posterior 4 feet.....	85
Figure 4.210 Shear stress S_{zx} Posterior 4 feet.....	85
Figure 4.211 Normal stress S_x Posterior 5 feet	86
Figure 4.212 Normal stress S_x Posterior 5 feet	86
Figure 4.213 Normal stress S_y Posterior 5 feet	86
Figure 4.214 Normal stress S_y Posterior 5 feet	86
Figure 4.215 Normal stress S_z Posterior 5 feet.....	86
Figure 4.216 von Mises stress Posterior 5 feet	86
Figure 4.217 Shear stress S_{xy} Posterior 5 feet	87
Figure 4.218 Shear stress S_{xy} Posterior 5 feet	87
Figure 4.219 Shear stress S_{yz} Posterior 5 feet.....	87
Figure 4.220 Shear stress S_{yz} Posterior 5 feet.....	87
Figure 4.221 Shear stress S_{zx} Posterior 5 feet.....	87
Figure 4.222 Shear stress S_{zx} Posterior 5 feet.....	87
Figure 4.223 Comparison of Pressure on brain and HICP during Posterior Impact.....	89
Figure 4.224 Maximum Principal stress (Tension) and von Mises Stress on brain obtained from FE Simulation of Posterior Impacts	89
Figure 4.225 Stress Variation on brain with respect to drop height during Posterior Impact	90
Figure 4.226 von Mises stress Vs Drop height for different regions of impact.....	91

Figure 4.227 Maximum Principal stress Vs Drop height for different regions of impact	91
Figure 5.1 Maximum Shear Stress Vs Drop Height for the Frontal Region Impact	95
Figure 5.2 Maximum Shear Stress Vs Drop Height for the 45 to Frontal Region Impact	95
Figure 5.3 Maximum Shear Stress Vs Drop Height for the Lateral Region Impact.....	96
Figure 5.4 Maximum Shear Stress Vs Drop Height for the Posterior Region Impact.....	96
Figure 5.5 Linear TBI tolerance for HICP and Pressure on Brain Located on plot of Comparison of Pressure on Brain and HICP during Frontal Impact	100
Figure 5.6 Linear TBI tolerance for Maximum Principal Stress and von Mises stress located on plot of Comparison of Maximum Principal stress and von Mises stress during Frontal Impact	100
Figure 5.7 Plot for Variation of Max. Linear Acceleration & Shear stress Vs height for frontal impact	101
Figure 5.8 Plot for Variation of Max. Linear Acceleration & Normal stress Vs height for frontal impact	101
Figure 5.9 Linear TBI tolerance for HICP and Pressure on Brain Located on plot of Comparison of Pressure on Brain and HICP during 45 to Frontal Impact	102
Figure 5.10 Linear TBI tolerance for Maximum Principal Stress and von Mises stress located on plot of Comparison of Maximum Principal stress and von Mises stress during 45 to Frontal Impact	102
Figure 5.11 Plot for Variation of Max. Linear Acceleration & Shear stress Vs height for 45 to frontal impact.....	103
Figure 5.12 Plot for Variation of Max. Linear Acceleration & Normal stress Vs height for 45 to frontal impact	103
Figure 5.13 Linear TBI tolerance for HICP and Pressure on Brain Located on plot of Comparison of Pressure on Brain and HICP during Lateral Impact	104
Figure 5.14 Linear TBI tolerance for Maximum Principal Stress and von Mises stress located on plot of Comparison of Maximum Principal stress and von Mises stress during Lateral Impact.....	104
Figure 5.15 Plot for Variation of Max. Linear Acceleration & Shear stress Vs height for Lateral impact	105

Figure 5.16 Plot for Variation of Max. Linear Acceleration & Normal stress Vs height for Lateral impact	105
Figure 5.17 Linear TBI tolerance for HICP and Pressure on Brain Located on plot of Comparison of Pressure on Brain and HICP during Frontal Impact	106
Figure 5.18 Linear TBI tolerance for Maximum Principal Stress and von Mises stress located on plot of Comparison of Maximum Principal stress and von Mises stress during Frontal Impact	106
Figure 5.19 Plot for Variation of Max. Linear Acceleration & Shear stress Vs height for frontal impact	107
Figure 5.20 Plot for Variation of Max. Linear Acceleration & Normal stress Vs height for frontal impact	107
Figure A1 Pressure Film Deformation for Frontal 2 feet Impact	118
Figure A2 Pressure Film Deformation for Frontal 3 feet Impact	118
Figure A3 Pressure Film Deformation for Frontal 4 feet Impact	118
Figure A4 Pressure Film Deformation for Frontal 5 feet Impact	118
Figure A5 Topaq Analyzer output for Frontal 2 feet Impact.....	119
Figure A6 Topaq Analyzer output for Frontal 3 feet Impact.....	119
Figure A7 Topaq Analyzer output for Frontal 4 feet Impact.....	119
Figure A8 Topaq Analyzer output for Frontal 5 feet Impact.....	120
Figure A9 Pressure Film Deformation for 45° to Frontal 2 feet Impact.....	120
Figure A10 Pressure Film Deformation for 45° to Frontal 3 feet Impact.....	120
Figure A11 Pressure Film Deformation for 45° to Frontal 4 feet Impact.....	120
Figure A12 Pressure Film Deformation for 45° to Frontal 5 feet Impact.....	120
Figure A13 Topaq Analyzer output for 45° to Frontal 2 feet Impact	121
Figure A14 Topaq Analyzer output for 45° to Frontal 3 feet Impact	121
Figure A15 Topaq Analyzer output for 45° to Frontal 4 feet Impact	121
Figure A16 Topaq Analyzer output for 45° to Frontal 5 feet Impact	122
Figure A17 Pressure Film Deformation for Lateral 2 feet Impact.....	122
Figure A18 Pressure Film Deformation for Lateral 3 feet Impact.....	122

Figure A19 Pressure Film Deformation for Lateral 4 feet Impact.....	122
Figure A20 Pressure Film Deformation for Lateral 5 feet Impact.....	122
Figure A21 Topaq Analyzer output for Lateral 2 feet Impact	123
Figure A22 Topaq Analyzer output for Lateral 3 feet Impact	123
Figure A23 Topaq Analyzer output for Lateral 4 feet Impact	123
Figure A24 Topaq Analyzer output for Lateral 5 feet Impact	124
Figure A25 Pressure Film Deformation for Posterior 2 feet Impact	124
Figure A26 Pressure Film Deformation for Posterior 3 feet Impact	124
Figure A27 Pressure Film Deformation for Posterior 4 feet Impact	124
Figure A28 Pressure Film Deformation for Posterior 5 feet Impact	124
Figure A29 Topaq Analyzer output for Posterior 2 feet Impact	125
Figure A30 Topaq Analyzer output for Posterior 3 feet Impact	125
Figure A31 Topaq Analyzer output for Posterior 4 feet Impact	125
Figure A32 Topaq Analyzer output for Posterior 5 feet Impact	126
Figure B1 Pressure Frontal 2 feet	127
Figure B2 Pressure Frontal 2 feet	127
Figure B3 Mohr Circle for Frontal 2 Impact	127
Figure B4 Pressure Frontal 3 feet	128
Figure B5 Pressure Frontal 3 feet	128
Figure B6 Mohr Circle for Frontal 3 Impact	128
Figure B7 Pressure Frontal 4 feet	129
Figure B8 Pressure Frontal 4 feet	129
Figure B9 Mohr Circle for Frontal 4 Impact	129
Figure B10 Pressure Frontal 5 feet	130
Figure B11 Pressure Frontal 5 feet	130
Figure B12 Mohr Circle for Frontal 5 Impact	130
Figure B13 Pressure 45° to Frontal 2 feet	131
Figure B14 Pressure 45° to Frontal 2 feet	131
Figure B15 Mohr Circle for 45° to Frontal 2 Impact	131
Figure B16 Pressure 45° to Frontal 3 feet	132

Figure B17 Pressure 45° to Frontal 3 feet	132
Figure B18 Mohr Circle for 45° to Frontal 3 Impact	132
Figure B19 Pressure 45° to Frontal 4 feet	133
Figure B20 Pressure 45° to Frontal 4 feet	133
Figure B21 Mohr Circle for 45° to Frontal 4 Impact	133
Figure B22 Pressure 45° to Frontal 5 feet	134
Figure B23 Pressure 45° to Frontal 5 feet	134
Figure B24 Mohr Circle for 45° to Frontal 5 Impact	134
Figure B25 Pressure Lateral 2 feet.....	135
Figure B26 Pressure Lateral 2 feet.....	135
Figure B27 Mohr Circle for Lateral 2 Impact.....	135
Figure B28 Pressure Lateral 3 feet.....	136
Figure B29 Pressure Lateral 3 feet.....	136
Figure B30 Pressure Lateral 3 feet.....	136
Figure B31 Pressure Lateral 3 feet.....	136
Figure B32 Mohr Circle for Lateral 3 Impact.....	137
Figure B33 Pressure Lateral 4 feet.....	137
Figure B34 Pressure Lateral 4 feet.....	137
Figure B35 Pressure Lateral 4 feet.....	138
Figure B36 Pressure Lateral 4 feet.....	138
Figure B37 Mohr Circle for Lateral 4 Impact.....	138
Figure B38 Pressure Lateral 5 feet.....	139
Figure B39 Pressure Lateral 5 feet.....	139
Figure B40 Mohr Circle for Lateral 5 Impact.....	139
Figure B41 Pressure Posterior 2 feet	140
Figure B42 Pressure Posterior 2 feet	140
Figure B43 Mohr Circle for Posterior 2 Impact.....	140
Figure B44 Pressure Posterior 3 feet	141
Figure B45 Pressure Posterior 3 feet	141
Figure B46 Mohr Circle for Posterior 3 Impact.....	141

Figure B47 Pressure Posterior 4 feet	142
Figure B48 Pressure Posterior 4 feet	142
Figure B49 Mohr Circle for Posterior 4 Impact.....	142
Figure B50 Pressure Posterior 5 feet	143
Figure B51 Pressure Posterior 5 feet	143
Figure B52 Mohr Circle for Posterior 5 Impact.....	143
Figure C1 Selecting the User profile in Hyperworks environment	144
Figure C2 Importing FE Model from other environment	145
Figure C3 Creation of Mesh	145
Figure C4 Mesh Properties	146
Figure C5 Material assignment Tab.....	146
Figure C6 Component assignment Tab.....	147
Figure C7 Property Assignment Tab	147
Figure C8 Mechanical Property Assignment to the FE model	148
Figure C9 Creation of Spring Element	148
Figure C10 Creation of Contact Surfaces	149
Figure C11 Creation of Input plots	149
Figure C12 Creation of Load Collector	150
Figure C13 Boundary Condition manager.....	151
Figure C14 Engine File 1 showing output time step settings	152
Figure C15 Enginefile	152
Figure C16 Creation of Altair® RADIOSS® file	153
Figure C17 Importing results into Hyperview	154
Figure C18 Output Property manager in HyperView	154
Figure C19 Editing output scale in the Analysis Viewer.....	154
Figure D1 Different Layers of human Head	155
Figure D2 Cross Section of Brain showing different lobes	156
Figure D3 Different regions of brain and their respective functions	157

List of Tables

Table 3.1 Maximum Linear accelerations of different drop heights with their respective orientations.....	19
Table 3.2 Area of impact for different drops	21
Table 3.3 HICP for different drop heights and respective orientations.	24
Table 3.4 Pressure Film Types and their ranges of pressures	26
Table 3.5 HICP for different drops and their respective orientations from Pressure Films	28
Table 3.6 HICP Comparison between Siglab and Pressure Films.....	29
Table 3.7 Maximum Linear Acceleration Vs Drop Heights for different regions.....	32
Table 3.8 Drop Heights Vs Max HICP for different Drops.....	33
Table 4.1 Material Properties of FE Model	38
Table 4.2 Normal Stress Values on brain from FE Simulation of Frontal Impact	54
Table 4.3 Shear Stress values on brain from the FE Simulation of Frontal Impact	54
Table 4.4 Results Obtained from Mohr Circle Analysis for Frontal Impacts.....	54
Table 4.5 Pressures on the Brain due to Frontal Impact from different heights	55
Table 4.6 Normal Stress Values on brain from FE Simulation of 45° to Frontal Impact .	64
Table 4.7 Shear Stress values on brain from the FE Simulation of 45° to Frontal Impact	64
Table 4.8 Results Obtained from Mohr Circle Analysis for 45° to Frontal Impacts	64
Table 4.9 Pressures on the Brain due to 45° to Frontal Impact from different heights	65
Table 4.10 Normal Stress Values on brain from FE Simulation of Lateral Impact.....	77
Table 4.11 Shear Stress values on brain from the FE Simulation of Lateral Impact.....	77
Table 4.12 Results Obtained from Mohr Circle Analysis for Lateral Impacts	77
Table 4.13 Pressures on the Brain due to Lateral Impact from different heights	78
Table 4.14 Normal Stress Values on brain from FE Simulation of Posterior Impact	88
Table 4.15 Shear Stress values on brain from the FE Simulation of Posterior Impact.....	88
Table 4.16 Results Obtained from Mohr Circle Analysis for Posterior Impacts.....	88
Table 4.17 Pressures on the Brain due to Posterior Impact from different heights	89

Table 5.1 Maximum Shear Stress on Brain and TBI Tolerance Drop Heights for the respective regions of Impact	97
Table 5.2 Drop Height tolerance for TBI caused by Linear Acceleration.....	98
Table 5.3 Drop Height tolerance for TBI for respective regions of Impact	99
Table 5.4 TBI Tolerance Limits for different regions of Impact.....	108
Table 5.5 Safety criteria for drops in respective region using the TBI Tolerance values from Table 5.4	108
Table 5.6 TBI Stress criterion for Frontal Impact using Eq. 5.1	111
Table 5.7 TBI Stress criterion for 45° to Frontal Impact using Eq. 5.1	111
Table 5.8 TBI Stress criterion for Lateral Impact using Eq. 5.1.....	111
Table 5.9 TBI Stress criterion for Posterior Impact using Eq. 5.1.....	112
Table 6.1 TBI Tolerance Limits for different regions of Impact.....	115

Abbreviations Used

1. NOCSAE-National Operating Committee on Standards for Athletic Equipment
2. FE – Finite Element
3. Pressure Film – Fuji Film Prescale
4. Head Form – Hybrid-III Dummy Head form
5. Max - Maximum
6. MPa – Mega Pascal
7. KPa – Kilo Pascal
8. Acc – Acceleration
9. TBI – Traumatic Brain injury
10. HICP – Head Impact Contact Pressure

Acknowledgements

On the first note, I would like to thank my mother, Maha Lakshmi Bhamidipati, for everything, giving everything she had, in fact going an extra mile to help me achieve my goal, to do my Masters. Without you I am nothing, you are my Super hero, Friend, guide and everything. Thank you god, for giving me such a great Mother. I owe you one.

Secondly, Rama Devi Rachakonda, my life partner, without your moral boost it would have taken me a lot of effort to go through every problem I had, Thank you for believing me that I can achieve my goal and for being always available anytime I need you. I am lucky to have you in my life.

A person, without whom this work would not have been possible, my advisor Dr. Gopal Jayaraman for believing me that I could do this work and without your kind guidance I wouldn't have completed my Masters and I should not forget another important person, Mr. David Labyak, for guiding me through my entire research work and always being available for every question I had. Thanks to my defense committee Dr. KVC Rao, Dr. Ibrahim Miskioglu and Dr.Allan Struthers for taking out time from your busy schedule in going through my work.

Last but not the least, my family away from my home, my friends, Deepika JayaPrakash, Jaswanth Kalavagadda, Prathik Meruva, Pruthvi Raviraj Bachu and Raviteja Zakkam at Michigan Tech, for everything, for believing me that I could do this, supporting me when I am down, guiding me when I am struck. You guys made my masters life a sweet journey, And Sandhya Nadipalli and Shanmukha Modugula for supporting me and helping me resume my work and concentrate on it even in a hectic schedule. Without you all I am nowhere, Thank you god for giving me such a good friends.

Finally, Thank you Michigan Tech for shaping me into a better person

Abstract

How many times have you seen a person slip and fall down and had a good laugh about it? How many times we slip and fall down on the floor, got up and walked away thinking everything is normal? Probably we might wonder “Are drops which occur at such a small height dangerous?” Yes, they can be. Brain injuries are main reason for the fatality in youth [1], and low level falls are one of the most neglected and understated injuries.

The main objective of this study is to study the response of the brain for low level falls from a drop height of 2-5 feet. Earlier studies have related the brain kinematics to injuries, while fewer data is available regarding the relation of brain kinetics to a Traumatic Brain Injury (TBI). The main purpose of this work is to study the effect of an impact due to free fall on the head. The Linear acceleration of the head is measured using accelerometers and Siglab unit by performing drop tests as per NOCSAE standards in Frontal, 45° to Frontal, Lateral and Posterior regions from a height of 2 feet, 3 feet, 4 feet and 5 feet. The corresponding pressure on head called Head Impact Contact Pressure (HICP), has been measured using Fujifilm Prescale and validated by the HICP values calculated from the linear head accelerations. The corresponding Impact pressure curves has been used as an input for finite element (FE) analysis in Altair® RADIOSS® module from Hypermesh, using a 3-D FE model of a 50th percentile human male from the National Library of Medicine (NLM) Visible Human Project (VHP), to study the response of brain during these impacts. Various entities like resultant pressure on the brain, Normal and Shear stresses on the brain, Maximum principal stresses and von Mises Stresses were extracted from the FE analysis. These values are used in conjunction with the Kang and Ward’s [24] criteria and

Anna's [25] criteria for Traumatic Brain Injury (TBI) to determine the tolerance values of drop height, linear head acceleration, Maximum Principal Stresses and von Mises stresses for a chance of risk of TBI. It is been observed that a TBI can be caused either by linear acceleration component or angular acceleration component or both. Hence, a new formula has been proposed to determine the chance of TBI due to impact in particular region.

It is been observed that the lateral region of the brain is more susceptible to injury followed by the Posterior region, a mere drop height of 2.52 feet produces a HICP of 1.21 MPa, an acceleration of 138.67 G, a von Mises stresses of 30.1 KPa and a maximum Principal stress of 0.154 MPa. These values are the tolerance limits for TBI in lateral region and a value higher than those might cause a TBI although any external damage is not observed on the head.

Chapter 1

Introduction

1.1 Introduction

How many times have you seen a person fall on a floor by slipping or tripping and had a good laugh about it? How many times we had some fall on the floor and immediately got up and thought nothing was wrong. Well, is a fall from such a small height can be dangerous? The research says “yes, it could be”.

The brain is one of the complex organs in the human body. In spite of stellar research in fields of science, there are still many areas which are still in dark. Brain is one among them. Because of its complexity very little data is available for its response under injury.

The data which is available has been acquired through the studies on the cadaver subjects, data from accidents and research on animals. Although the research on animals gave some idea about the functionality and response of brain the same cannot be completely relied on as their response is different from human brain in many aspects. [1]

Head Injury is major cause of fatality in young (age group of 15-24), especially due to highway accidents and sport related injuries [2] [3]. This is really a tragic loss because there is a huge life ahead of them and they have a lot to lose. There are many fatalities in all age groups due to head injuries.

"You don't have to see external injury to have injury to the brain, to evaluate a person's response after a minor trauma, it is recommended checking the size of their pupils and asking questions such as the person's name and what year it is. In the hours following, it is recommended monitoring the person's cognitive skills and to bring them in to get a

CAT scan if there is a change in behavior”, said Dr. Philip Stieg, chair of neurosurgery at NYP/Weill Cornell [4].

It’s a common knowledge that drops from heights more than 20 feet can be fatal, but what about the drops from a height lesser than that, what about slips which are quite common amongst all age groups? [4][5]. "A patient can appear so deceptively normal at first, but they actually have a brain bleed and as the pressure builds up, they'll experience classic symptoms of a traumatic brain injury." said Graffagnino, director of Duke University Medical Center's Neurosciences Critical Care Unit [4].

