Riot Helmet Shells with Continuous Reinforcement for Improved Protection

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BILAL ZAHID

SCHOOL OF MATERIALS
# LIST OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>LIST OF CONTENTS</td>
<td>2</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>8</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>14</td>
</tr>
<tr>
<td>ABSTRACT</td>
<td>15</td>
</tr>
<tr>
<td>DECLARATION</td>
<td>16</td>
</tr>
<tr>
<td>COPYRIGHT STATEMENT</td>
<td>17</td>
</tr>
<tr>
<td>ACKNOWLEDGMENTS</td>
<td>18</td>
</tr>
<tr>
<td>BIOGRAPHICAL</td>
<td>19</td>
</tr>
<tr>
<td>CHAPTER 1 INTRODUCTION</td>
<td>22</td>
</tr>
<tr>
<td>1.1 PREAMBLE</td>
<td>22</td>
</tr>
<tr>
<td>1.2 BACKGROUND OF THE RESEARCH</td>
<td>23</td>
</tr>
<tr>
<td>1.3 RESEARCH AIM AND OBJECTIVES</td>
<td>24</td>
</tr>
<tr>
<td>1.4 THESIS LAYOUT</td>
<td>25</td>
</tr>
<tr>
<td>CHAPTER 2 LITERATURE REVIEW AND METHODOLOGY</td>
<td>27</td>
</tr>
<tr>
<td>2.1 INTRODUCTION</td>
<td>27</td>
</tr>
<tr>
<td>2.2 HISTORY OF HELMETS</td>
<td>27</td>
</tr>
<tr>
<td>2.3 A BRIEF INTRODUCTION TO COMPOSITES</td>
<td>28</td>
</tr>
<tr>
<td>2.3.1 CLASSIFICATION OF COMPOSITES</td>
<td>29</td>
</tr>
<tr>
<td>2.3.2 VACUUM BAGGING</td>
<td>30</td>
</tr>
<tr>
<td>2.4 TESTING METHODS FOR COMPOSITE STRUCTURES</td>
<td>30</td>
</tr>
<tr>
<td>2.4.1 METHOD OF TESTING TENSILE PROPERTIES</td>
<td>31</td>
</tr>
<tr>
<td>2.4.2 METHOD OF TESTING SHEAR PROPERTIES</td>
<td>32</td>
</tr>
<tr>
<td>2.4.3 METHOD OF CALCULATING DENSITY BY IMMERSION TECHNIQUE</td>
<td>34</td>
</tr>
<tr>
<td>2.4.4 METHOD FOR CONSTITUENTS OF COMPOSITE SPECIMENS</td>
<td>34</td>
</tr>
<tr>
<td>2.5 IMPACT PHENOMENON OF COMPOSITE RIOT HELMETS</td>
<td>35</td>
</tr>
<tr>
<td>2.5.1 LOW-VELOCITY IMPACTS</td>
<td>35</td>
</tr>
</tbody>
</table>
2.5.2 Modes of failure in composite riot helmet shells .............................................36
2.5.2.1 Matrix mode .................................................................................................36
2.5.2.2 Delamination mode .....................................................................................36
2.5.2.3 Fibre failure mode ......................................................................................37
2.5.2.4 Penetration mode .......................................................................................37
2.5.3 Factors influencing impact characteristics ......................................................38
2.5.3.1 Impactor shape ............................................................................................38
2.5.3.2 Impactor velocity and laminate thickness .....................................................38
2.5.3.3 Single-piece and multi-piece laminates .........................................................38
2.5.3.4 Curvature of laminates ..............................................................................39
2.5.4 Behaviour of textile composites .....................................................................40

2.6 The drop weight impact ....................................................................................41
2.6.1 Instron Dynatup 8200 drop weight tester - Impact testing instrument ..........41
2.6.1.1 The drop weight assembly ..........................................................................42
2.6.1.2 The drop weight release mechanism ............................................................43
2.6.1.3 The drop tower framework .........................................................................44
2.6.1.4 The anvils ...................................................................................................44

2.7 Composition of a riot helmet ..........................................................................44
2.7.1 Helmet shell ...................................................................................................45
2.7.1.1 Thermoplastic shells and manufacturing method .........................................45
2.7.1.2 Composite shells and manufacturing method ..............................................46
2.7.1.3 Multi-piece composite riot helmet shell ......................................................47
2.7.1.4 Single-piece composite riot helmet shell .....................................................48
2.7.2 Protective padding ..........................................................................................49
2.7.2.1 Expanded polystyrene foam liners ...............................................................49
2.7.2.2 Polypropylene, polyethylene, and polybutylene foams liners .....................49
2.7.2.3 Polyurethane foam liner ..............................................................................50
2.7.2.4 Polyvinylidene chloride foam .....................................................................50
2.7.3 Comfort padding ............................................................................................50
2.7.4 Retention system ...........................................................................................50
2.7.5 Visor ................................................................................................................51
2.7.6 Neck guard .....................................................................................................51
2.7.7 Additional equipment .....................................................................................51