According to the 2006 Liberty Mutual Workplace Safety Index, “the annual direct cost of disabling occupational injuries due to slips, trips and falls is estimated to exceed \$11 billion. The Index reports that falls on the same level are the second most costly occupational injury (estimated annual cost of \$6.7 billion), just behind overexertion. It also shows that injuries from slipping or tripping, is the third highest injury category, followed by falls to a lower level (4.6 billion).[6]

What is the difference between a slip and a fall? “When you slip, you slip on a floor, and lose your balance, a fall is when you move from one level to another.”[6].

Hence it can be considered that slips are one of the understated injuries, and it is important to study the effects and types of injuries on brain for falls between 2-5 feet. This work concentrates on effects of the slips and their response on the brain by determining the tolerances for an injury on the brain due to free fall.

1.2 Demography of Head Injuries.

- In North America, Nearly 0.54 Million injuries which require hospital care occur due to slip fall every year. Out of which 300,000 results in disabilities, while over 20,000 are fatalities i.e. 55 people per day are dying because of slip falls. [6]
- It is the second leading cause of accidental death and disability after automobile accidents. [6]
- Slips and falls are the primary cause of accidents in the home and workplace. [6]
- Slip-Falls kill more workers than all other combined forms of workplace accidents. [6]
- Slip-Falls are the number one cause of accidents in Hotels, Restaurants and Public Buildings; 70% occur in flat and level surfaces. [6]
- Slip-Fall accidents account for 30% of all reported injuries. [6]
- The total expense resulting from slip-fall injuries alone is a \$100 million per day problem. [6]

The demographics of slip falls with respective age groups has been explained below

Demographics of fall in Children

- The slips and fall among children and adolescents account for more than 3 million emergency department visits each year, and more than 40 percent occur among infants, toddlers, and preschoolers.[7]
- Accounting for 5.9 percent of childhood deaths due to trauma, falls represent the third leading cause of death in children [7][8]. Death due to falls is generally from a head injury [9].

- Falls in children are mostly common, they can be from balconies, windows, and trees, and playgrounds. Approximately 75% of the falls in children are unintentional.[7][10]

Demographics of Falls in Adults

- More than 50% of the of non-occupational falls in adults and 17 percent of occupational falls are because of the use of alcohol [11].

Demographics of Falls in the Elderly

- Falls in the elderly are likely to occur with daily activities.
- They account for 29 percent of injury deaths among adults aged 65 and older.[8]
- Older adults are five times more likely to be hospitalized due to falls than any other injuries [7][12].

1.3 Wayne State Tolerance Curve:

The Wayne State Tolerance (WST) curve was presented in 1960, it was the basis for all injury curves. It was the first attempt to relate head linear acceleration in terms of G's with the impact time to study the injuries on the head. [13] It shows that the effect of acceleration on impact decreases with an increase in time.

Figure 1.1 Wayne State Tolerance Curve

1.4 Objective & Strategy

After looking at the above figures, one can realize how serious low level falls could get and proper safety equipment should be designed at least to reduce the effects of the brain injuries. In order to design proper safety equipment, one must have a proper idea about the tolerance levels on the brain for an injury and the response of the brain under an impact. The main objective of this study is

- To determine the effect of drop height on a brain injury.
- To determine the amount of pressure transferred from the head to brain during injury.
- To propose a proper tolerance criteria to determine the chance of a brain injury.
- To study the effect of region of impact on the brain injury.
- To study whether the injury restricts itself to the region of impact.

In order to study the above objectives the following approach have been followed in this study:

- Conduct experimental drop tests according to NOCSAE standards to determine the linear accelerations during impact.
- Study the impact pressures by using experimental methods
- Measure the area of impacts using means available.
- Apply the impact curves derived from the experimental methods as an input to the Finite element analysis.
- Study the response of brain to the given pressure
- Propose a tolerance level of stresses on brain, corresponding linear accelerations and drop height from the previously available data for determining brain injuries

Chapter 2

Brain Injuries

As mentioned earlier brain being one of the most complex organs in the human body there is a little data available about brain injuries which was obtained from the cadaver subjects, volunteers and anesthetized animals. The Centers for Disease Control (CDC) has defined a Traumatic Brain Injury (TBI) as “an occurrence of injury to the head arising from blunt or penetrating trauma or from acceleration-deceleration forces that is associated with any of the following symptoms or signs attributed to injury: decreased levels of consciousness, amnesia, other neurologic or neuropsychological abnormalities, skull fracture, diagnosed intracranial lesions, or death” [14]. The general Consequences of a TBI are temporary memory loss, and problems with judgement, mood, strength, coordination, balance and vision. Mild injuries when occur in repeated manner can sometimes be fatal [2]. The injuries which are caused due to external impact can be majorly classified into two types.

2.1 Focal Injuries

If an injury occurs as a result of the direct blow to the cranial vault or penetration through the skull then it is known as a focal brain injury [15]. Focal brain injury usually results in localized area of bleeding at the site of impact, which is generally known as hematoma. Contusions, epidural hematoma, subdural hematoma are general kind of focal injuries [16].

2.1.1 Contusion

The bruising of brain generally called as contusion occurs due to the inwards deformation of the skull under applied impact, which causes rupture of blood vessels. This causes the compression of brain against skull. Coup and Contre coup injury are general forms of contusions [15]. The injury which generally occurs at the site of injury is called Coup injury and the brain bounces off from the opposite wall of the skull causing Contre Coup injury [17].

2.1.2 Epidural Hematoma

It is an injury in which blood is collected between duramater and interior of Skull [15].

2.1.3 Subdural Hematoma

It is an injury in which the bleeding occurs in the subdural space as a result of breakage of veins in that area. These veins drain the blood from the surface of the brain and force them to the sinuses. The blood accumulates between dura and brain increasing the compression on brain which results in a higher compressive stresses than those of the epidural hematoma [15].

2.2 Diffuse Injuries

These injuries occurs as a result of global disruption of neurological functions. Cerebral concussions and diffuse axonal injuries are general kinds of diffuse injuries [15].

2.2.1 Concussion

Concussions are generally defined as “A post traumatic stage that results in loss of consciousness” [16]. Cerebral functions such as loss of consciousness, equilibrium problems and disturbance of vision are generally effected. The severity of concussion is

generally determined based upon the level of confusion and the state of consciousness [16]. Concussions are most common type of head injuries in athletic injuries. [16]

The concussions can be classified into 3 grades

Grade 1 or mild concussion which involves no loss of consciousness, but involve confusion without amnesia which lasts for less than 30 minutes. [16]

Grade 2 or moderate concussion involves loss of consciousness for less than 5 minutes and confusion associated with amnesia which lasts from 30 minutes to 24 hours. [16]

Grade 3 or severe concussion involves loss of consciousness for more than 5 minutes with amnesia which lasts for more than 24 hours. [16]

2.2.2 Diffuse Axonal Injury

It is one of the most severe brain injuries which have high chances to be fatal. It is generally a shearing injury in which the white matter fiber which runs from cortex to the mid brain, and from the brain stem to spinal cord, disrupts throughout the cerebral hemispheres. The results will be immediate loss of consciousness for more than a day which could last up to weeks. In some cases patient will be under coma with permanent memory loss or other disabilities [16].

Chapter 3

Experiments, Results and Discussions

Head Acceleration & HICP Vs Drop Height

3.1 Experimental Procedure:

In this chapter the real time head injuries due to impact are simulated in the lab by conducting drop tests as per NOCSAE standards. The HICP developed on the head due to free fall head form on the anvil is measured by two different approaches;

- 1) NOCSAE Drop Tests
- 2) Pressure Films and Topaq Pressure Analyzer

By observing the HICP developed on the head-form due to the free fall, the following comparisons were drawn in this chapter.

- a. Comparison of HICP obtained from Topaq Analyzer and NOCSAE Drop Tests.
- b. Linear Acceleration of the Head Vs Drop Heights
- c. HICP from NOCSAE Tests Vs Drop Heights.

3.2 NOCSAE Drop Tests:

3.2.1 Setup:

NOCSAE [18] has defined some standards for testing the protective head gear equipment and the head form which should be used for testing purposes. A NOCSAE standard Drop Instrumentation has been set up at Michigan Technological University which is shown in Fig 3.1.

Fig. 3.1 NOCSAE Drop Test Instrumentation at Michigan Tech.

Drop tests were performed with a NOCSAE Hybrid III dummy head (Here after referred as head form) on a polyurethane elastomer based anvil with a steel base. The Head form is equipped with uniaxial accelerometers to study the impact acceleration in G's during the drop. The head form was allowed to fall freely from 2 feet, 3 feet, 4 feet and 5 feet oriented in Frontal (along positive Z-axis), 45 ° to Frontal (along XY-axis), Lateral (along negative X-axis) and Posterior (along negative Z-axis) to anvil.

The accelerometers relay the readings during the drops to the Siglab unit which will calculate the Linear Acceleration in terms of G's and Severity Index and thus calculates a linear acceleration curve from the moment the head form comes in contact with the anvil.

3.2.2 Head Linear Acceleration Curve

The data which is imported from the Siglab unit is in the form of large text file, which can be exported to excel format for further processing. The head linear acceleration (here after referred to as Linear Acceleration) curve can be plotted from the same.

Fig. 3.2 Linear Acceleration Plot obtained from the Siglab Unit.

In the above figure we can find a linear acceleration plot obtained from the Siglab unit. Channels 2, 3 and 4 corresponds to linear acceleration in X, Y and Z axes respectively while Channel 1 is the Resultant Linear acceleration. By observing the above plot (Fig 3.2) one can observe that the curve has started from the negative time, it is because the Siglab will start recording the readings from the instant the head form touches the anvil (which is considered as $t=0$) and the values earlier to that are the disturbances during the drop.

The X,Y,Z axes of the head-form are shown in fig. below.

Fig 3.3 Headform with its X,Y,Z Axes

The Linear acceleration curves for different heights and different orientations are shown below

3.2.2.1 Frontal

Fig 3.4 Linear Acceleration curve for Frontal 2 feet drop

Fig 3.5 Linear Acceleration curve for Frontal 3 feet drop

Fig 3.6 Linear Acceleration curve for Frontal 4 feet drop

Fig 3.7 Linear Acceleration curve for Frontal 5 feet drop

3.2.2.2 45° to Frontal:

Fig 3.8 Linear Acceleration curve for 45° to Frontal 2 feet drop

Fig 3.9 Linear Acceleration curve for 45° to Frontal 3 feet drop

Fig 3.10 Linear Acceleration curve for 45° to Frontal 4 feet drop

Fig 3.11 Linear Acceleration curve for 45° to Frontal 5 feet drop

3.2.2.3 Lateral:

Fig 3.12 Linear Acceleration curve for Lateral 2 feet drop

Fig 3.13 Linear Acceleration curve for Lateral 3 feet drop

Fig 3.14 Linear Acceleration curve for Lateral 4 feet drop

Fig 3.15 Linear Acceleration curve for Lateral 5 feet drop

3.2.2.4 Posterior

Fig 3.16 Linear Acceleration curve for Posterior 2 feet drop

Fig 3.17 Linear Acceleration curve for Posterior 3 feet drop

Fig 3.18 Linear Acceleration curve for Posterior 4 feet drop

Fig 3.19 Linear Acceleration curve for Posterior 5 feet drop

The maximum Linear Accelerations measured from the Siglab unit and extracted from the acceleration curves has been tabulated below.

Table 3.1 Maximum Linear accelerations of different drop heights with their respective orientations.

Orientati on	Drop Heig ht (feet)	Severity Index	Max Linear Acceleration (G)	Max. Linear Acceleratio n From Siglab Unit (G)	Percent age Differe nce ¹	Time of Peak Acceler ation (Sec)
Frontal	2	385	109.92	107	2.69%	3.52E-03
	3	652	136.77	135	1.30%	3.52E-03
	4	1047	170.80	170	0.47%	3.52E-03
	5	1493	206.31	205	0.64%	3.32E-03
45° to Frontal	2	336	101.14	98	3.16%	3.91E-03
	3	545	130.36	128	1.83%	3.71E-03
	4	875	153.75	152	1.14%	3.52E-03
	5	1107	169.58	173	-2.00%	3.52E-03
Lateral	2	405	124.55	120	3.72%	3.91E-03
	3	704	154.54	153	1.00%	3.71E-03
	4	1107	185.11	182	1.70%	3.91E-03
	5	1482	212.12	209	1.48%	3.71E-03
Posterior	2	484	122.05	119	2.53%	4.10E-03
	3	848	156.71	155	1.10%	3.91E-03
	4	1316	191.96	191	0.50%	3.71E-03
	5	1700	213.36	213	0.17%	3.71E-03

The variations in the values of acceleration is due to the voltage fluctuations and other errors in the Siglab equipment. We see that the Percentage difference in the acceleration values is low (<5%). Hence we can go ahead and use these values in the analysis. The

¹ Percentage Difference = $\left(\frac{A_1 - A_2}{(A_1 + A_2)/2} \right) * 100$

peak value of the Impact occurs almost at the same time interval (3.5 – 4 msec), with frontal being the lower (3.5msec) and Posterior being the highest (4.1 msec).

3.2.3 Measurement of Area of Impact

Area of Impact plays an important role in the measurement of Head Impact Contact Pressure (HICP) and Impact Force. The measurement of area of impact is a bit tedious because of the complicated shape of the Head Form and it would be really difficult to measure the actual surface which is in contact with the anvil during Impact, also the minute time of contact and the Area of contact which is in 3D makes the task much herculean.

After considering various methods, chalk measuring technique was proved to be appropriate for the measurement of Area of Impact with minute errors. In this process wet chalk powder is applied to the head form and allowed to dry.

After the drop we can find the imprint of the Area of Impact which is a 2D projection of the Area of Impact.

Fig 3.20 Head form with chalk applied for Area measurement

Fig 3.21 Projected Area of Impact on the Anvil

The Area of Impact for Different Falls in different orientations is shown below.

Table 3.2 Area of Impact for different drops

Orientation	Drop Height (feet)	Major Axis (2a) (mm)	Minor Axis (2b) (mm)	Impact Area πab (m2)
Frontal (Semi-Elliptical = $\pi ab/2$)	2	65	55	0.0056
	3	65	60	0.0061
	4	68	62	0.0066
	5	70	65	0.0071
45° to Frontal	2	70	55	0.0030
	3	72	57	0.0032
	4	74	60	0.0035
	5	77	60	0.0036
Lateral	2	95	70	0.0052
	3	98	75	0.0058
	4	100	77	0.0060
	5	102	80	0.0064
Posterior	2	70	62	0.0034
	3	74	67	0.0039
	4	76	68	0.0041
	5	78	68	0.0042

The projected area is approximated to be an ellipse for easy calculation purposes. It can be observed that the Area of Impact is higher for Frontal followed by Lateral, Posterior and 45° to Frontal.

3.2.4 Calculation of Impact Force and HICP

The Impact Force and the HICP can be calculated from the Newton's Second Law of Motion.

It states that, "The rate of change of momentum of a body is proportional to the impulse impressed on the body, and happens along the straight line on which that impulse is impressed." In common terms it can be expressed as that the resultant net force on a body is equal to the rate of change of linear momentum.

It can be mathematically expressed as:

$$\vec{F} = \frac{d(\rho)}{dt}$$

The linear momentum (ρ) can be expressed as the product of the mass and resultant velocity of the body. Thus the above equation can be rewritten as:

$$\vec{F} = \frac{d(m\vec{v})}{dt}$$

Where $\vec{F}$ is the resultant force acting on the body,

m is the mass of the body and

$\vec{v}$ is the resultant velocity

As the mass of the body is constant, the resultant equation would be

$$\vec{F} = m \frac{d(\vec{v})}{dt}$$

We know that the rate of change of velocity is acceleration ($\vec{a}$)

$$\vec{F} = m\vec{a} \quad \text{..... (Eq. 1)}$$

The above relation can be used to calculate the Impact Pressure due to free fall.

As we know,

$m = m_h$ = Mass of the Head form = 4.716 kg.

$(\vec{a}) = \vec{a}_{lg}$ = Linear Acceleration expressed in m/s^2 .

The linear acceleration values obtained from the drop test are in terms of 'Gs'. It can be converted into m/s^2 by multiplying acceleration due to gravity (g).

Thus the above Eq.1 can be modified as

$$\text{Impact Force} = \vec{F}_t = m_h \cdot \vec{a}_{lg} \quad \text{..... (Eq. 2)}$$

Pressure Calculation:

Pressure (P) can be defined as the Force per unit Area acting on the body.

$$P = \frac{\vec{F}}{A}$$

$$\vec{F} = P \cdot A \quad \text{..... (Eq. 3)}$$

Applying the above Eq. to our criteria,

$$\text{Impact Force} = \vec{F}_t = m_h \cdot \vec{a}_{lg} = P_i \cdot A_i$$

Where,

P_i = Head Impact Contact Pressure (HICP)

A_i = Area of Impact

The Area of Impact is assumed to be constant during the drop.

The HICP (P_i) can be redefined as:

$$P_i = \frac{m_h \times \vec{a}_{lg}}{A_i} \quad \text{..... (Eq. 4)}$$

3.2.5 Discussion

The HICP values for different drops in their respective orientations has been calculated and tabulated below.

It should be noted that the Impact Pressure and Impact forces follow the similar profile as the acceleration curves as the mass of the head form and Area of impact were assumed to be constant.

Table 3.3 HICP for different drop heights and respective orientations

Orientation	Drop Height (feet)	Linear Acceleration (G) (From Graph)	Impact Force = (m*g*G) (N)	HICP (MPa)
Frontal	2	109.92	5305.298071	0.94
	3	136.77	6601.301863	1.08
	4	170.80	8243.737613	1.24
	5	206.31	9957.633879	1.39
45° to frontal	2	91.74	4427.831469	1.46
	3	120.25	5803.740637	1.80
	4	139.09	6713.398322	1.93
	5	163.19	7876.430978	2.17
Lateral	2	120.76	5828.662766	1.12
	3	156.05	7531.674869	1.30
	4	182.64	8815.164479	1.46
	5	206.41	9962.620804	1.55
Posterior	2	120.14	5798.548527	1.70
	3	153.25	7396.680007	1.90
	4	183.03	8833.856075	2.18
	5	210.35	10152.65203	2.44

3.3 Pressure Film and Topaq Analyzer.

3.3.1 Pressure Films [19]

A Fujifilm Prescale (Here after referred as a pressure film) is a tool which is used to study the distribution and magnitude of Pressure between two surfaces in contact. It is an extremely thin mylar based film (Thickness is approximately 1-2 μm). It contains of layer of microcapsules which rupture upon application of force revealing a pressure distribution profile between the two contacting surfaces similar to litmus paper. Higher the color intensity (Dark red), higher the pressure between the surfaces.

Figure 3.22 Explanation of working of a Pressure Film and C.S View of a Film from Sensor Prod. Inc [25]

Image Courtesy: *Sensor Products Inc. website* [20]

3.3.2 Selection of Pressure Films

There are different kinds of Pressure films available with their respective ranges of pressures which they can measure.

Table 3.4 Pressure Film Types and their ranges of pressures

S.No	Pressure Film Type	Pressure Range
1	Extreme Low	7.2-28 PSI (0.5-2 kg/cm ²)
2	Ultra Low	28-85 PSI (2-6 kg/cm ²)
3	Super Low	70-350 PSI (5-25 kg/cm ²)
4	Low	350-1400 PSI (25-100 kg/cm ²)
5	Medium	1400 - 7100 PSI (100 - 500 kg/cm ²)
6	High	7100 -18,500 PSI (500 - 1300 kg/cm ²)
7	Super High	18,500 - 43,200 PSI (1300-3000 kg/cm ²)

Upon observing the readings from the Siglab unit during the drop tests it has been observed that the pressure range of the entire experiments falls in the range of 350-7100 PSI. Hence Medium and Low pressure films were selected depending upon the drop height and orientation.

Temperature and Relative humidity also plays a major role in the operation of the pressure films.

3.3.3 Topaq Analyzer

A Topaq Analyzer is a system which looks similar to a normal scanner but when used with the Pressure film produce a high resolution, color calibrated description of distribution of pressure on the film. It consists of a specially calibrated densitometric scanner which

interprets the stress marks on the films and produce results such as Area, Impact force, Average pressure and also Pressure histograms.

3.3.4 Setup

A Pressure film set consists of the two different sheets as explained in the figure above (3.22), A Donor sheet (Transfer sheet) and a Receiver sheet (Developer sheet). Both the sheets have a textured matte side. While performing the operation both the sheets are to be placed in such a manner that the textured surfaces must be in contact with one another. Care should be taken while handling the films as a set because minute pressures are sufficient to rupture the bubbles leaving a permanent color in the film causing discrepancies in the reading. A Donor sheet is not required when using the Low pressure films as the sensitivity of these films is really high.

The Pressure film set is to be placed on the anvil in such manner that the receiver film is on the bottom and the Donor sheet is on the top. It is to be tightly attached to the anvil restricting any movement of the film.

3.3.5 Results

Drop Tests were performed from 2 feet, 3 feet, 4 feet and 5 feet in Frontal, 45° to Frontal, Lateral and Posterior orientations as per NOCSAE standards, and the Deformations on the Pressure films, Results and the Pseudo image obtained from the Topaq scanner and the results have been shown in Appendix-A.

3.6 Discussions

The results obtained from the analyzer are congregated in the tabular form below

Table 3.5 HICP for different drops and their respective orientations from Pressure Films

Orientation	Height (feet)	HICP (MPa)
Frontal	2	2.79
	3	2.84
	4	3.25
	5	3.42
45° to Frontal	2	3.85
	3	4.04
	4	4.26
	5	4.63
Lateral	2	3.32
	3	3.49
	4	3.55
	5	3.64
Posterior	2	2.77
	3	3.9
	4	4.01
	5	4.2

We observe that the HICP increases with the increase in height. The peak values of HICP of 4.63 MPa, is observed in the 5 feet drop of 45° to Frontal Region. While the lowest value of 2.79 MPa is observed in the 2 feet drop of Frontal Region.

One can observe that we can only get the average pressure values from the analyzer.

There is also a lot of discrepancies in the Area of Impacts and the Impact forces which will be explained further.²

² Mail conversation with SensorProd explaining the reasons is attached

3.4 Comparison of Results and Discussions

In this chapter we will compare the HICP values obtained from both the experimental methods.

3.4.1 Comparison of HICP between Pressure films and Accelerometers

Table 3.6 HICP Comparison between Siglab and Pressure Films

Orientation	Drop Height (feet)	HICP (MPa) - Accelerometers	HICP (MPa) - Pressure Films	Percentage Difference
Frontal	2	0.94	2.79	99.20%
	3	1.08	2.84	89.80%
	4	1.24	3.25	89.53%
	5	1.39	3.42	84.41%
45° to Frontal	2	1.46	3.85	90.02%
	3	1.8	4.04	76.71%
	4	1.93	4.26	75.28%
	5	2.17	4.63	72.35%
Lateral	2	1.12	3.32	99.10%
	3	1.3	3.49	91.44%
	4	1.46	3.55	83.43%
	5	1.55	3.64	80.54%
Posterior	2	1.7	2.77	47.87%
	3	1.9	3.9	68.97%
	4	2.18	4.01	59.13%
	5	2.44	4.2	53.01%

The HICP values obtained from the Siglab Unit and the Pressure films have been compared in the Table 3.6 and the following observations can be inferred.

The difference in the HICP values from the experiments can be due to the following reasons.

- 1) The Analyzer is generally used for the static analysis and rarely used for the Impact testing.
- 2) The source of error can be due to the multiple impacts of Head form with the film. The Analyzer works perfect for the single Impact conditions. As we can't control the minor re-bouncing of the head form, we are prone to get some errors.
- 3) Out of many outputs only the Pressure and Contact area are reliable as the Analyzer is not designed for the Impact force measurement.
- 4) The Pressure films are designed for the Flat surfaces, as our head form has a curved profile, the center region of the Impact area is prone to have more pressure concentration than the other regions, which in turn varies the average pressure.
- 5) The Eye brow region of the head form is involved in impact which modifies the area and the pressure acting on the film.
- 6) The approximation with the area of impact might lead to some discrepancies in the HICP measurement.

Considering the above conditions the head form has been torqued to 180 lb.-in as per NOCSAE standards, for every drop and care was taken to tighten the equipment to minimize the rebound effect.

The following observations can be made from the Table-3.6

1. Both the methods show similar profile in the HICP increase with increase in height.
2. It can be observed that the Frontal region has the lowest range of HICP in both the methods.

3. 45° to Frontal region has the highest range of HICP values than the other regions as per the pressure films, although it has lower linear acceleration values when compared to the other regions. It might be because of the lower surface areas. We can also observe that the discrepancies between both the methods is higher in this region because of the lower surface area leads to maximum rebound resulting in multiple impacts on the film.
4. The highest range of HICP values is found the posterior region which is verified by both the methods and the highest HICP values can be observed for 5 feet drop of the posterior region which implies that there is a higher chance of HICP if the impact happens in this region.
5. Although lateral and posterior region has similar range of linear accelerations, the difference in the range of HICP values can be because of the variance in impact area which proves the importance of impact area in HICP measurement.

While with the siglab unit the approximations might also lead to some discrepancies in the calculations too, but as we cannot get the acceleration profiles from the Pressure films and by comparing the HICP values to the previous experiments the readings obtained from the Siglab unit were considered for the Finite Element Analysis which will be explained in the further chapters.

3.4.2 HICP Plots

3.4.2.1 Drop Height Vs. Maximum Linear Acceleration

Figure 3.23 Maximum Linear Acceleration Vs Drop Height

From the above plot it can be observed that the Linear acceleration is lower (91 – 164 G) for 45° to frontal region for any given height while posterior region is on the higher end (120 – 210 G).

It can also be observed that the Posterior and Lateral regions have their linear accelerations distributed in the same range.

Table 3.7 Maximum Linear Acceleration Vs Drop Heights for different regions

		Maximum Linear Acceleration (G's)			
Orientation		Frontal	45° to Frontal	Lateral	Posterior
Height	2	109.92	91.74	120.76	120.14
	3	136.77	120.25	156.05	153.25
	4	170.80	139.09	182.64	183.03
	5	206.31	163.19	206.41	210.35

3.4.2.2 Drop Heights Vs. Maximum HICP

Figure 3.24 HICP Vs Drop Heights

From the above plot it can be inferred that the Posterior range have higher range of HICP with the highest value being 2.44 MPa for 5 feet drop which occurs at 3.71 ms. The Frontal region has the lowest values of HICP for any given height with the lowest being 0.94 MPa for 2 feet drop which occurs at 3.52 msec.

Table 3.8 Drop Heights Vs Max HICP for different Drops

		Maximum HICP (MPa)			
Orientation		Frontal	45° to Front	Lateral	Posterior
Height	2	0.94	1.46	1.12	1.70
	3	1.08	1.80	1.30	1.90
	4	1.24	1.93	1.46	2.18
	5	1.39	2.17	1.55	2.44

3.4.2.3 Drop Height Vs. Maximum HICP Vs Maximum Linear Acceleration

Figure 3.25 Plot of Drop Height Vs HICP Vs Linear Acceleration for Frontal region of Impact

Figure 3.26 Plot of Drop height Vs HICP Vs Linear Acceleration for 45 to Frontal region of Impact

Figure 3.27 Plot of Drop Height Vs HICP Vs Linear Acceleration for Lateral region of Impact

Figure 3.28 Plot of Drop Height Vs HICP Vs Linear Acceleration for Posterior region of Impact

We can observe that the both the manually calculated HICP and the Linear acceleration follow the similar profile with increase in height. Hence we can go ahead and use these values in the Finite Element Simulation.

Chapter 4

HICP Vs Stress Distribution in Brain by Finite Element Analysis

4.1 Introduction

In chapter-3 kinetic response of head namely linear accelerations Vs drop heights and HICP Vs drop heights were studied. In this chapter kinetic response of brain namely stress distribution in brain Vs HICP are studied by Finite Element Analysis.

As discussed earlier majority of the TBI occurs when HICP is transferred to the brain through the outer layer (scalp) and through the interior layers as Skull, Dura Mater, and Cerebral Spinal Fluid. If one can measure the kinetic response of the brain due to a given HICP, then one can quantify brain injuries such as concussion, and contusion, and other TBIs. The best way to quantify the kinetic response of the brain due to HICP is either by medical imaging like CT scan or through Finite Element Method (FEM) of Stress analysis. Although the former method is accurate clinically readily acceptable solution, the later provides quantitative measure of the kinetic response of the brain in terms of pressure and shear stress distribution in the brain corresponding to a given mechanics of HICP.

Also using FEM of stress analysis one can correlate kinematic response of the head (discussed in chapter 3) with kinetic response of the brain for the same HICP to elicit the connection between the cause and effect for the brain concussion.

4.2 FE model of Human Head

An accurate FE model is a primary requirement for any analysis. The FE model for this study has been generated by using Geometric surface scanning. The Generation and

validation of the model has been explained in detail in thesis work of Mr. David M Labyak[20].

The validated model was meshed in Abaqus, and stored as an .inp* format. Hypermesh was selected for the analysis depending upon the availability of the licenses in the university and the efficiency of Altair® RADIOSS® in impact analysis. Although the model has been set up correctly in Abaqus there were some errors with the mesh when the model was imported into Hypermesh. The imported model has an impactor and anvil in the model which were deleted. The model was re-meshed with tetra element maintaining a consistent aspect ratio and a proper element size.

The model consists of Scalp, Skull, Dura mater and the Brain.

Figure 4.1 Meshed 3D form Model with Impact Areas Marked on it

4.2.1 Material Properties

Element properties plays an important role in a Finite Element (Here after referred to as FE) study. The element type was assumed to be elastic and the properties of different

layers were considered from Mr. David M Labyak's thesis[21], which were shown below.

Table 4.1 Material Properties for the FE Model [21]

Layer	Density (Kg/m3)	Young's Modulus (MPa)	Poisson's Ratio	Number of elements
Scalp	1.41E-09	8.05	0.49	3665
Skull	2.70E-09	6500	0.22	22930
Dura mater	1.04E-09	0.148	0.4996	4154
Brain Tissue	1.04E-09	0.533	0.4996	17088

The material properties have been applied to the respective layers in the model are explained in detail in Appendix-C.

The different areas of impact applied on the model are shown below.

Figure 4.2 FE Model for Frontal Impact

Figure 4.3 FE Model for 45° to Frontal Impact

Figure 4.4 FE Model for Lateral Impact

Figure 4.5 FE Model for posterior Impact

As observed in the Table-3.2 we see that the area of Impact is different for different orientations and heights, the locations of the area of impact is measured from the drop tests and the average area for respective orientations has been calculated and applied on the model following the contour of the area of Impact. The area of Impacts were imposed on the model assuming that the center of mass of head form coincides with center of mass of the FE Model.

4.3 HICP Input Curves

A general acceleration curve developed from the Siglab unit during drop test has been shown in the earlier sections. However for the FEA only the peak curve of the Impact (the curve which has the peak Linear Acceleration) was considered assuming that the majority of the injury is caused by the maximum acceleration of the peak curve.

The maximum acceleration peak curve has been scaled to start from $t=0$ sec, and the corresponding acceleration values has been scaled accordingly which in turn effects the Impact pressure values.

The load is assumed to be uniformly distributed and is applied in terms of the pressure Vs time (Transient loading), to the model.

Different Pressure curves used for the analysis were shown below.

Figure 4.6 Impact Pressure Curves for Impact in Frontal Region

Figure 4.7 Impact Pressure curves for impact in 45 to Frontal region

Figure 4.8 Impact pressure curve for Impact in Lateral region

Figure 4.9 Impact pressure curves for Impact in Posterior region

It can be observed that the Impact time is different for different heights in the same region. It can be because of the approximation considered in the curve fitting.

The Impact pressure is considered as a positive entity in this work hence all the tensile stresses would be in negative magnitude.

4.4 Boundary Conditions

Constraining the model is another important step in a FE analysis. The constraints have been applied to the model in order to replicate the testing conditions and the actual

scenario. The model was constrained at the brainstem and the stem junction at skull similar to the head form.

When the fixed constraints were applied at the above locations the deformation were being produced at these locations as they were constrained to move under pressure causing discrepancies in the results obtained.

Hence a ground fixed node was created at a unit distance from the stem junction and all the nodes on the model which are supposed to be constrained were attached to the fixed node with spring elements giving them the a proper flexibility to deform under applied pressure.

Figure 4.10 Unit Spring elements connecting skull to the Ground point

Different spring constants were applied for the spring element to study the behavior of elements under applied load. The element shouldn't be too rigid as too much rigidity effects the results while on the other if it's flexible the effect of the pressure causes the material to oscillate more. Hence after many trials and comparing the values to those from the previous research performed by Chandrika Abhang and David Labyak, the

spring constant value is assumed to 10000 N/m making it stronger than skull but not too rigid to completely defy its purpose.

4.5 Output Settings and Time step

Time steps plays an important role in the measurement of output in transient analysis. It refers to the time interval at which the system should record the output. One must make sure that the time interval should not be too small as it increases the processing time while a bigger interval leads to improper measurement of output as bigger interval might miss the sudden changes in the output profiles.

The time step details used in the Altair® RADIOSS® analysis will be explained along with the detail description of entire procedure in Appendix-C.

4.6 Results & Discussions

The model has been converted into Altair® RADIOSS® file (*.Rad) and analyzed in the Altair® RADIOSS® solver. The engine file has been set to give an output of pressure and maximum shear and principal stresses. The result file has been analyzed in Hyperview and the maximum value of the pressures and stresses has been found out from them. But due to the limitations of the software version available at the university, in order to calculate the maximum principal and shear stresses, the stresses in the directions of X, Y, Z, XY, YZ and XZ were calculated and 3 dimensional Mohr's circle approach [21] was used to get the required outputs which would be maximum von Mises stresses, maximum Shear stresses and maximum tensile stresses from the available values.

The results obtained along with their input pressure curves are shown below

4.6.1 Frontal

4.6.1.1 Drop Height of 2 feet

Figure 4.11 von Mises stress Frontal 2 feet

Figure 4.12 Normal stress S_x Frontal 2 feet

Figure 4.13 Normal stress S_y Frontal 2 feet

Figure 4.14 Normal stress S_z Frontal 2 feet

Figure 4.15 Normal stress S_x Frontal 2 feet

Figure 4.16 Normal stress S_y Frontal 2 feet

Figure 4.17 Shear stress S_{xy} Frontal 2 feet

Figure 4.18 Shear stress S_{xy} Frontal 2 feet

Figure 4.19 Shear stress S_{yz} Frontal 2 feet

Figure 4.20 Shear stress S_{yz} Frontal 2 feet

Figure 4.21 Shear stress S_{yz} Frontal 2 feet

Figure 4.22 Shear stress S_{xz} Frontal 2 feet

Figure 4.23 Shear stress S_{zx} Frontal 2 feet

Figure 4.24 Shear stress S_{zx} Frontal 2 feet

4.6.1.2 Drop Height of 3 feet

Figure 4.25 Normal stress S_x Frontal 3 feet

Figure 4.26 Normal stress S_x Frontal 3 feet

Figure 4.27 Normal stress S_y Frontal 3 feet

Figure 4.28 Normal stress S_y Frontal 3 feet

Figure 4.29 Normal stress S_z Frontal 3 feet

Figure 4.30 von Mises stress Frontal 3 feet

Figure 4.31 Shear stress S_{xy} Frontal 3 feet

Figure 4.32 Shear stress S_{xy} Frontal 3 feet

Figure 4.33 Shear stress S_{yz} Frontal 3 feet

Figure 4.34 Shear stress S_{yz} Frontal 3 feet

Model info: Frontal_3feet
Result: H:\STudies\Dr.Jay\current\results\Frontal\3feet\Frontal_3feetA002
Loadcase 1: Time = 0.000e+000
Frame 02

Model info: Frontal_3feet
Result: H:\STudies\Dr.Jay\current\results\Frontal\3feet\Frontal_3feetA002
Loadcase 1: Time = 0.000e+000
Frame 02

Figure 4.35 Shear stress S_{zx} Frontal 3 feet

Figure 4.36 Shear stress S_{zx} Frontal 3 feet

4.6.1.3 Drop Height of 4 feet

Model info: Frontal_4feet
Result: H:\STudies\Dr.Jay\current\results\Frontal\4feet\Frontal_4feetA005
Loadcase 1: Time = 3.0400e-003
Frame 39

Model info: Frontal_4feet
Result: H:\STudies\Dr.Jay\current\results\Frontal\4feet\Frontal_4feetA005
Loadcase 1: Time = 3.0400e-003
Frame 39

Figure 4.37 von Mises stress Frontal 4 feet

Figure 4.38 Normal stress S_x Frontal 4 feet

Model info: Frontal_4feet
Result: H:\STudies\Dr.Jay\current\results\Frontal\4feet\Frontal_4feetA005
Loadcase 1: Time = 3.0400e-003
Frame 39

Model info: Frontal_4feet
Result: H:\STudies\Dr.Jay\current\results\Frontal\4feet\Frontal_4feetA005
Loadcase 1: Time = 3.0400e-003
Frame 39

Figure 4.39 Normal stress S_x Frontal 4 feet

Figure 4.40 Normal stress S_x Frontal 4 feet

Figure 4.41 Normal stress S_y Frontal 4 feet

Figure 4.42 Normal stress S_y Frontal 4 feet

Figure 4.43 Normal stress S_z Frontal 4 feet

Figure 4.44 Shear stress S_{xy} Frontal 4 feet

Figure 4.45 Shear stress S_{xy} Frontal 4 feet

Figure 4.46 Shear stress S_{xy} Frontal 4 feet

Figure 4.47 Shear stress S_{yz} Frontal 4 feet

Figure 4.48 Shear stress S_{yz} Frontal 4 feet

Figure 4.49 Shear stress S_{zx} Frontal 4 feet

Figure 4.50 Shear stress S_{zx} Frontal 4 feet

4.6.1.4 Drop Height of 5 feet

Figure 4.51 von Mises stress Frontal 5 feet

Figure 4.52 Normal Stress S_x Frontal 5 feet

Contour Plot
Stress X (Scalar value)
Simple Average
-5.689E-02
-4.000E-02
-2.011E-02
-1.529E-04
-1.980E-02
-3.950E-02
-5.937E-02
-7.925E-02
Min = -4.920E-02
Node 9799
Min = -8.384E-02
Node 7990

Figure 4.53 Normal stress S_x Frontal 5 feet

Model info: Frontal_Sheet
Result: H:\Studies\Dr.Jay\current\results\Frontal_Sheet\Frontal_SheetA085
Loadcase 1: Time = 2.9803e-003
Frame 38

Contour Plot
Stress X (Scalar value)
Simple Average
-5.689E-02
-4.000E-02
-2.011E-02
-1.529E-04
-1.980E-02
-3.950E-02
-5.937E-02
-7.925E-02
Min = -4.920E-02
Node 9799
Min = -8.384E-02
Node 7990

Figure 4.54 Normal stress S_x Frontal 5 feet

Model info: Frontal_Sheet
Result: H:\Studies\Dr.Jay\current\results\Frontal_Sheet\Frontal_SheetA085
Loadcase 1: Time = 2.9803e-003
Frame 38

Contour Plot
Stress Y (Scalar value)
Simple Average
-5.689E-02
-4.000E-02
-2.011E-02
-1.529E-04
-1.980E-02
-3.950E-02
-5.937E-02
-7.925E-02
Min = -4.920E-02
Node 9799
Min = -8.477E-02
Node 7990

Figure 4.55 Normal stress S_y Frontal 5 feet

Model info: Frontal_Sheet
Result: H:\Studies\Dr.Jay\current\results\Frontal_Sheet\Frontal_SheetA085
Loadcase 1: Time = 2.9803e-003
Frame 38

Contour Plot
Stress Y (Scalar value)
Simple Average
-5.689E-02
-4.000E-02
-2.011E-02
-1.529E-04
-1.980E-02
-3.950E-02
-5.937E-02
-7.925E-02
Min = -4.920E-02
Node 9799
Min = -8.477E-02
Node 7990

Figure 4.56 Normal stress S_y Frontal 5 feet

Model info: Frontal_Sheet
Result: H:\Studies\Dr.Jay\current\results\Frontal_Sheet\Frontal_SheetA085
Loadcase 1: Time = 2.9803e-003
Frame 38

Contour Plot
Stress Z (Scalar value)
Simple Average
-5.689E-02
-4.000E-02
-2.011E-02
-1.529E-04
-1.980E-02
-3.950E-02
-5.937E-02
-7.925E-02
Min = -4.720E-02
Node 9799
Min = -8.384E-02
Node 7990

Figure 4.57 Normal stress S_z Frontal 5 feet

Model info: Frontal_Sheet
Result: H:\Studies\Dr.Jay\current\results\Frontal_Sheet\Frontal_SheetA085
Loadcase 1: Time = 2.9803e-003
Frame 38

Contour Plot
Stress XY (Scalar value)
Simple Average
-5.689E-02
-4.000E-02
-2.011E-02
-1.529E-04
-1.980E-02
-3.950E-02
-5.937E-02
-7.925E-02
Min = -4.720E-02
Node 9799
Min = -8.384E-02
Node 7990

Figure 4.58 Shear stress S_{xy} Frontal 5 feet

Model info: Frontal_Sheet
Result: H:\Studies\Dr.Jay\current\results\Frontal_Sheet\Frontal_SheetA085
Loadcase 1: Time = 2.9803e-003
Frame 38

Figure 4.59 Shear stress S_{xy} Frontal 5 feet

Figure 4.60 Shear stress S_{xy} Frontal 5 feet

Figure 4.61 Shear stress S_{xy} Frontal 5 feet

Figure 4.62 Shear stress S_{yz} Frontal 5 feet

Figure 4.63 Shear stress S_{yz} Frontal 5 feet

Figure 4.64 Shear stress S_{yz} Frontal 5 feet

Figure 4.65 Shear stress S_{zx} Frontal 5 feet

Figure 4.66 Shear stress S_{zx} Frontal 5 feet

4.6.1.5 Discussion

The normal stresses values obtained from the Finite element simulation are listed below.

It should be remembered that as the input pressure is considered as positive the resultant tensile stress on the brain would be negative.

Table 4.2 Normal Stress Values on brain from FE Simulation of Frontal Impact

Height (feet)	Stress X (MPa)		Stress Y (MPa)		Stress Z (MPa)	
	Tension	Compression	Tension	Compression	Tension	Compression
2	-6.32E-02	5.07E-02	-6.37E-02	5.07E-02	-6.32E-02³	5.07E-02
3	-6.40E-02	5.10E-02	-6.47E-02	5.10E-02	-6.42E-02	5.10E-02
4	-7.41E-02	5.91E-02	-7.52E-02	5.98E-02	-7.41E-02	5.91E-02
5	-7.93E-02	5.99E-02	-8.00E-02	5.99E-02	-7.93E-02	5.99E-02

The Shear stress values obtained for different drops from the finite element simulation are listed below

Table 4.3 Shear Stress values on brain from the FE Simulation of Frontal Impact

Height (feet)	Stress XY (MPa)	Stress YZ (MPa)	Stress ZX (MPa)
2	1.62E-03	2.22E-03	-6.80E-04
3	1.60E-03	2.20E-03	-1.00E-03
4	1.90E-03	2.40E-03	-1.25E-03
5	2.20E-03	2.70E-03	-1.41E-03

The Values when used in the Mohr Circle calculation, yielded the following results

Table 4.4 Results Obtained from Mohr Circle Analysis for Frontal Impacts

Height (feet)	Principal Stresses (MPa)			Max Shear Stress (MPa)	von Mises (MPa)
	P-1	P-2	P-3		
2	-6.10E-02	-6.26E-02	-6.65E-02	2.76E-03	4.93E-03
3	-6.16E-02	-6.31E-02	-6.72E-02	2.83E-03	5.06E-03
4	-7.21E-02	-7.29E-02	-7.83E-02	3.09E-03	5.83E-03
5	-7.68E-02	-7.79E-02	-8.38E-02	3.52E-03	6.55E-03

³ Values in **bold** are maximum values which are used in FE Simulation

The Maximum Pressure values observed on the brain obtained from the simulation are tabulated below.

Table 4.5 Pressures on the Brain due to Frontal Impact from different heights

Height (feet)	HICP (MPa)	Velocity of Fall $(2gh)^{0.5}$ m/s	Pressure on Brain – Tension (MPa)
2	0.94	3.46	6.20E-02
3	1.08	4.24	6.29E-02
4	1.24	4.89	7.35E-02
5	1.39	5.47	7.89E-02

Figure 4.67 Comparison of Pressure on Brain and HICP during Frontal Impact

Figure 4.68 Maximum Principal Stress and von Mises Stress on Brain obtained from FE Simulation for Frontal Impacts

Figure 4.69 Stress variation on brain with respect to drop height in Frontal Impact

Upon observing the results of the simulation the following information can be inferred.

- One can see that the pressure wave travels from the frontal lobe (site of impact) to parietal lobe and thus to occipital lobe and gets reflected back in the opposite direction as a tensile stress wave surfacing upon the frontal lobe towards the site of Injury, thus explaining the concept of Coup and Contre Coup Injury. Consider the Fig.4.53 which shows the frontal lobe under compression and the change in the magnitude of stress towards occipital lobe which is in tension as observed in Fig 4.54. The maximum pressure is observed around the peak value of the acceleration.
- The maximum Shear stress values are obtained in the regions of frontal lobe and occipital lobe which are under compression, while parietal and temporal lobes are under tension.
- The maximum von Mises stress values are obtained in the regions around the brain stem. The concussions which happen in this region are due to shear stress as location of maximum von Mises stress is not on the brain.

4.6.2 45° to Frontal

4.6.2.1 Drop Height of 2 feet

Figure 4.70 Normal stress S_x 45° to Frontal 2 feet

Figure 4.71 Normal stress S_x 45° to Frontal 2 feet

Figure 4.72 Normal stress S_y 45° to Frontal 2 feet

Figure 4.73 Normal stress S_y 45° to Frontal 2 feet

Figure 4.74 Normal stress S_z 45° to Frontal 2 feet

Figure 4.75 von Mises 45° to Frontal 2 feet

4.6.2.2 Drop Height of 3 feet

Figure 4.82 Normal Stress S_x 45° to Frontal 3 feet

Figure 4.83 Normal Stress S_x 45° to Frontal 3 feet

Figure 4.84 Shear stress S_{xy} 45° to Frontal 3 feet

Figure 4.85 Shear stress S_{xy} 45° to Frontal 3 feet

Figure 4.86 Normal stress S_y 45° to Frontal 3 feet

Figure 4.87 von Mises stress 45° to Frontal 3 feet

Contour Plot
Stress (S_{yz} in MPa)
Single Average
Min = -1.10E-01
Max = 4.49E-01
Node 919

Y
Z
X

Figure 4.88 Shear stress S_{yz} 45° to Frontal 3 feet

Model info: k8dmg_3dmg
Result: H:\ST\studies\Dr.Jay\comet\results\k8dmg\k8dmg_3dmg_4000
Loadcase 1: Time = 5.040E+003
Frame 64

Contour Plot
Stress (S_{xx} in MPa)
Single Average
Min = -1.10E-01
Max = 4.49E-01
Node 919

Y
Z
X

Figure 4.89 Normal stress S_{xx} 45° to Frontal 3 feet

Contour Plot
Stress (S_{xx} in MPa)
Single Average
Min = -1.10E-01
Max = 4.49E-01
Node 919

Y
Z
X

Figure 4.90 Normal stress S_{xx} 45° to Frontal 3 feet

Model info: k8dmg_3dmg
Result: H:\ST\studies\Dr.Jay\comet\results\k8dmg\k8dmg_3dmg_4000
Loadcase 1: Time = 5.7600E+003
Frame 40

Contour Plot
Stress (S_{xx} in MPa)
Single Average
Min = -1.10E-01
Max = 4.49E-01
Node 919

Y
Z
X

Figure 4.91 Shear stress S_{yx} 45° to Frontal 3 feet

4.6.2.3 Drop Height of 4 feet

Contour Plot
Stress (S_{xx} in MPa)
Single Average
Min = -1.10E-01
Max = 4.49E-01
Node 919

Y
Z
X

Figure 4.92 Normal Stress S_{xx} 45° to Frontal 4 feet

Model info: k8dmg_3dmg
Result: H:\ST\studies\Dr.Jay\comet\results\k8dmg\k8dmg_3dmg_4000
Loadcase 1: Time = 5.000E+003
Frame 46

Contour Plot
Stress (S_{yy} in MPa)
Single Average
Min = -1.10E-01
Max = 4.49E-01
Node 919

Y
Z
X

Figure 4.93 Normal Stress S_{yy} 45° to Frontal 4 feet

Figure 4.95 Shear stress S_{xy} 45° to Frontal 4 feet

Figure 4.97 Shear stress S_{yz} 45° to Frontal 4 feet

Figure 4.99 Normal stress S_z 45° to Frontal 4 feet

A diagram illustrating the addition of two vectors, T and F , to find their resultant R using the triangle rule. Vector T is represented by a green arrow pointing upwards and to the right. Vector F is represented by a blue arrow pointing downwards and to the right. The resultant vector R is represented by a red arrow that connects the tip of vector F to the tip of vector T , forming a triangle.

62

Contour Plot
Stress YZ (Scalar value)
Simple Average

8.94E-03
7.06E-03
4.49E-03
1.97E-03
-7.17E-04
-3.31E-03
-5.96E-03
-8.49E-03

Max = 7.568E-03
Node 6347
Min = -6.583E-03
Node 6167

Contour Plot
Stress Z (Scalar value)
Simple Average

1.425E-01
9.705E-02
5.156E-02
6.866E-03
3.943E-02
8.482E-02
-1.304E-01
-1.798E-01

■ No result

Max = 1.196E-01
Node 9450
Min = -1.531E-01

Carbor-Plot
Von Mises/Scalar
Simple Average

2.40E-02
2.10E-02
1.742E-02
1.379E-02
1.006E-02
6.534E-03
2.98E-03
-7.250E-04

No result

Min = 2.292E-02
Node 6734

4.6.2.5 Discussion

The normal stresses values obtained from the Finite element simulation are listed below.

Table 4.6 Normal Stress values on brain from FE Simulation of 45° to Frontal Impact

Height (feet)	Stress X (MPa)		Stress Y (MPa)		Stress Z (MPa)	
	Tension	Compression	Tension	Compression	Tension	Compression
2	-1.16E-01	9.06E-02	-1.09E-01	9.06E-02	-1.12E-01	9.06E-02
3	-1.50E-01	1.20E-01	-1.42E-01	1.19E-01	-1.43E-01	1.19E-01
4	-1.60E-01	1.21E-01	-1.50E-01	1.21E-01	-1.51E-01	1.21E-01
5	-1.85E-01	1.43E-01	-1.75E-01	1.43E-01	-1.76E-01	1.43E-01

The Shear stress values obtained for different drops from the finite element simulation are listed below

Table 4.7 Shear Stress values on brain from the FE Simulation of 45° to Frontal Impact

Height (feet)	Stress XY (MPa)	Stress YZ (MPa)	Stress ZX (MPa)
2	-9.80E-03	6.37E-03	5.09E-03
3	-1.23E-02	8.04E-03	6.58E-03
4	-1.33E-02	9.01E-03	7.01E-03
5	-1.46E-02	9.65E-03	7.77E-03

The Values when used in the Mohr Circle calculation, yielded the following results

Table 4.8 Results Obtained from Mohr Circle Analysis of 45° to Frontal Impact

Height (feet)	Principal Stresses (MPa)			Max Shear Stress (MPa)	von Mises (MPa)
	P-1	P-2	P-3		
2	-1.01E-01	-1.09E-01	-1.27E-01	1.28E-02	2.29E-02
3	-1.32E-01	-1.39E-01	-1.64E-01	1.59E-02	2.89E-02
4	-1.39E-01	-1.47E-01	-1.74E-01	1.75E-02	3.18E-02
5	-1.63E-01	-1.72E-01	-2.01E-01	1.90E-02	3.45E-02

The Maximum Pressure values observed on the brain obtained from the simulation are tabulated below.

Table 4.9 Pressures on the Brain due to 45° to Frontal Impact from different heights

Height (feet)	HICP	Velocity of Fall (2gh) ^{0.5} m/s	Pressure on Brain –Tension (MPa)
2	1.46	3.46	1.10E-01
3	1.80	4.24	1.42E-01
4	1.93	4.89	1.51E-01
5	2.17	5.47	1.75E-01

Figure 4.112 Comparison of Pressure on Brain and HICP during 45° to Frontal Impact

Figure 4.113 Maximum Principal Stress and von Mises Stress on Brain obtained from FE Simulation of 45° to Frontal Impact

Figure 4.114 Stress variation on brain with respect to drop height in 45 to Frontal Impact

Upon observing the results of the simulation the following information can be inferred.

- One can see that the pressure wave travels from the frontal lobe (site of impact) to parietal lobe and then to occipital lobe and gets reflected back in the opposite direction as a tensile stress wave surfacing upon the frontal lobe towards the site of impact explaining the concept of Coup and Contre Coup Injury. One can observe that in Fig 4.70 the site of injury is in compression and in Fig 4.71 the change in magnitude of stress to tension in occipital lobe specifying the travel of wave. The maximum pressure is observed around the peak of the impact curve specifying the travel of the pressure wave during the impact.
- The maximum shear stress values are obtained in the regions of parietal lobe (top of the head) and occipital lobe which are under tension, while brain is under compression from both sides along the ears.
- The maximum von Mises stress values are obtained in the regions around the brain stem and on the parietal lobe and occipital lobe along the line of impact. The rotation of the brain is predominant in this region when compared to frontal region implying the effect of angular acceleration along with the linear acceleration for an injury in this region.

4.6.3 Lateral

4.6.3.1 Drop Height of 2 feet

Contour Plot
Stress 1 (Sdstrvalue)
Stress Average
1.000E-01
-1.700E-02
-1.400E-02
-1.100E-02
-8.000E-03
-5.000E-03
-2.000E-03
0.000E+00
Max = 1.000E-01
Min = -1.700E-02
Node 12010

Figure 4.115 von Mises stress Lateral 2 feet

Model info: Sdstr_2feet
Result: H:\ST\stud\Dr.Jay\current\results\skull\2feet\Sdstr_2feetA036
Loadcase 1: Time = 0.000s+003
Frame 78
Contour Plot
Stress 1 (Sdstrvalue)
Stress Average
1.000E-01
-1.700E-02
-1.400E-02
-1.100E-02
-8.000E-03
-5.000E-03
-2.000E-03
0.000E+00
Max = 1.000E-01
Min = -1.700E-02
Node 12010

Figure 4.116 Normal stress S_x Lateral 2 feet

Contour Plot
Stress 1 (Sdstrvalue)
Stress Average
1.000E-01
-1.700E-02
-1.400E-02
-1.100E-02
-8.000E-03
-5.000E-03
-2.000E-03
0.000E+00
Max = 1.000E-01
Min = -1.700E-02
Node 12010

Figure 4.117 Normal stress S_y Lateral 2 feet

Model info: Sdstr_2feet
Result: H:\ST\stud\Dr.Jay\current\results\skull\2feet\Sdstr_2feetA036
Loadcase 1: Time = 0.000s+003
Frame 51
Contour Plot
Stress 1 (Sdstrvalue)
Stress Average
1.000E-01
-1.700E-02
-1.400E-02
-1.100E-02
-8.000E-03
-5.000E-03
-2.000E-03
0.000E+00
Max = 1.000E-01
Min = -1.700E-02
Node 12010

Figure 4.118 Normal stress S_z Lateral 2 feet

Contour Plot
Stress 1 (Sdstrvalue)
Stress Average
1.000E-01
-1.700E-02
-1.400E-02
-1.100E-02
-8.000E-03
-5.000E-03
-2.000E-03
0.000E+00
Max = 1.000E-01
Min = -1.700E-02
Node 12010

Figure 4.119 Normal stress S_x Lateral 2 feet

Model info: Sdstr_2feet
Result: H:\ST\stud\Dr.Jay\current\results\skull\2feet\Sdstr_2feetA036
Loadcase 1: Time = 0.000s+003
Frame 51
Contour Plot
Stress 1 (Sdstrvalue)
Stress Average
1.000E-01
-1.700E-02
-1.400E-02
-1.100E-02
-8.000E-03
-5.000E-03
-2.000E-03
0.000E+00
Max = 1.000E-01
Min = -1.700E-02
Node 12010

Figure 4.120 Normal stress S_y Lateral 2 feet

Figure 4.121 Normal stress S_z Lateral 2 feet

Figure 4.122 Normal stress S_z Lateral 2 feet

Figure 4.123 Normal stress S_z Lateral 2 feet

Figure 4.124 Shear stress S_{xy} Lateral 2 feet

Figure 4.125 Shear stress S_{xy} Lateral 2 feet

Figure 4.126 Shear stress S_{xy} Lateral 2 feet

A diagram of a lever system. A horizontal beam is pivoted on a triangular fulcrum. A red weight (load) is attached to the left end of the beam, and a blue weight (effort) is attached to the right end. The beam is tilted upwards at an angle.

69

4.6.3.2 Drop Height of 3 feet

Figure 4.133 Normal stress S_x Lateral 3 feet

Figure 4.134 Normal stress S_x Lateral 3 feet

Figure 4.135 Normal stress S_x Lateral 3 feet

Figure 4.136 Normal stress S_y Lateral 3 feet

Figure 4.137 Normal stress S_z Lateral 3 feet

Figure 4.138 Normal stress S_z Lateral 3 feet

Figure 4.139 Shear stress S_{xy} Lateral 3 feet

Figure 4.140 Shear stress S_{xy} Lateral 3 feet

Figure 4.141 Shear stress S_{xy} Lateral 3 feet

Figure 4.142 Shear stress S_{xy} Lateral 3 feet

Figure 4.143 Shear stress S_{yz} Lateral 3 feet

Figure 4.144 Shear stress S_{yz} Lateral 3 feet

Figure 4.151 von Mises stress Lateral 4 feet

Figure 4.152 Normal stress S_z Lateral 4 feet

Figure 4.153 Shear stress S_{xy} Lateral 4 feet

Figure 4.154 Shear stress S_{xy} Lateral 4 feet

Figure 4.155 Shear stress S_{yz} Lateral 4 feet

Figure 4.156 Shear stress S_{yz} Lateral 4 feet

Figure 4.157 Shear stress S_{xx} Lateral 4 feet

Figure 4.158 Shear stress S_{xx} Lateral 4 feet

4.6.3.4 Drop Height of 5 feet

Figure 4.159 Normal stress S_x Lateral 5 feet

Figure 4.160 Normal stress S_x Lateral 5 feet

Figure 4.161 Normal stress S_x Lateral 5 feet

Figure 4.162 Normal stress S_y Lateral 5 feet

Figure 4.164 Normal stress S_z Lateral 5 feet

Figure 4.166 Shear stress S_{xy} Lateral 5 feet

Figure 4.168 Shear stress S_{yz} Lateral 5 feet

Contour Plot
Stress (2-D Stress Intensity)
Simple Average
Min = -1.171E-03
Max = 1.171E-03
Node 7927
Node 8107

Figure 4.169 Shear stress S_{yz} Lateral 4 feet

Model info: Side_Sheet
Result: H1STab0101JoyCurrentResultSideSheet_Side_Sheet
Loadcase 1: Time = 0.001s
Frame 78

Contour Plot
Stress (2-D Stress Intensity)
Simple Average
Min = -1.171E-03
Max = 1.171E-03
Node 7927
Node 8107

Figure 4.170 Shear stress S_{zx} Lateral 5 feet

Contour Plot
Stress (2-D Stress Intensity)
Simple Average
Min = -1.171E-03
Max = 1.171E-03
Node 7927
Node 8107

Figure 4.171 Shear stress S_{zx} Lateral 5 feet

Model info: Side_Sheet
Result: H1STab0101JoyCurrentResultSideSheet_Side_Sheet
Loadcase 1: Time = 0.001s
Frame 87

Contour Plot
Von Mises Stress Intensity
Simple Average
Min = -1.171E-03
Max = 1.171E-03
Node 7927
Node 8107

Figure 4.172 von Mises Lateral 5 feet

4.6.2.5 Discussion

The normal stresses values obtained from the Finite element simulation are listed below.

Table 4.10 Normal Stress Values on brain from FE Simulation of Lateral Impact

Height (feet)	Stress X (MPa)		Stress Y (MPa)		Stress Z (MPa)	
	Tension	Compression	Tension	Compression	Tension	Compression
2	-1.45E-01	1.09E-01	-1.37E-01	1.16E-01	-1.44E-01	1.18E-01
3	-1.72E-01	1.41E-01	-1.59E-01	1.21E-01	-1.58E-01	1.23E-01
4	-1.99E-01	1.30E-01	-1.92E-01	1.34E-01	-1.93E-01	1.34E-01
5	-2.20E-01	1.40E-01	-2.05E-01	1.49E-01	-2.11E-01	1.50E-01

The Shear stress values obtained for different drops from the finite element simulation are listed below

Table 4.11 Shear Stress values on brain from the FE Simulation of Lateral Impact

Height (feet)	Stress XY (MPa)	Stress YZ (MPa)	Stress ZX (MPa)
2	-1.12E-02	-6.91E-03	-8.42E-03
3	-1.30E-02	-8.93E-03	-7.93E-03
4	-1.44E-02	-9.22E-03	-9.99E-03
5	-1.54E-02	-1.10E-02	-1.42E-02

The values when used in the Mohr Circle calculation, yielded the following results

Table 4.12 Results Obtained from Mohr Circle Analysis for lateral Impact

Height (feet)	Principal Stresses (MPa)			Max Shear Stress (MPa)	von Mises (MPa)
	P-1	P-2	P-3		
2	-1.29E-01	-1.37E-01	-1.60E-01	1.56E-02	2.81E-02
3	-1.49E-01	-1.55E-01	-1.85E-01	1.81E-02	3.34E-02
4	-1.80E-01	-1.86E-01	-2.18E-01	1.86E-02	3.49E-02
5	-1.95E-01	-2.01E-01	-2.40E-01	2.28E-02	4.31E-02

The Maximum Pressure values observed on the brain obtained from the simulation are tabulated below.

Table 4.13 Pressures on the Brain due to Lateral Impact from different heights

Height (feet)	HICP (MPa)	Velocity of Fall $(2gh)^{0.5}$ m/s	Pressure on Brain Tension (MPa)
2	1.12	3.46	1.44E-01
3	1.30	4.24	1.62E-01
4	1.46	4.89	1.86E-01
5	1.55	5.47	2.00E-01

Figure 4.173 Comparison of Pressure on Brain and HICP during Lateral Impact

Figure 4.174 Maximum Principal Stress and von Mises Stress on Brain obtained from FE Simulation of Lateral Impact

Figure 4.175 Stress variations on brain with respect to height for impacts in Lateral region

Upon observing the results of the simulation the following information can be inferred.

- One can see that the pressure wave travels from the ear side of the brain (site of impact on parietal lobe) to other side and gets reflected back in the opposite direction as a tensile stress wave surfacing upon the occipital lobe towards the site of impact explaining the concept of Coup and Contre Coup Injury (Refer to Fig B28-B41). The maximum pressure is observed around the peak acceleration of the impact curve.
- The maximum Shear stress values are obtained in the regions of parietal lobe (top of the head) near the impact region and temporal lobe which are under compression, while the parietal lobe and regions of temporal lobe near the impact regions are under tension.
- The maximum von Mises stress values are obtained in the regions around the brain stem and on the parietal lobe and occipital lobe along the line of impact.
- Shear stress distribution for the given HICP is predominant in this region when compared to other regions implying the presence of dominating angular acceleration compared with the linear acceleration in this region.

4.6.4 Posterior

4.6.4.1 Drop height of 2 feet

Figure 4.176 Normal stress S_x Posterior 2 feet

Figure 4.177 Normal stress S_x Posterior 2 feet

Figure 4.178 von Mises stress Posterior 2 feet

Figure 4.179 Normal stress S_y Posterior 2 feet

Figure 4.180 Normal stress S_z Posterior 2 feet

Figure 4.181 Shear stress S_{xy} Posterior 2 feet

Figure 4.182 Shear stress S_{xy} Posterior 2 feet

Figure 4.183 Shear stress S_{xy} Posterior 2 feet

Figure 4.184 Shear stress S_{yz} Posterior 2 feet

Figure 4.185 Shear stress S_{yz} Posterior 2 feet

Figure 4.186 Shear stress S_{xz} Posterior 2 feet

Figure 4.187 Shear stress S_{xz} Posterior 2 feet

4.6.3.2 Drop Height of 3 feet

Figure 4.188 Normal stress S_x Posterior 3 feet

Figure 4.189 Normal stress S_x Posterior 3 feet

Figure 4.190 Normal stress S_y Posterior 3 feet

Figure 4.191 Normal stress S_y Posterior 3 feet

Figure 4.192 Normal stress S_z Posterior 3 feet

Figure 4.193 von Mises stress Posterior 3 feet

Figure 4.194 Shear stress S_{xy} Posterior 3 feet

Figure 4.195 Shear stress S_{xy} Posterior 3 feet

Figure 4.196 Shear stress S_{yz} Posterior 3 feet

Figure 4.197 Shear stress S_{yz} Posterior 3 feet

Figure 4.198 Shear stress S_{xz} Posterior 3 feet

Figure 4.199 Shear stress S_{xz} Posterior 3 feet

4.6.4.3 Drop Height of 4 feet

Figure 4.200 Normal Stress S_x Posterior 4 feet

Figure 4.201 Normal Stress S_x Posterior 4 feet

Figure 4.202 Normal stress S_y Posterior 4 feet

Figure 4.203 Normal stress S_y Posterior 4 feet

Figure 4.204 Normal stress S_z Posterior 4 feet

Figure 4.205 Shear stress S_{xy} Posterior 4 feet

Figure 4.207 von Mises stress Posterior 4 feet

Figure 4.209 Shear stress S_{zx} Posterior 4 feet

85

4.6.3.4 Drop Height of 5 feet

Figure 4.211 Normal stress S_x Posterior 5 feet

Figure 4.212 Normal stress S_x Posterior 5 feet

Figure 4.213 Normal stress S_y Posterior 5 feet

Figure 4.214 Normal stress S_y Posterior 5 feet

Figure 4.215 Normal stress S_z Posterior 5 feet

Figure 4.216 von Mises stress Posterior 5 feet

Contour Plot
Stress (12.0 MPa units)
Stress Average
Min = 1.01E-02
Max = 1.01E-02
Node 9147

Figure 4.217 Shear stress S_{xy} Posterior 5 feet

Model info: back_Sheet
Result: H:\STudies\OJ\j\comet\results\Back\Sheet\back_Sheet\007
Loadcase 1: Time = 5.5254e-003
Frame 16

Contour Plot
Stress (12.0 MPa units)
Stress Average
Min = 1.01E-02
Max = 1.01E-02
Node 9147

Figure 4.218 Shear stress S_{xy} Posterior 5 feet

Contour Plot
Stress (12.0 MPa units)
Stress Average
Min = 1.01E-02
Max = 1.01E-02
Node 9147

Figure 4.219 Shear stress S_{yz} Posterior 5 feet

Model info: back_Sheet
Result: H:\STudies\OJ\j\comet\results\Back\Sheet\back_Sheet\007
Loadcase 1: Time = 5.5254e-003
Frame 16

Contour Plot
Stress (12.0 MPa units)
Stress Average
Min = 1.01E-02
Max = 1.01E-02
Node 9147

Figure 4.220 Shear stress S_{yz} Posterior 5 feet

Contour Plot
Stress (12.0 MPa units)
Stress Average
Min = 1.01E-02
Max = 1.01E-02
Node 9147

Figure 4.221 Shear stress S_{xz} Posterior 4 feet

Model info: back_Sheet
Result: H:\STudies\OJ\j\comet\results\Back\Sheet\back_Sheet\007
Loadcase 1: Time = 5.5254e-003
Frame 16

Contour Plot
Stress (12.0 MPa units)
Stress Average
Min = 1.01E-02
Max = 1.01E-02
Node 9147

Figure 4.222 Shear stress S_{xz} Posterior 5 feet

4.6.4.5 Discussion

The normal stresses values obtained from the Finite element simulation are listed below.

Table 4.14 Normal Stress Values on brain from FE Simulation for Posterior Impact

Height (feet)	Stress X (MPa)		Stress Y (MPa)		Stress Z (MPa)	
	Tension	Comp	Tension	Comp	Tension	Comp
2	-1.26E-01	1.11E-01	-1.28E-01	1.11E-01	-1.26E-01	1.11E-01
3	-1.43E-01	1.30E-01	-1.42E-01	1.30E-01	-1.43E-01	1.30E-01
4	-1.66E-01	1.47E-01	-1.68E-01	1.47E-01	-1.66E-01	1.47E-01
5	-1.90E-01	1.63E-01	-1.92E-01	1.63E-01	-1.90E-01	1.63E-01

The Shear stress values obtained for different drops from the finite element simulation are listed below

Table 4.15 Shear Stress values on brain from the FE Simulation for posterior impact

Height (feet)	Stress XY (MPa)	Stress YZ (MPa)	Stress ZX (MPa)
2	7.14E-03	-1.35E-02	-6.15E-03
3	8.36E-03	-1.53E-02	-6.85E-03
4	9.47E-03	-1.70E-02	-7.87E-03
5	1.13E-02	-2.00E-02	-9.14E-03

The Values when used in the Mohr Circle calculation, yielded the following results

Table 4.16 Results Obtained from Mohr Circle Analysis for posterior impact.

Height (feet)	Principal Stresses (MPa)			Max Shear Stress (MPa)	von Mises (MPa)
	P-1	P-2	P-3		
2	-1.08E-01	-1.31E-01	-1.41E-01	1.61E-02	2.86E-02
3	-1.22E-01	-1.48E-01	-1.58E-01	1.81E-02	3.25E-02
4	-1.43E-01	-1.72E-01	-1.84E-01	2.04E-02	3.64E-02
5	-1.63E-01	-1.98E-01	-2.11E-01	2.41E-02	4.32E-02

The Maximum Pressure values observed on the brain obtained from the simulation are tabulated below.

Table 4.17 Pressures on the Brain due to posterior Impact from different heights

Height (feet)	HICP (MPa)	Velocity of Fall (2gh) ^{0.5} m/s	Pressure on Brain - Tension(MPa)
2	1.12	3.46	1.44E-01
3	1.30	4.24	1.62E-01
4	1.46	4.89	1.86E-01
5	1.55	5.47	2.00E-01

Figure 4.223 Comparison of Pressure on Brain and HICP during posterior Impact

Figure 4.224 Maximum Principal Stress and von Mises Stress on Brain obtained from FE Simulation for posterior impact.

Figure 4.225 Stress Variation on Brain with height during impact on posterior region

Upon observing the results of the simulation the following information can be inferred.

- One can see that the pressure wave travels from the occipital lobe (site of impact) to parietal lobe and thus to frontal lobe and gets reflected back in the opposite direction as a pressure wave surfacing upon the occipital lobe (Refer to Fig B47 and B480 towards the site of impact explaining the concept of Coup and Contre Coup Injury. The maximum Pressure is observed around the peak acceleration of the impact curve specifying the travel of the pressure wave during the impact.
- The maximum shear stress values are obtained in the regions of parietal lobe (top of the head) and occipital lobe which are under tension, while the brain is in compression from both the opposite sides.
- The maximum von Mises stress values are obtained in the regions around the brain stem and on the parietal lobe.
- The moment of the brain is not so predominant in this region when compared to 45° to frontal and lateral region implying the injury in this region is mainly due to linear acceleration

4.6.5 Overall Results Discussion

An overall comparison of the outputs obtained from all the drops will be discussed in this section.

Figure 4.226 von Mises stress Vs Drop height for different regions of impact

Figure 4.227 Maximum Principal Stress Vs Drop Height for different regions of Impact

- We know that brain is strong in compression, and weak in tension, hence only tensile stresses are considered in the injury analysis.
- The peak value of pressure on the brain (0.2 MPa-Tension) is observed in the Lateral 5 feet drop while the peak values of the HICP are observed in the posterior region. The range of pressures (0.14-0.2 MPa Tension) developed in these region are higher when compared to similar drops in other region. The maximum values of pressures developed on the brain in 45° to frontal impact (0.175 MPa Tension) and posterior region (0.177 MPa Tension) are lesser than the pressure on the brain at lateral 4 feet drop (0.186 MPa Tension). On the other hand the lowest range of pressures can be observed on the frontal region (0.06 - 0.08 MPa Tension).
- Although the Posterior regions have the highest values of HICP than the lateral region we can also observe that the lateral region has lowest impact times than the posterior region. Hence it can be understood that the injury in the lateral region is much more critical than the posterior region according to the Wayne state tolerance curve [13], which states that lower the time duration, higher the impact on brain for a given acceleration.
- The Maximum principal stress (tension) values are almost similar to that of the pressure developed on the brain, but they are in opposite sense. All the principal stress discussed above in this chapter are in negative magnitude. The maximum principal stress is observed in the lateral 5 feet drop (0.24 MPa) while the minimum is observed for frontal region (0.065 MPa). Hence either pressure or principal stress can be used as determining factor measuring the extent of brain injuries.
- The Maximum values of von Mises stress (0.043 MPa) are also observed in the Lateral 5 feet Impact while the minimum is observed for the frontal 2 feet impact (0.005 MPa).

- The shear stress can cause concussion when the maximum von Mises stresses are observed at the brain stem.
- The von Mises stresses for lateral and posterior are in the same range while the posterior and 45 to frontal region have their principal stresses in the same range for a given height.
- For any given height the lateral region has highest values of principal stresses and von Mises stresses, while the least are observed in the frontal region.
- Tensile stresses will be a deciding criteria for TBI only if there is an impact without rotation (only linear acceleration and no angular acceleration). But as we know all the impacts have rotation associated with it, hence von Mises stresses are also considered as a deciding criteria.

Hence it can be inferred that the lateral region is more susceptible to injury than other regions. This can be due to higher area of impacts, lesser thickness of skull and scalp in these regions and can be mainly due to the presence of Angular acceleration component as the line of injury is not passing through the center of mass of the head. While on the other hand the frontal region values are much low when compared to other regions making it much less susceptible to injuries.

Chapter 5

Correlation between Head acceleration and Brain Stress Distributions

5.1 Introduction

In earlier chapters the Kinematics of the Head during free fall are studied using the experimental methods and the results has been used as an input to study the brain kinetics.

In this chapter the tolerance levels for a TBI which are collected from the previous experiments will be used to determine the tolerance values of heights of drop after which the chances are higher for a TBI.

The shear stress tolerance value for a probable brain injury has been proposed by Kang [22] in his research work. The tolerance of the human brain in shear is defined as 16.5 KPa [23].

The tolerance drop heights for probable TBI from Chandrika's [25] work has been collected and the minimum of these two values will be used to determine a relation using which we can state the risk of a TBI for a given fall.

5.2 Determination of TBI Tolerance drop height using Maximum Shear stress

The Shear stress values for brain which are obtained from the Mohr's circle are plotted Y-axis for their corresponding heights for all the four region of drops namely Frontal, 45° to frontal, lateral and posterior. Considering the shear stress tolerance for the TBI as 16.5 KPa, a straight line has been drawn across the plot to determine the tolerance drop heights for the TBI. The point of intersection of the TBI limit line with the plot has been

traced down to X-axis to determine the TBI tolerance drop heights. The profile of the shear stress is approximated as a quadratic equation to minimize the human errors.

Figure 5.1 Maximum Shear Stress Vs Drop Height for the Frontal Region Impact

Figure 5.2 Maximum Shear Stress Vs Drop Height for the 45° to Frontal Region Impact

Figure 5.3 Maximum Shear Stress Vs Drop Height for the Lateral Region Impact

Figure 5.4 Maximum Shear Stress Vs Drop Height for the Posterior Region Impact

The TBI drop height tolerances for the four region of impacts calculated using the Shear stress tolerance for TBI have been tabulated below:

Table 5.1 Maximum Shear Stress on Brain and TBI Tolerance Drop Heights for the respective regions of Impact

Height (feet)	Region of Impact				Max Shear Stress (Kpa)
	Frontal	45 to Frontal	Lateral	Posterior	
2	2.759	12.808	15.574	16.089	
3	2.827	15.871	18.136	18.074	
4	3.093	17.54	18.625	20.417	
5	3.52	18.963	22.793	24.135	
TBI Tolerance Height	--	3.35	2.52	2.25	
Linear Acceleration (G)	--	125	138.67	129.14	

The following observations can be made from the Table 5.1

It should be noted that the above Tolerance heights are for TBI due to shear stress which is majorly due to the rotation of head during the impact.

- In the Frontal region it can be noted that the shear stress values are much below the tolerance level. Hence the risk of a TBI due to shear stress is minimal in this region. It can also be inferred as the effect of angular acceleration is minimal in this region which has already been discussed in earlier chapters. The higher Area of impacts and lower HICP can also be the other reasons.
- In the 45° to Frontal region the TBI tolerance for linear acceleration due to shear stress is the TBI tolerance drop height due to shear stress is 3.35 feet (125 G). It is higher than that of the lateral and posterior regions. Although it has same Pressure range as the posterior region, smaller area of Impact and smaller range of linear accelerations can be a

reason for an increase in the tolerance height. Hence it can be inferred that the angular acceleration has some role to play in causing TBI's in this region.

- In lateral region the tolerance for TBI due to shear stress is 2.52 feet (138.67 G).

Although this region has higher range of pressures on the brain, the presence of higher area of impact can be a factor in higher tolerance limit than that of the posterior region as both the lateral and posterior regions have their linear accelerations distributed over the same range. Hence it can be deduced that the Area of Impact plays an important role in Height tolerance value for TBI due to shear stress. Higher the area lower the shear stress values and higher the tolerance limit. It can also be inferred that angular acceleration has an important role for TBI in this region.

- In Posterior region the tolerance for TBI due to shear stress is 2.25 feet (129.14 G) which is lowest of all regions. It can be because of higher von Mises stresses, higher HICP and lower surface areas. It can also be observed that there is some discrepancies in the measurements in FE Analysis which also might have modified the results.

5.3 Determination of TBI Tolerance drop height using Linear Accelerations

The research in this area has been done by our research group following the criteria by Anna and group [23] and the following results have been generated by Chandrika S Abhang and have been documented in her work [24].

Table 5.2 Drop Height tolerance for TBI caused by Linear Acceleration [25]

Region	TBI Tolerance Drop Height (feet)
Front	3.125
45-to-Frontal	4.25
Lateral	2.625
Posterior	2.825

The above table shows the tolerance limit for the drop height for TBI caused by linear acceleration. It follows the similar profile as of the Principal stress. Higher the principal stress lower the TBI tolerance drop height limit.

5.4 TBI Criteria

Considering the drop height tolerances from Maximum Shear stress and Maximum Linear acceleration, the TBI can happen either because of the two cases or at least by any one of them. Hence the minimal of the two cases will be used to study injuries on the brain and to determine the tolerance limits for TBI. The Drop height tolerance level to cause TBI is tabulated below.

Table 5.3 Drop Height tolerance for TBI for respective regions of Impact

Region	TBI Tolerance Drop Height (feet)
Front	3.125
45-to-Frontal	3.35
Lateral	2.52
Posterior	2.25

It can be observed that unlike Frontal and 45 to Frontal, the TBI tolerance drop height is similar for Lateral and posterior regions which have major risk of TBI's.

The above values will be used to calculate the TBI Tolerance limits for von Mises, Maximum Principal Stress, from the plots drawn in earlier chapters.

5.4.1 Frontal region of Impact

Figure 5.5 Linear TBI tolerance for HICP and Pressure on Brain Located on plot of Comparison of Pressure on Brain and HICP during Frontal Impact.

Figure 5.6 Linear TBI tolerance for Maximum Principal Stress and von Mises stress located on plot of Comparison of Maximum Principal stress and von Mises stress during Frontal Impact.

Figure 5.7 Plot for Variation of Max. Linear Acceleration & Shear stress Vs height for frontal impact

Figure 5.8 Plot for Variation of Max. Linear Acceleration & Normal stress Vs height for frontal impact

5.4.2 45° to Frontal region of impact

Figure 5.9 Linear TBI tolerance for HICP and Pressure on Brain Located on plot of Comparison of Pressure on Brain and HICP during 45 to Frontal Impact

Figure 5.10 Linear TBI tolerance for Maximum Principal Stress and von Mises stress located on plot of Comparison of Maximum Principal stress and von Mises stress during 45 to Frontal Impact

Figure 5.11 Plot for Variation of Max. Linear Acceleration & Shear stress Vs height for 45 to frontal impact

Figure 5.12 Plot for Variation of Max. Linear Acceleration & Tensile stress Vs height for 45 to frontal impact.

5.4.3 Lateral region of impact

Figure 5.13 Linear TBI tolerance for HICP and Pressure on Brain Located on plot of Comparison of Pressure on Brain and HICP during Lateral Impact

Figure 5.14 Linear TBI tolerance for Maximum Principal Stress and von Mises stress located on plot of Comparison of Maximum Principal stress and von Mises stress during Lateral Impact.

Figure 5.15 Plot for Variation of Max. Linear Acceleration & Shear stress Vs height for lateral impact

Figure 5.16 Plot for Variation of Max. Linear Acceleration & Tensile stress Vs Height for Lateral impact

5.4.4 Posterior region of impact

Figure 5. 17 Linear TBI tolerance for HICP and Pressure on Brain Located on plot of Comparison of Pressure on Brain and HICP during Posterior Impact

Figure 5.18 Linear TBI tolerance for Maximum Principal Stress and von Mises stress located on plot of Comparison of Maximum Principal stress and von Mises stress during Posterior Impact.

Figure 5.19 Plot for Variation of Max. Linear Acceleration & Shear stress Vs height for Posterior impact

Figure 5.20 Plot for Variation of Max. Linear Acceleration & Tensile stress Vs height for Posterior impact

Perpendiculars have been drawn from the TBI Tolerance heights from the X-axis on to the plots and the plots are approximated to be curves which are derived from the curve fittings and corresponding tolerance values for HICP, Pressure on Brain, Linear acceleration, Maximum principal stress and von Mises stress have been extracted and tabulated below.

Table 5.4 TBI Tolerance Limits for different regions of Impact

Region	TBI Tolerance Limits (MPa)					
	Drop Height (feet)	Max Linear Acceleration (G)	HICP (MPa)	Pressure on Brain (MPa)	Maximum Principal Stress (MPa)	von Mises Stress (MPa)
Frontal	3.125	143.83	1.11	6.72E-02	7.16E-02	5.1E-03
45 to Frontal	3.35	125	1.80	1.42E-01	1.63E-01	3.04E-02
Lateral	2.52	138.67	1.21	1.54E-01	1.74E-01	3.01E-02
Posterior	2.25	129.14	1.74	1.32E-01	1.44E-01	2.94E-02

The following observations can be made from the table 5.4:

- As the HICP and the other corresponding values for a given height is lesser for the frontal region when compared to other regions, the tolerance limits for this region are pretty high when compared to other region. Hence higher drop heights but lower Pressures and stresses are capable of causing TBI in this region but it can be observed that most of the impact is not transferred to the brain in this region making this region safer when compared to other regions of impact. For example 3 feet drop generate a stress of 0.067 MPa in this region while Lateral region generate a stress of 0.174 MPa for just 2.5 feet. The drops below 3 feet are in the tolerance level while the drops higher than 3 feet might cause TBI's.
- For a given height, 45 to frontal have higher tolerance values for TBI's followed by frontal region of Impact. The drops below 3 feet are safe while 4 feet and 5 feet drops can cause TBI's. The 3.35 feet drop generates a stress of 0.164 MPa on brain for 3.35 feet while similar amount of 0.174 MPa can be generated for just 2.5 feet. Hence drops below 3 feet are safer in this region while the same might cause TBI's in other regions like Lateral and Posterior.

- For a given height the tolerance levels for the Lateral region are pretty lower when compared to other 3 regions. The drops below 2 feet are safe while the drops above this height might cause TBI. The highest values of von Mises stresses (0.03 MPa) and Maximum Principal Stress (0.174 MPa) are observed in this region for a lower height of 2.52 feet drop making this region more susceptible to injuries than the other regions.
- For a given drop height the tolerance levels of principal stress for the posterior regions are lower after lateral region. A mere drop at 2.25 feet produces a stress of 0.144 MPa. The drops under 2 feet are safe while the drops above 2 feet might cause TBI's. The presence of cerebellum and spinal cord makes this region pretty sensitive to injury.
- The highest value of TBI tolerance for the acceleration is observed for frontal region with 143.83 G for a drop height of 3.125 feet, while the lowest tolerance is 125 G for a drop height of 3.35 feet for 45 to frontal region. But when observed along with drop height the a higher TBI tolerance acceleration of 138.67 G is observed for a mere height of 2.52 feet, making this region more susceptible to injury, while for 45 to frontal region the tolerance value is around 125 G even for a height of 3.35 feet making this region less susceptible to TBI when compared to other regions.

The above observations can be consolidated as the following table.

Table 5.5 Safety criteria for drops in respective region using the TBI Tolerance values from table 5.4

	Drop Height (feet)			
Region	2	3	4	5
Frontal	Safe	Safe	Unsafe	Unsafe
45 to Frontal	Safe	Safe	Unsafe	Unsafe
Lateral	Safe	Unsafe	Unsafe	Unsafe
Posterior	Safe	Unsafe	Unsafe	Unsafe

5.5 Formula Proposition

From the above observations it is evident that the tolerance values for TBI's is different for different regions. TBI's can be caused either by Maximum Principal Stresses⁴ and von Mises stresses or at least one of them. Hence our research team have proposed a new formula to study the role of von Mises and Principal stress in causing TBI.

$$\frac{\sigma_{VM-regional}}{\sigma_{VM-TBI-max}} + \frac{\sigma_{MP-regional}}{\sigma_{MP-TBI-max}} \leq 1 \text{ then no TBI} \quad \dots \text{ (Eq. 5.1)}$$

Where,

$\sigma_{VM-regional}$ = von Mises stress developed on the brain due to drop or Impact,

$\sigma_{VM-TBI-max}$ = Tolerance value for TBI caused to von Mises Stress for that region of Impact
... (refer Table 5.4)

$\sigma_{MP-regional}$ = Maximum Principal Stress developed on the brain due to drop or Impact,

$\sigma_{MP-TBI-max}$ = Tolerance value for TBI caused to Maximum Principal Stress for that region
... (refer Table 5.4)

The above formula when utilized in our case yields the following results which are tabulated below

⁴ As mentioned earlier Maximum principal stress behave similar to the pressure developed on the brain, but more efficient that the later. Hence maximum principal stress are consider for the Formula Generation.

Table 5.6 TBI Stress criterion for Frontal Impact using Eq. 5.1

Height (feet)	Max Principal Stress (Mpa)	TBI tolerance for Principal Stress	Principal Stress Ratio	von Mises (Mpa)	TBI tolerance for von Mises Stress	von Mises Stress Ratio	TBI Condition
2	6.65E-02	7.16E-02	0.93	4.93E-03	5.10E-03	0.97	1.90
3	6.72E-02		0.94	5.06E-03		0.99	1.93
4	7.83E-02		1.09	5.83E-03		1.14	2.24
5	8.38E-02		1.17	6.55E-03		1.28	2.45

Table 5.7 TBI Stress criterion for 45 to Frontal Impact using Eq. 5.1

Height (feet)	Max Principal Stress Mpa	TBI tolerance for Principal Stress	Principal Stress Ratio	von Mises (Mpa)	TBI tolerance for von Mises Stress	von Mises Stress Ratio	TBI Condition
2	1.27E-01	1.63E-01	0.78	2.29E-02	3.04E-02	0.75	1.53
3	1.64E-01		1.00	2.89E-02		0.95	1.95
4	1.74E-01		1.07	3.18E-02		1.05	2.12
5	2.01E-01		1.23	3.45E-02		1.14	2.37

Table 5.8 TBI Stress criterion for Lateral Impact using Eq. 5.1

Height (feet)	Max Principal Stress (Mpa)	TBI tolerance for Principal Stress	Principal Stress Ratio	von Mises (Mpa)	TBI tolerance for von Mises Stress	von Mises Stress Ratio	TBI Condition
2	1.60E-01	1.74E-01	0.92	2.81E-02	3.01E-02	0.93	1.85
3	1.85E-01		1.06	3.34E-02		1.11	2.17
4	2.18E-01		1.25	3.49E-02		1.16	2.41
5	2.40E-01		1.38	4.31E-02		1.43	2.81

Table 5.9 TBI Stress criterion for Posterior Impact using Eq. 5.1

Height (feet)	Max Principal Stress (Mpa)	TBI tolerance for Principal Stress	Principal Stress Ratio	von Mises (Mpa)	TBI tolerance for von Mises Stress	von Mises Stress Ratio	TBI Condition
2	1.41E-01	1.44E-01	0.98	2.86E-02	2.94E-02	0.97	1.95
3	1.58E-01		1.10	3.25E-02		1.11	2.21
4	1.84E-01		1.28	3.64E-02		1.24	2.52
5	2.11E-01		1.47	4.32E-02		1.47	2.94

The above proposed formula should be considered only when either of $\frac{\sigma_{VM-regional}}{\sigma_{VM-TBI-max}}$ or

$\frac{\sigma_{MP-regional}}{\sigma_{MP-TBI-max}}$ is less than 1. For example consider the Impact for a drop height of 2 feet at

45 to Frontal the TBI tolerance ratio for principal stress is 0.78 and the TBI tolerance ratio for the von Mises stress is 0.75. Although it may seem that the von Mises and Principal stresses don't cause any TBI individually, but when considered together its sum is greater than 1 implying that there is a sufficient chance of TBI in this region for 2 feet drop in 45 to frontal region.

Hence it is evident that although the individual effect Principal Stress or von Mises Stress might occur as if they won't cause any TBI, but in reality their effect as an entity together might cause TBI.

Chapter 6

Conclusions and Recommendations

6.1 Conclusions

In this study Kinematics of the head were studied by conducting experiments using a Hybrid Dummy Head form and the HICP developed due to free fall from different heights has been used as an input to a 3-D FE model to study the kinetics of the brain and based upon the shear stress criteria by Ward [3], the TBI tolerances heights were obtained which were used in conjunction with the TBI drop heights obtained from the work of Chandrika Abhang[25] which used Anna[24] criteria, based on accelerations to obtain TBI tolerance drop heights. The above results were used to calculate the TBI tolerance values for linear acceleration, Principal stresses and von Mises stresses. The response of the brain to an input of HICP was also studied and the following observations were made:

- TBI's are highly dependent on the site of Impact. Criteria for Linear acceleration which cause TBI differ from region to region. A HICP which is safe in a particular region might cause serious injury when applied in another region.
- The rotation of head which implies presence of angular accelerations is observed more in Lateral and 45 to Frontal regions when compared to Frontal and Posterior regions.
- The Tensile stresses, pressure on the brain and maximum principal stresses were almost similar hence principal stress values were used in formula proposition for determining a TBI. The tensile stress and pressure travel in the similar manner while the principal stress travels in opposite direction of above two.

- Shear stress plays a major role in causing TBI if von Mises stress is not dominant in that region.
- von Mises stresses gives a better idea about the angular acceleration of head during impact than shear stresses, hence they were also used in formula proposition for determining a risk of TBI.
- Area of Impact also plays an important role in determination of TBI tolerance limits due to shear stress. Higher the area, lower the shear stress values and higher the tolerance limit.
- A new formula has been proposed to determine the risk of TBI in a particular region due to free fall

$$\frac{\sigma_{VM-regional}}{\sigma_{VM-TBI-max}} + \frac{\sigma_{MP-regional}}{\sigma_{MP-TBI-max}} \leq 1 \text{ then no TBI}$$

Where,

$\sigma_{VM-regional}$ = von Mises stress developed on the brain due to drop or Impact,

$\sigma_{VM-TBI-max}$ = Tolerance value for TBI caused to von Mises Stress for that region of Impact

$\sigma_{MP-regional}$ = Maximum Principal Stress developed on the brain due to drop or Impact,

$\sigma_{MP-TBI-max}$ = Tolerance value for TBI caused to Maximum Principal Stress for that region

Where $\frac{\sigma_{VM-regional}}{\sigma_{VM-TBI-max}}$ accounts for the angular acceleration of head during impact and

$\frac{\sigma_{MP-regional}}{\sigma_{MP-TBI-max}}$ accounts for the linear component. Hence it can be inferred that angular

acceleration component in additional to linear acceleration component plays an important role in causing a TBI.

- Although when considered individually, Principal Stress or von Mises Stress might be below the tolerance level and can be mistaken for no risk of TBI, but in reality their effect as an entity together might increase the risk of TBI.
- The lateral region is much susceptible for a TBI followed by posterior, while the chances of injury for a given HICP is lesser for Frontal region.
- The TBI Tolerance limits have been tabulated below

Table 6.1 TBI Tolerance Limits for respective regions of Impact

Region	TBI Tolerance Limits					
	Drop Height (feet)	Max Linear Acceleration (G)	HICP (MPa)	Pressure on Brain (MPa)	Maximum Principal Stress (MPa)	von Mises Stress (MPa)
Frontal	3.125	143.83	1.11	6.72E-02	7.16E-02	5. 1E-03
45 to Frontal	3.35	125	1.80	1.42E-01	1.63E-01	3.04E-02
Lateral	2.52	138.67	1.21	1.54E-01	1.74E-01	3.01E-02
Posterior	2.25	129.14	1.74	1.32E-01	1.44E-01	2.94E-02

6.2 Recommendations

There are several suggestions to improve the quality of study to obtain a detail response of brain under applied HICP on head. The following suggestions can be helpful for future research:

- Area of Impact- Proper methods to measure the 3 dimensional area of impact has to be used as it was evident from this study that it plays a major role in Impact pressure calculations and other tolerance values.
- Impact Pressure- The impact pressures which were calculated manually has been used in this study. A proper means to measure the impact pressure during the impact should be followed to validate the pressures for calculating precision tolerances. With more means available to measure the impact pressure being available, the same should be used to precision validation and pressure measurement.
- Pressure Films- New variety of Pressure films are available which are specifically designed for measuring Impact pressures, The drop tests can be repeated with these to get an accurate value of the HICP during Impact.
- Material properties for the head – Update the material properties of the model as new data would be available from latest research.
- Improvisation of Model – The model has some layers of the head missing in it, a developed model with Cerebro Spinal Fluid, separate hemispheres, cerebellum and other minute details such as foldings on the surface of the brain should be prepared, which would give much more precise results.
- Angular Acceleration: As it was evident that the angular accelerations caused due to the rotation of head plays a major role in the TBI, Proper experimental set up has

to be developed to perform drop tests to record the angular acceleration during impact, and the same can be used as an input to recalculate the more appropriate tolerance value for TBI's.

- A new criteria for determination of TBI using accelerations can be developed.

$$\frac{a_{Max-regional}}{a_{TBI}} + \frac{\alpha_{Max-regional}}{\alpha_{TBI}} \leq 1 \text{ then no TBI}$$

Where,

$a_{Max-regional}$ = Maximum Linear acceleration in a particular region during impact.

a_{TBI} = Tolerance value of linear acceleration for TBI in that particular region.

$\alpha_{Max-regional}$ = Maximum angular acceleration in a particular region during impact.

α_{TBI} = Tolerance value of angular acceleration for TBI in that particular region.

- The velocity of fall during impact has been tabulated in earlier sections, proper validation has to be done to propose the TBI tolerance values for velocity.
- Instead of the peak acceleration curve the entire impact curve should be used in FE study to observe the response of brain under application of given pressure on head.

Appendix A

The results obtained from the Topaq Analyzer have been shown below

A1 Frontal

A1.1 Pressure film deformations

Fig. A1 Frontal 3 feet

Fig. A2 Frontal 2 Feet

Fig. A3 Frontal 4 feet

Fig. A4 Frontal 5 Feet

A1.2 Topaq analyzer Outputs

Fig. A5 Topaq Analyzer output for Frontal 2 feet Impact

Fig. A6 Topaq Analyzer output for Frontal 3 feet Impact

Fig. A7 Topaq Analyzer output for Frontal 4 feet Impact

Fig. A8 Topaq Analyzer output for Frontal 5 feet Impact

A2 45° to Frontal

A2.1 Pressure film deformations

Fig. A9 2 feet 45° to Frontal

Fig. A10 3 feet 45° to Frontal

Fig. A11 4 feet 45° to Frontal

Fig. A12 5 feet 45° to Frontal

A2.2 Topaq analyzer Outputs

Fig. A13 Topaq Analyzer output for 45° to Frontal 2 feet

Fig. A14 Topaq Analyzer output for 45° to Frontal 3 feet

Fig. A15 Topaq Analyzer output for 45° Frontal 4 feet Impact

Fig. A16 Topaq Analyzer output for 45° Frontal 5 feet Impact

A3 Lateral

A3.1 Pressure film deformations

Fig. A17 2 feet Lateral

Fig. A18 3 feet Lateral

Fig. A19 4 feet Lateral

Fig. A20 5 feet Lateral

A3.2 Topaq analyzer Outputs

Fig. A21 Topaq Analyzer output for Lateral 2 feet Impact

Fig. A22 Topaq Analyzer output for Lateral 3 feet Impact

Fig. A23 Topaq Analyzer output for Lateral 4 feet Impact

Fig. A24 Topaq Analyzer output for Lateral 5 feet Impact

A4 Posterior

A4.1 Pressure film deformations

Fig. A25 2 feet Posterior

Fig. A26 3 feet Posterior

Fig. A27 4 feet Posterior

Fig. A28 5 feet Posterior

A4.2 Topaq analyzer Outputs

Fig. A29 Topaq Analyzer output for Posterior 2 feet Impact

Fig. A30 Topaq Analyzer output for Posterior 3 feet Impact

Fig. A31 Topaq Analyzer output for Posterior 4 feet Impact

Fig. A32 Topaq Analyzer output for Posterior 5 feet Impact

Appendix B

The results obtained from the FE Simulation are placed below.

B1 Frontal

B1.1 Drop Height of 2 feet

Contour Plot
Pressure (Equivalent)
Drop Average
Max = 1.375E-02
Min = -1.375E-02
Nodes 9325

Model info: Frontal_2feet
Result: H10T04en04j04en04en04Frontal_2feet_2feet_003
Location 1: Time = 2.3625E-03
Frame 38

Contour Plot
Pressure (Equivalent)
Drop Average
Max = 1.375E-02
Min = -1.375E-02
Nodes 9325

Figure B1 Pressure Frontal 2 feet

Figure B2 Pressure Frontal 2 feet

STRESS TENSOR DEFINITION					
σ_{xx} [MPa]	-6.32	τ_{xy} [MPa]	0.162	τ_{yz} [MPa]	-0.068
τ_{yx} [MPa]	0.162	σ_{yy} [MPa]	-6.37	τ_{yz} [MPa]	0.222
τ_{zx} [MPa]	-0.068	τ_{zy} [MPa]	0.222	σ_{zz} [MPa]	-6.32

MOHR CIRCLE SOLUTION		
σ_I [MPa]	Principal stress I	-6.1011
σ_{II} [MPa]	Principal stress II	-6.256
σ_{III} [MPa]	Principal stress III	-6.6529
τ_{MAX} [MPa]	Guest - Tresca	0.2759
σ_{VM} [MPa]	Huber - Hencky - Von Mises	0.4929

Figure B3 Mohr Circle for Frontal 2 Feet Impact

B1.2 Drop Height of 3 feet

Contour Plot
Pressure(Scalar value)
Simple Average
-5.294E-02
-4.867E-02
-3.945E-02
-1.614E-02
-2.133E-03
-1.840E-02
-3.487E-02
-5.094E-02
Min = 5.373E-02
Node 7890
Min = 4.837E-02
Node 8205

Figure B4 Pressure Frontal 3 feet

Model info: Frontal_3feet
Result: H:\STudies\Dr.Jay\current\results\Frontal_3feet\Frontal_3feetA002
Loadcase 1: Time = 2.9003e-003
Frame 38

Contour Plot
Pressure(Scalar value)
Simple Average
-5.294E-02
-4.867E-02
-3.945E-02
-1.614E-02
-2.133E-03
-1.840E-02
-3.487E-02
-5.094E-02
Min = 5.373E-02
Node 7890
Min = 4.837E-02
Node 8205

Figure B5 Pressure Frontal 3 feet

STRESS TENSOR DEFINITION					
σ_{xx} [MPa]	-6.40	τ_{xy} [MPa]	0.160	τ_{xz} [MPa]	-0.1
τ_{yx} [MPa]	0.160	σ_{yy} [MPa]	-6.374	τ_{yz} [MPa]	0.222
τ_{zx} [MPa]	-0.1	τ_{zy} [MPa]	0.222	σ_{zz} [MPa]	-6.42

MOHR CIRCLE SOLUTION		
σ_I [MPa]	Principal stress I	-6.1581
σ_{II} [MPa]	Principal stress II	-6.3125
σ_{III} [MPa]	Principal stress III	-6.7235
τ_{MAX} [MPa]	Guest - Tresca	0.2827
σ_{VM} [MPa]	Huber - Hencky - Von Mises	0.5062

Figure B6 Mohr Circle for Frontal 3 Feet

B1.3 Drop Height of 4 feet

Contour Plot
Pressure (Scalar value)
Simple Average
7.346E-02
-4.491E-02
-3.637E-02
-1.703E-02
-7.220E-04
-1.827E-02
-3.781E-02
-4.639E-02
0
Min = 2.716E+00
Node 1459
Min = 3.250E-01
Node 5311

Figure B7 Pressure Frontal 4 feet

Contour Plot
Pressure (Scalar value)
Simple Average
7.346E-02
-4.491E-02
-3.637E-02
-1.703E-02
-7.220E-04
-1.827E-02
-3.781E-02
-4.639E-02
0
Min = 2.716E+00
Node 1459
Min = 3.250E-01
Node 5311

Figure B8 Pressure Frontal 4 feet

Figure B9 Mohr Circle for Frontal 4 Feet Impact

B1.4 Drop Height of 5 feet

Contour Plot
Pressure(Scalar value)
Simple Average
-8.88E-02
-4.894E-02
-3.821E-02
-1.937E-02
-4.857E-04
-2.030E-02
-4.014E-02
-2.887E-02
Min = 8.430E-02
Node 7190
Max = -4.819E-02
Node 8798

Y
X
Z

Model info: Frontal_Steel
Result: H:\STudies\Dr.Jay\current\results\Frontal\Steel\Frontal_SteelA055
Loadcase 1: Time = 2.98703e-03
Frame 38

Contour Plot
Pressure(Scalar value)
Simple Average
-8.88E-02
-4.894E-02
-3.821E-02
-1.937E-02
-4.857E-04
-2.030E-02
-4.014E-02
-2.887E-02
Min = 8.430E-02
Node 7190
Max = -4.819E-02
Node 8798

Y
X
Z

Model info: Frontal_Steel
Result: H:\STudies\Dr.Jay\current\results\Frontal\Steel\Frontal_SteelA055
Loadcase 1: Time = 2.98703e-03
Frame 38

Figure B10 Pressure Frontal 5 feet

Figure B11 Pressure Frontal 5 feet

STRESS TENSOR DEFINITION					
σ_{xx} [MPa]	-7.93	τ_{xy} [MPa]	0.22	τ_{xz} [MPa]	-0.141
τ_{yx} [MPa]	0.22	σ_{yy} [MPa]	-8	τ_{yz} [MPa]	0.27
τ_{zx} [MPa]	-0.141	τ_{zy} [MPa]	0.27	σ_{zz} [MPa]	-7.93

MOHR CIRCLE SOLUTION		
σ_I [MPa]	Principal stress I	-7.6808
σ_{II} [MPa]	Principal stress II	-7.7945
σ_{III} [MPa]	Principal stress III	-8.3847
τ_{MAX} [MPa]	Guest - Tresca	0.352
σ_{VM} [MPa]	Huber - Hencky - Von Mises	0.6546

Figure B12 Mohr Circle for Frontal 5 Feet Impact

B2 45° to Frontal

B2.1 Drop Height of 2 feet

Figure B13 Pressure 45° to Frontal 2 feet

Figure B14 Pressure 45° to Frontal 2 feet

Figure B15 Mohr Circle for 45° to Frontal 2 Feet Impact

B2.2 Drop Height of 3 feet

Custom Plot
Pressure (Stress value)
Range
Min = -1.42E-01
Max = 1.24E-01
Min/Max
Min = -0.0142
Max = 0.124
Nodes 9450

Y
Z

Model info: Abaqus: Steel
Result: H107TubexDr.Jay.comet.msh.abi0601Steel45deg_3feet4000
Loadcase 1: Time = 3.700e-03
Frame 40

Custom Plot
Pressure (Stress value)
Range
Min = -1.42E-01
Max = 1.24E-01
Min/Max
Min = -0.0142
Max = 0.124
Nodes 9450

Y
Z

Model info: Abaqus: Steel
Result: H107TubexDr.Jay.comet.msh.abi0601Steel45deg_3feet4000
Loadcase 1: Time = 3.700e-03
Frame 40

Figure B16 Pressure 45° to Frontal 3 feet

Figure B17 Pressure 45° to Frontal 3 feet

STRESS TENSOR DEFINITION					
σ_{xx} [MPa]	-15.0	τ_{xy} [MPa]	-1.23	τ_{xz} [MPa]	.658
τ_{yx} [MPa]	-1.23	σ_{yy} [MPa]	-14.2	τ_{yz} [MPa]	0.804
τ_{zx} [MPa]	.658	τ_{zy} [MPa]	0.804	σ_{zz} [MPa]	-14.3

MOHR CIRCLE SOLUTION		
σI [MPa]	Principal stress I	-13.2092
σII [MPa]	Principal stress II	-13.9074
σIII [MPa]	Principal stress III	-16.3834
τ_{MAX} [MPa]	Guest - Tresca	1.5871
σ_{VM} [MPa]	Huber - Hencky - Von Mises	2.8891

Figure B18 Mohr Circle for 45° to Frontal 3 Feet Impact

B2.3 Drop Height of 4 feet

Contour Plot
Pressure (Scalar Value)
Single Range
Min = 1.147E-01
Max = 7.796E-02
Nodes: 1453
Elements: 1453
Time: 3.000E+003
Frame: 46

Figure B19 Pressure 45° to Frontal 4 feet

Model Info: B2.3.3
Result: 11/17/2017 10:00:00
Location: 1: Time = 3.000E+003
Frame: 46

Contour Plot
Pressure (Scalar Value)
Single Range
Min = 1.147E-01
Max = 7.796E-02
Nodes: 1453
Elements: 1453
Time: 3.000E+003
Frame: 46

Figure B20 Pressure 45° to Frontal 4 feet

STRESS TENSOR DEFINITION					
σ_{xx} [MPa]	-16	τ_{xy} [MPa]	-1.33	τ_{xz} [MPa]	.701
τ_{yx} [MPa]	-1.33	σ_{yy} [MPa]	-15	τ_{yz} [MPa]	.901
τ_{zx} [MPa]	.701	τ_{zy} [MPa]	.901	σ_{zz} [MPa]	-15.1

MOHR CIRCLE SOLUTION		
σ_I [MPa]	Principal stress I	-13.9285
σ_{II} [MPa]	Principal stress II	-14.7352
σ_{III} [MPa]	Principal stress III	-17.4364
τ_{MAX} [MPa]	Guest - Tresca	1.754
σ_{VM} [MPa]	Huber - Hencky - Von Mises	3.1822

Figure B21 Mohr Circle for 45° to Frontal 4 Feet Impact

B2.4 Drop Height of 5 feet

Contour Plot
Pressure (kPa)
Range: Average
Min = 1.00E-01
Max = 1.00E-01
Node 1000
Node 1000

Figure B22 Pressure 45° to Frontal 5 feet

Model Info: Kibling, Shell
Result: H1STudent20.Jay's current results/45toFrontal_5feet/Shell/Shell/4507
Loadcase 1: Time = 3.000E+003
Frame 45

Contour Plot
Pressure (kPa)
Range: Average
Min = 1.00E-01
Max = 1.00E-01
Node 1000
Node 1000

Figure B23 Pressure 45° to Frontal 5 feet

STRESS TENSOR DEFINITION					
σ_{xx} [MPa]	-18.5	τ_{xy} [MPa]	-1.46	τ_{yz} [MPa]	0.777
τ_{yx} [MPa]	-1.46	σ_{yy} [MPa]	-17.5	τ_{yz} [MPa]	.965
τ_{zx} [MPa]	0.777	τ_{zy} [MPa]	.965	σ_{zz} [MPa]	-17.6

MOHR CIRCLE SOLUTION		
σ_I [MPa]	Principal stress I	-16.3235
σ_{II} [MPa]	Principal stress II	-17.1605
σ_{III} [MPa]	Principal stress III	-20.116
τ_{MAX} [MPa]	Guest - Tresca	1.8963
σ_{VM} [MPa]	Huber - Hencky - Von Mises	3.451

Figure B24 Mohr Circle for 45° to Frontal 5 Feet Impact

B3 Lateral

B3.1 Drop Height of 2 feet

Custom Plot
Pressure (Strain Rate)
Display Range
Min = 1.435E-01
Max = 1.435E-01
Node 938

Figure B25 Pressure Lateral 2 feet

Model Info: Side_2feet
Result: H15TSide02.jpg/comment/multibody/2feet/Side_2feet4086
Loadcase 1: Time = 4.0002e-03
Frame 51

Custom Plot
Pressure (Strain Rate)
Display Range
Min = 1.435E-01
Max = 1.435E-01
Node 938

Figure B26 Pressure Lateral 2 feet

Figure B27 Mohr Circle for Lateral 2 Feet Impact

B3.2 Drop Height of 3 feet

Figure B28 Pressure Lateral 3 feet

Figure B29 Pressure Lateral 3 feet

Figure B30 Pressure Lateral 3 feet

Figure B31 Pressure Lateral 3 feet

Figure B32 Mohr Circle for Lateral 3 Feet Impact

B3.3 Drop Height of 4 feet

Figure B33 Pressure Lateral 4 feet

Figure B34 Pressure Lateral 4 feet

Contour Plot
Pressure (Stress value)
Stress Range
-1.00E-01
-0.80E-02
-4.20E-02
-8.00E-03
-5.40E-02
-1.00E-01
-1.50E-01
Min = -1.00E-01
Max = -1.00E-01
Node 1591
Node 1591
Node 1591

Figure B35 Pressure Lateral 4 feet

Model info: id648
Result: H:\STUdent\Q\J\comfresub\id648\id648A07
Loadcase 1: Time = 3.000e+003
Frame 41
Contour Plot
Pressure (Stress value)
Stress Range
-1.00E-01
-0.80E-02
-4.20E-02
-8.00E-03
-5.40E-02
-1.00E-01
-1.50E-01
Min = -1.00E-01
Max = -1.00E-01
Node 1591
Node 1591
Node 1591

Figure B36 Pressure Lateral 4 feet

Figure B37 Mohr Circle for Lateral 4 Feet

B3.4 Drop Height of 5 feet

Contour Plot
Pressure (Stress value)
Stress Average
Min = -2.00E-01
Max = 1.40E-01
Node 9286

Figure B38 Pressure Lateral 5 feet

Model info: side 51
Result: H:\STUser\Olay\comet\resub\side\side_51_0407
Loadcase 1: Time = 3.7023e-03
Frame 40

Contour Plot
Pressure (Stress value)
Stress Average
Min = -2.00E-01
Max = 1.40E-01
Node 9286

Figure B39 Pressure Lateral 5 feet

Figure B40 Mohr Circle for Lateral 5 Feet

B4 Posterior

B4.1 Drop Height of 2 feet

Contour Plot
Pressure (Scalar value)
Stress range
1.304E-01
-1.205E-02
-5.679E-02
-2.409E-02
-8.871E-03
-1.305E-02
-7.843E-02
-1.102E-01
Min = 1.804E-01
Node 8242
Max = 1.102E-01
Node 8109

Model info: back_2feet
Result: H1StaticOnJob\currentresubr\Back\Checkback_2feet\006
Loadcase 1: Time = 3.7629e-03
Frame 40
Contour Plot
Pressure (Scalar value)
Stress range
1.304E-01
-1.205E-02
-5.679E-02
-2.409E-02
-8.871E-03
-1.305E-02
-7.843E-02
-1.102E-01
Min = 1.804E-01
Node 8242
Max = 1.102E-01
Node 8109

Model info: back_2feet
Result: H1StaticOnJob\currentresubr\Back\Checkback_2feet\006
Loadcase 1: Time = 3.7629e-03
Frame 40

Figure B41 Pressure Posterior 2 feet

Figure B42 Pressure Posterior 2 feet

STRESS TENSOR DEFINITION

σ_{xx} [MPa]	-12.6	τ_{xy} [MPa]	0.714	τ_{xz} [MPa]	-0.615
τ_{yx} [MPa]	0.714	σ_{yy} [MPa]	-12.80	τ_{yz} [MPa]	-1.35
τ_{zx} [MPa]	-0.615	τ_{zy} [MPa]	-1.35	σ_{zz} [MPa]	-12.6

MOHR CIRCLE SOLUTION

σ_I [MPa]	Principal stress I	-10.8454
σ_{II} [MPa]	Principal stress II	-13.0912
σ_{III} [MPa]	Principal stress III	-14.0633
τ_{MAX} [MPa]	Guest - Tresca	1.6089
σ_{VM} [MPa]	Huber - Hencky - Von Mises	2.8586

Figure B43 Mohr Circle for Posterior 2 Feet impact

B4.2 Drop Height of 3 feet

Figure B44 Pressure Posterior 3 feet

Figure B45 Pressure Posterior 3 feet

Figure B46 Mohr Circle for Posterior 3 Feet

B4.3 Drop Height of 4 feet

Contour Plot
Pressure (kPa value)
Drop Height
1.00E-01
-1.00E-01
-2.00E-02
-3.00E-02
-4.00E-02
-5.00E-02
-6.00E-02
-7.00E-02
-8.00E-02
-9.00E-02
-1.00E-01
Max = 1.00E-01
Min = -1.00E-01
Node 1000

Y
X
Z

Figure B47 Pressure Posterior 4 feet

Model info: back_4feet
Result: H1Studies\Q1\Jury\comet\result\Back_4feet\Back_4feet\007
Loadcase 1: Time = 3.000E+003
Frame 47

Contour Plot
Pressure (kPa value)
Drop Height
1.00E-01
-1.00E-01
-2.00E-02
-3.00E-02
-4.00E-02
-5.00E-02
-6.00E-02
-7.00E-02
-8.00E-02
-9.00E-02
-1.00E-01
Max = 1.00E-01
Min = -1.00E-01
Node 1000

Y
X
Z

Figure B48 Pressure Posterior 4 feet

Figure B49 Mohr Circle for Posterior 4 Feet Impact

B4.4 Drop Height of 5 feet

Figure B50 Pressure Posterior 5 feet

Figure B51 Pressure Posterior 5 feet

Figure B52 Mohr Circle for Posterior 5 Feet impact

Appendix C

Approach to Finite Element Analysis in Hypermesh.

The detailed approach followed for the FE analysis in Altair Hypermesh⁵ has been explained below.

1. Opening the Environment

Figure C1 selecting the user profile in Hyperworks environment

Open the Hypermesh environment and select Altair® RADIOSS® and Block 110 module for the Impact analysis.

2. Importing the Model.

The 3D model of the head form has been imported into the Altair® RADIOSS® environment. This model has the properties imported along with the environments.

⁵ All Images in this chapter are screen shots taken from Altair Hyperworks software and has been used as a representation for a step by step guide to FE Analysis work done in this work.

Image Courtesy: <http://www.altairuniversity.com/category/united-states/>

Figure C2 Importing FE Model from other environment

3. Creating a Mesh.

The mesh has been created by following the steps below and the properties of the mesh has also been shown.

Figure C3 Creation of mesh

Figure C4 Mesh Properties

Tetra mesh was used for this purpose and care should be taken not to mesh all the layers at a time and keep the other layers hidden while meshing a particular layer. The element size should not be too big that there would be a chance for error while it should not be too small to increase the analysis time.

4. Creating a material.

Create a material and assign the cards accordingly. The material was considered elastic for our analysis.

Figure C5 Material assignment Tab

5. Creating a Component.

Create a component for each and every layer. Assign the “part” card file for the same.

Figure C6 Component Assignment tab

6. Assign a Property.

Figure C7 Property assignment tab

Create a property for every layer and Assign the “P14 Solid” card for every component.

Edit the card for that particular component to assign the properties which were shown in the table 4.1

Figure C8 Mechanical Property assignment to the FE Model

7. Spring element

Figure C9 Creation of Spring element

Create a node at a unit distance from all the elements which need to be constrained.

Create a spring element to constrain the 6 degrees of freedom for all the nodes.

Create a corresponding property and material and assign the spring constant for the spring element.

8. Contact surfaces

The area of impacts are imposed on the model as contact surfaces. Create the contact surfaces for respective regions of impact by selecting the particular elements.

Figure C10 Creation of Contact Surfaces

9. Curves

The HICP has been applied to the FE model in terms of Impact curve. Create the curve for every Impact.

Figure C11 Creation of Input plots

10. Load Collector

Create a load collector for Boundary condition and the pressure input. Assign the corresponding card images for them.

Figure C12 Creation of Load collector

11. BC Manager

It is the step in which we constrain the model and assign the HICP curves to the model.

Constrain the spring node in all directions (6 Degrees of Freedom).

Figure C13 BC Manager

Create a corresponding BC manager property for constraining the model, select the appropriate pressure curve and corresponding area as the input.

12. Engine File

It is an important step where we select the properties which we want in the output. It is an important step where we create the output time step.

In the Fig C14 TStop corresponds to the value in which we want the analysis to stop, while Time frequency refers to the point where we decide how many time steps we want for the analysis. We have considered a time step of 100 for this analysis.

ANIM Key1 corresponds to the selection of output parameters like stresses and pressures in the analysis.

Figure C14 Engine File 1 showing output time step settings

Figure C15 Engine File 2

13. Exporting the Engine File to Altair® RADIOSS® solver:

The engine file needs to be exported and saved as Altair® RADIOSS® solvable format (*.rad) in order to be in a valid format to be run by the Altair® RADIOSS® solver.

Figure C16 Creation of Altair® RADIOSS® File

The particular file can be run using the Altair® RADIOSS® solver.

14. Post Processing.

There would be a huge data which is obtained as an output and the animation files will be analyzed in Hyper View, which is a post processing tool.

The loaded animated file would be processed for obtaining the output.

Figure C17 Importing results file into HyperView

Figure C18 Output Property manager in Hyperview

Select the colored format as the required output and select the result type which we want to analyze (Pressure in the above case) and select the averaging method to be simple and edit the legend in order to get the output in the range of values for the brain by trial and error method.

Figure C19 Editing the output scale in the analysis viewer

Appendix D

Anatomy of Human Head

The basic anatomy of the human head is required in order to properly understand the terminology used in the above study. The human head consists of different layers which are explained in order below.

Scalp- It is a 5-7 mm thick outer covering and it consists of facial skin and hair. It starts above the eyebrows and extends all the way up to the jawline.

Skull – It is the strongest part of human head and made up of bones which encapsulates brain. It is like a natural helmet for the brain. The average thickness of the skull is around 4-7 mm.[15]

Figure D1 Different Layers of Human Head [25]

Meningeal covering – It's a 3 layered membrane which separates the brain and the skull. It is made up of duramatter, arachnoid and pia mater. Because of its role in injury only the dura mater is considered in the FE analysis.

Cerebro Spinal Fluid – It serves as a protection layer saving injury by absorbing the vibrations and shocks. It is an incompressible fluid which is helpful in providing nutrients to brain. In order to reduce the complexity of the FE model this layer was not considered in the analysis.

Brain – It is one of the most important parts of the human body. It is generally made up of nerve cells and it's a gel like substance mostly consists of water. The brain is divided into lobes which are shown in Fig.D2

Figure D2 Cross section of brain showing different lobes [20]

The frontal lobe is located to the anterior side and is mainly responsible for the consciousness. Just below the frontal lobe is the temporal lobe which controls the audio system. The parietal lobe which is situated on the top is responsible for controlling body senses. The occipital lobe which lies on the posterior of the brain is responsible for vision[26]. The cerebellum lies beneath the parietal and occipital lobes and the brain stem co-ordinate the higher level functions of the body by connecting into spinal cord. The following figure depicts the regions of the brain and their respective functions.

Figure D3 Different regions of brain and their respective functions [27]

Image taken from Headway – the brain injury association, U.K.

References

- [1] C.C Ward , P.E.Nikravesch and R.B.Thompson. “Biodynamic finite element models used in brain injury research”, Journal of Aviation, Space and Environmental medicine, vol 49, no.1, 1978
- [2] Centers for Disease Control and Prevention (CDC), 2003, “Traumatic Brain Injury in the United States: Fact Sheet” [Online]. Available
http://www.cdc.gov/traumaticbraininjury/get_the_facts.html [Accessed 10 Oct,2015]
- [3] Ward, C., Chan, M., Nahum, A., “Intracranial Pressure – A Brain Injury Criterion.” The Society of Automotive Engineers Paper # 801304, pp 3867-3880, 1980.
- [4] CNN, “Minor head injuries can turn serious rapidly, experts say” Wed Mar 18,2009, [Online] : Available [Accessed on 10 Sep,2015]
<http://www.cnn.com/2009/HEALTH/03/18/brain.injury/index.html?iref=24hours>
- [5] Murray JA, Chen D, Velmahos GC, et al. Pediatric falls: Is height a predictor of injury and outcome? Am Surg. 2000;66(9):863-865.
- [6] HSP Supply Inc,. National Safety Products Inc,. .[Online]:Available
<http://hspsupplyinc.com/stats.htm> [Accessed on 1 Sep,2015]
- [7] American College of Surgeons, “Injuries Due to Falls from Heights”, Oct 17, 2002.[Online]:Available <https://www.facs.org/quality%20programs/trauma/ipc/falls>
[Accessed on 1 Sep,2015]
- [8] Centers for Disease Control and Prevention. Injury Research Agenda: Preventing Injuries at Home and in the Community. National Center for Injury Prevention and Control. [Online]. Available at

<http://www.cdc.gov/homeandrecreationalafety/falls/adultfalls.html> [Accessed on 21 Sep,2015]

- [9] Hall JR, Reyes HM, Horvat M, et al. The mortality of childhood falls. *J Trauma*. 1989;29(9):1273-1275.
- [10] Lallier M, Bouchard S, St-Vil D, et al. Falls from heights among children: A retrospective review. *J Pediatr*. 1999;Surg 34(7):1060-1063.
- [11] Alleyne B, Stuart P, Copes R. Occupational and other drug use in occupational fatalities. *J Occup Med*. 1991;33:496.
- [12] Alexander BH, Rivara FP, Wolf ME. The cost and frequency of hospitalization for fall-related injuries in older adults. *Am J Public Health*. 1992;82(7):1020-1023.
- [13] Fan, W.R.S., "Internal Head Injury Assessment." *Proc. 15th Stapp Car Crash Conf.*, The Society of Automotive Engineers Paper # 710870, pp 645-665, 1971.
- [14] Thurman, D. J., Branche, C. M., Snizek, J. E., "The Epidemiology of Sports-Related Traumatic Brain Injuries in the United States: Recent Developments." *J. Head Trauma Rehabil*, Vol. 13, No. 2, pp. 1-8, 1998.
- [15] Melvin, J. W. and Lighthall, J. W., *Accidental Injury Biomechanics and Prevention Second Edition*. Nahum, A.M., Melvin, J.W., ed., Springer-Verlag, NY, pp.277-302, 2002.
- [16] Bailes, J. E., *Sports Neurology, Second Edition*, Jordan, B. D., ed., Lippincott-Raven Publishers, PA, pp. 215-233, 1998.
- [17] Shugar, T.A., "A Finite Element Head Injury Model." Report No. DOT HS 289-3-550-TA, Vol. 1, 1977.

-
- [18] Standard Linear Impactor Test Method And Equipment Used In Evaluating The Performance Characteristics Of Protective Headgear And Face Guards - NOCSAE Doc (Nd) 081- 04M04
- [19] Sensor Products Inc,. "Fujifilm Prescale® Tactile Pressure Indicating Sensor Film" [Online], Available at <http://www.sensorprod.com/fuji-prescale.php>
- [20] D. M. Labyak, "Interpretation of Head Injuries Due to Oblique Impact by Finite Element Modeling," Michigan Technological University, Houghton, 2003.
- [21] Granit Engineering, "3-DvMohr Circle Generator & Solver". [Online]; Available at <http://www.graniteng.com/mohr-3d?lang=en>
- [22] Kang, H., Willinger, R., Diaw, B. M., Chinn, B., "Validation of a 3D Anatomic Human Head Impact in Motorcycle Accident by Finite Element Modeling." The Society of Automotive Engineers Paper # 973339, 1997.
- [23] O. Anna, K. Clara, P. Andrew, R. Philippe, H. Blaine, M. Shawn, B. Susan, S. Aynsley and C. Michael, "An Examination of Headform Dynamic Response for Concussive and Traumatic Brain Injury," in *1st International Conference on Helmet Performance and Design*, London, UK, 2013.
- [24] Abhang, Chandrika S., "MEASURING HEAD IMPACT CONTACT PRESSURE IN COLLEGIATE FOOTBALL GAMES TO CORRELATE HEAD KINEMATICS TO BRAIN KINETICS ELUCIDATING BRAIN INJURY DYNAMICS", Master's report, Michigan Technological University, 2014.
- [25] Earsite.com, "Acoustic Neuroma," 2014. [Online]. Available: [Accessed on 08 Oct,2015] http://www.earsite.com/sites/default/files/userfiles/images/acoustic-neuroma/an4--head_layers.jpg

[26] Centre for Neuro Skills,” Brain Function”, Robert P. Lehr Jr., Ph.D.

Professor Emeritus, Department of Anatomy, School of Medicine,

Southern Illinois University,[online],Available [Accessed on 08 oct,2015]

<http://www.neuroskills.com/brain-injury/brain-function.php>

[27] Headway-The Brain Injury association “Executive dysfunction after brain

Injury”,[Online], Available:[Accessed on 12 Oct,2015]

<https://www.headway.org.uk/executive-dysfunction-after-brain-injury.aspx>

Permission to Use Figures from your work

5 messages

R Krishna Tej Bhamidipati <rbhamidi@mtu.edu> Thu, Nov 12, 2015 at 5:45 PM
To: Chandrika Abhang <csabhang@mtu.edu>

Chandrika,
I would like to use the following Figures from your work "MEASURING HEAD IMPACT CONTACT PRESSURE IN COLLEGIATE FOOTBALL GAMES TO CORRELATE HEAD KINEMATICS TO BRAIN KINETICS ELUCIDATING BRAIN INJURY DYNAMICS" in my thesis work.
2.6 - Cross section of a Fujifilm Prescale
D0.6 - Layers of human head
D0.7 - Structural differentiation of human brain.
Kindly respond inline with your approval.

Thank you
Regards,
R KrishnaTej Bhamidipati,
Graduate Student,
Mechanical Engineering Department
Michigan Technological University.
Ph.:- 906-281-8522

R Krishna Tej Bhamidipati <rbhamidi@mtu.edu> Thu, Nov 12, 2015 at 5:48 PM
To: David Labyak <dmlabyak@mtu.edu>

David,
I would like to use the following Figures from your work "Interpretation of Head Injuries Due to Oblique Impact by Finite Element Modeling" in my thesis work.
Figure 2.3 Wayne State Tolerance Curve
Figure 3.4 Side View of the Brain

Kindly respond inline with your approval.

Thank you
Regards,
R KrishnaTej Bhamidipati,
Graduate Student,
Mechanical Engineering Department
Michigan Technological University.
Ph.:- 906-281-8522

David Labyak <dmlabyak@mtu.edu>
To: Krishna <rbhamidi@mtu.edu>

Thu, Nov 12, 2015 at 5:49 PM

Krishna,

Yes you have my permission to use the figures from my thesis.

David Labyak

[Quoted text hidden]

R Krishna Tej Bhamidipati <rbhamidi@mtu.edu>
To: Chandrika Abhang <csabhang@mtu.edu>

Fri, Nov 20, 2015 at 9:04 PM

Please find the attached screenshots of the images.

Figure D0.7 Structural differentiation of human brain [32]

Figure D0.6 Layers of human head [31]

Kindly respond.
Thank you.

Regards,
R KrishnaTej Bhamidipati,
Graduate Student,
Mechanical Engineering Department
Michigan Technological University.
Ph.:- 906-281-8522

[Quoted text hidden]

Chandrika Abhang <csabhang@mtu.edu>
To: R Krishna Tej Bhamidipati <rbhamidi@mtu.edu>

Sat, Nov 21, 2015 at 11:03 PM

Hi Krishna,

Please go ahead and use images D0.6 and D0.7 from my report.

Thanks,
Chandrika
[Quoted text hidden]

The above correspondence refers to the permission for figures in Appendix-D

Fwd: Headway image

1 message

Krishna Tej <brkrishnatej@gmail.com>
To: R Krishna Tej Bhamidipati <rbhamidi@mtu.edu>

Thu, Nov 5, 2015 at 9:40 AM

----- Forwarded message -----

From: **Tamsin Ahmad** <publications@headway.org.uk>
Date: 5 November 2015 at 08:54
Subject: Headway image
To: brkrishnatej@gmail.com

Hi Krishna,

Thank you for recently making contact with us regarding using the Headway image of the brain explaining its functions. You would be welcome to use this image, but please ensure that you use proper referencing, ie: *image taken from Headway – the brain injury association, U.K.*

Kind regards,

Tamsin

Tamsin Ahmad

Publications and Research Manager

Bradbury House
190 Bagnall Road
Old Basford
Nottingham
NG6 8SF

Tel: 0115 924 0800/Direct line no: 0115 947 1915

This is an email from Headway - the brain injury association. The contents of this email are confidential to the ordinary user of the email address to which it is addressed. No-one else may place any reliance on it, or copy or forward all or any of it in any form.

Headway - the brain injury association is a Registered Charity No 1025852 and a company limited by guarantee Registered in England No. 2346893

The above correspondence refers to the permission for figure D3 in Appendix-D

Problem with the Topaq Analyzer

1 message

R Krishna Tej Bhamidipati <rbhamidi@mtu.edu> Wed, Jul 23, 2014 at 4:59 PM

To: Gopal Jayaraman <gjayar@mtu.edu>

Cc: Chandrika Abhang <csabhang@mtu.edu>, David Labyak <dmlabyak@mtu.edu>, achen@sensorprod.com, Vadim Shalyt <vshalyt@sensorprod.com>

Dear All,

I spoke to Mr. Andy Chen from Sensor prod, who's a technical contact person concerned with the Topaq Analyzer. The summary of the telephonic conversation regarding the problems we had with the analyzer are mentioned below.

- 1) The Analyzer is generally used for the static analysis and rarely used for the Impact testing.
- 2) The source of error can be due to the multiple impacts of Head form with the film. The Analyzer works perfect for the single Impact conditions. As we cant control the minor re-bouncing of the head form, we are prone to get some errors
- 3) Out of many outputs only the Pressure and Contact area are reliable as the Analyzer is not designed for the Impact force measurement.
- 4) The Pressure films are designed for the Flat surfaces, as our head form has a curved profile, the center region of the Impact area is prone to have more pressure concentration than the other regions, which in turn varies the average pressure.
- 5) The software is not suitable for multitasking, so we are supposed to analyze only one film at a time.

The above reasons are considered to cause discrepancies in the values measured from the analyzer.

Mr. Andy has advised to use the low films for 2-4 feet and medium film for 4-5 feet drops which have chances to reduce the error.

Thank you,

Regards,

R Krishna Tej Bhamidipati,

Graduate Student,

Mechanical Engineering Department

Student Supervisor - Van Pelt and Opie Library

Michigan Technological university.

Ph.:- 906-281-8522

Permission to Use the Prefilm Scale image in my Thesis Work

4 messages

R Krishna Tej Bhamidipati <rbhamidi@mtu.edu> Mon, Oct 26, 2015 at 5:26 PM
To: Vadim Shalyt <vshalyt@sensorprod.com>

Mr.Shalyt,
I hope you are doing good.I hope that you remember that I have used your pressure films and analyzer for our research work at Michigan Tech under the guidance of Dr.Jay. I would like to use one of the Image from your website showing the cross section of a pressure film.It would be great if you can extend me your permission to use the same in my report to document and provide information about the pressure films and the work I had done on them.
Would be waiting for your response.
Thank you

Regards,
R KrishnaTej Bhamidipati,
Graduate Student,
Mechanical Engineering Department
Michigan Technological University.
Ph.:- 906-281-8522

R Krishna Tej Bhamidipati <rbhamidi@mtu.edu> Thu, Nov 12, 2015 at 6:09 PM
To: Vadim Shalyt <vshalyt@sensorprod.com>

Kindly respond as I need your permission to present the details of the pressure films in my Thesis work.
Thank you

Regards,
R KrishnaTej Bhamidipati,
Graduate Student,
Mechanical Engineering Department
Michigan Technological University.
Ph.:- 906-281-8522

[Quoted text hidden]

Vadim Shalyt <vshalyt@sensorprod.com> Fri, Nov 13, 2015 at 7:10 AM
To: rbhamidi@mtu.edu

sure.
but be sure he names it properly as prescale film and not prefilm scale.

Vadim Shalyt
Sr. Application Specialist
Sensor Products Inc. USA
300 Madison Ave.
Madison, NJ 07940
1.973.428.8985 (phone)
1.973.495.9800 (cell)
vadim@sensorprod.com

Please contact me DIRECTLY for BEST Prices, Delivery, Service & Expert Advice.

The finest compliment I can ever receive from doing business is a referral from my clients.

From: R Krishna Tej Bhamidipati [<mailto:rbhamidi@mtu.edu>]
Sent: Thursday, November 12, 2015 7:10 PM
To: Vadim Shalyt
Subject: Re: Permission to Use the Prefilm Scale image in my Thesis Work

[Quoted text hidden]

R Krishna Tej Bhamidipati <rbhamidi@mtu.edu> Fri, Nov 13, 2015 at 8:16 AM
To: Vadim Shalyt <vshalyt@sensorprod.com>

Sure.... Definitely.

Thank you

Regards,
R KrishnaTej Bhamidipati,
Graduate Student,
Mechanical Engineering Department
Michigan Technological University.
Ph.: - [906-281-8522](tel:906-281-8522)

The above correspondance refers to the permission for Figure 3.22

R Krishna Tej Bhamidipati <rbhamidi@mtu.edu>

RE: A user sent a message via the contact form

2 messages

Rahul Ponginan <rahul.ponginan@altair.com> Tue, Dec 8, 2015 at 4:56 AM
To: Krishna Tej Bhamidipati <rbhamidi@mtu.edu>
Cc: "altairuniversity@altair.com" <altairuniversity@altair.com>

Hi Krishna,

Thanks for your email, please feel free to use snapshots and mention HyperWorks products in your thesis, provided the thesis is not critical of the products themselves,

Please be careful about plagiarism and make sure you clearly reference any Altair document you are mentioning in your thesis,

You will have to make sure however that the products are mentioned correctly and that you mention registered trademarks, for instance when mentioning RADIOSS use

Altair® RADIOSS® and note that

Altair and RADIOSS are registered trademarks of Altair Engineering Inc.

Please do send us a copy of your thesis, we will review it and if found suitable we may publish its abstract for instance on our website etc

Regards

Rahul Ponginan | Team Leader | HW Support

rahul.ponginan@altair.com | www.altairhyperworks.com

Altair | Innovation Intelligence®

Secure file dropbox <https://ftam1.altair.com/dropbox/~0simQA>

From: Altair HyperWorks Forum [mailto:altairuniversity@altair.com]
Sent: Tuesday, December 08, 2015 11:06 AM
To: altairuniversity@altair.com
Subject: A user sent a message via the contact form

Altair HyperWorks Forum

A user has sent a message using the Contact Us form.

Krishna Tej Bhamidipati said:

To the Concerned,

I have used the Radioss module for performing an Impact analysis in my thesis work and as a part of documentation, I have included the screen shots from the Hypermesh software with the properties I have used for my work. It would be really helpful if you can grant me a permission to use them in my thesis work. It would be really helpful if you can send me your response at your earliest, as the last date for the submission of the permissions to

my school is 12/12/15/
Waiting for a response
Thank you

— *Altair HyperWorks Forum*

Altair HyperWorks Forum, 1820 E. Big Beaver, Troy, Michigan, 48083

R Krishna Tej Bhamidipati <rbhamidi@mtu.edu> Tue, Dec 8, 2015 at 9:39 AM
To: Rahul Ponginan <rahul.ponginan@altair.com>
Cc: "altairuniversity@altair.com" <altairuniversity@altair.com>

Dear Mr.Ponginan,
Thank you very much for your kind response. I will forward my thesis document to you, once I get an approval from the Graduate School. I would like to inform you that I am just including the screen shots of the Properties and the Materials I have used in my work so that my research peers can continue their work.I will make sure that I include Altair® RADIOSS® in place of Radioss.
Thank you

Regards,
R KrishnaTej Bhamidipati,
Graduate Student,
Mechanical Engineering Department
Michigan Technological University.
Ph.:- [906-281-8522](tel:906-281-8522)

[Quoted text hidden]

The above correspondance refers to the permission for figures in Appendix-C