2.8 Impact performance of riot helmet ................................................................61
2.8.1 Riot helmet test standards ...........................................................................51
2.8.2 Impact site definitions by PSDB Protective Headwear Standard for UK Police (2004) .................................................................52
2.8.3 Impact site definitions: NIJ Standard for Riot Helmets and Face Shields ....54
2.8.4 Impact site definitions as per Canadian CAN/CSA-Z611-02 Riot Helmets and Face- shield Protection (2003) .................................................................54
2.9 PREVIOUS RESEARCH ON COMPOSITE HELMET SHELLS ..........................................................55
2.10 METHODOLOGY .....................................................................................................................58
  2.10.1 PRODUCTION OF FABRIC ..............................................................................................59
  2.10.2 MANUFACTURING OF FLAT COMPOSITE PANELS ......................................................59
  2.10.3 CREATION OF SINGLE-PIECE HELMET SHELL .............................................................59
  2.10.4 DEVELOPMENT OF A TEST RIG ...................................................................................60
  2.10.5 CREATION AND SIMULATION OF FINITE ELEMENT MODELS ...........................................60
2.11 SUMMARY ..............................................................................................................................61

CHAPTER 3 FABRIC WEAVING, MANUFACTURING AND EVALUATION OF FLAT COMPOSITE ..........................................................62

3.1 INTRODUCTION .......................................................................................................................62
3.2 DEFINITION AND SIGNIFICANCE OF AI- FABRIC FOR HELMET SHELL MANUFACTURING .......62
3.3 MANUFACTURING OF “THROUGH-THE-THICKNESS” ANGLE-INTERLOCK FABRIC ................64
  3.3.1 OPTIMISATION IN PRODUCING FABRICS ........................................................................66
3.4 MANUFACTURING OF FLAT PANEL COMPOSITES ...............................................................68
  3.4.1 NEED FOR DEVELOPMENT ...............................................................................................68
  3.4.2 RESIN INFORMATION .........................................................................................................68
  3.4.3 PRECAUTIONARY MEASURE .............................................................................................69
  3.4.4 EXPERIMENTAL METHOD IN THE LABORATORY .............................................................69
3.5 PROPERTIES OF 5-8-28 KEVLAR FLAT COMPOSITE PANELS ...............................................72
  3.5.1 TENSILE PROPERTIES .......................................................................................................72
  3.5.2 RESULTS OF IN-PLANE SHEAR MODULUS ......................................................................75
  3.5.3 RESULT OF 5-8-28 FLAT PANEL DENSITY – IMMERSION TECHNIQUE ..............................76
  3.5.4 CONSTITUENTS OF KEVLAR COMPOSITE SPECIMENS ..................................................76
3.6 SUMMARY ..............................................................................................................................78

CHAPTER 4 INNOVATIVE FABRICATION OF RIOT HELMET SHELL ..................79

4.1 INTRODUCTION .......................................................................................................................79
4.2 MANUFACTURING OF THREE DIMENSIONAL DOME-SHAPE COMPOSITE STRUCTURE ........79
  4.2.1 IMPORTANCE OF DOME-SHAPE STRUCTURE .................................................................81
4.3 CREATION OF SINGLE-PIECE HELMET SHELL FROM VACUUM BAGGING .......................82
4.4 FABRICATION ON NONWOVEN GLASS FIBRE MOULD .....................................................82
  4.4.1 REQUIRED CHARACTERISTICS OF A MOULD .................................................................82
  4.4.2 MATERIAL OF MOULD .......................................................................................................83
  4.4.3 MOULD DESIGNING ...........................................................................................................83
  4.4.4 CREATING WALL AND FILLING PART TECHNIQUE .........................................................85
  4.4.4.1 FIXING MECHANISM AND MOULD EDGE FORMATION ..................................................86
6.3 EVALUATION AND RESULTS OF FLAT PANEL TESTING .................................................. 122
6.3.1 EFFECT OF LAMINATE STACKING AND ORIENTATION ON ENERGY ABSORPTION .......... 123
6.3.2 EFFECT OF LAMINATE STACKING AND ORIENTATION ON FORCE ATTENUATED FACTOR ..... 125
6.3.3 SUMMARY OF RESULTS FOR 5-8-28 KEVLAR FLAT PANEL COMPOSITES ................... 129
6.4 CHARACTERISTICS OF HELMET SHELL LAMINATES .................................................. 129
6.4.1 THICKNESS OF SHELL AT DIFFERENT LOCATIONS ................................................ 130
6.4.2 DENSITY OF SHELL AT DIFFERENT LOCATIONS .................................................... 130
6.4.3 HELMET SHELL CURVATURES AT IMPACT LOCATIONS .......................................... 131
6.5 EXPERIMENTAL RESULTS OF HELMET SHELL TESTING ........................................... 133
6.5.1 ENERGY ABSORPTION ............................................................................................... 135
6.5.2 PEAK TRANSMITTED FORCE ..................................................................................... 138
6.5.3 FORCE ATTENUATED FACTOR .................................................................................. 141
6.5.4 HELMET SHELL WITH INTERNAL Padding .............................................................. 143
6.5.4.1 INFLUENCE OF INTERNAL Padding ON ENERGY ABSORPTION ...................... 144
6.5.4.2 INFLUENCE OF INTERNAL Padding ON FORCE ATTENUATED FACTOR .......... 145
6.6 SUGGESTIONS FOR HELMET SHELL IMPROVEMENT ............................................... 146
6.6.1 OPTIMISATION OF HELMET SHELL TOP LOCATION ............................................ 146
6.6.2 OPTIMISATION OF HELMET SHELL SIDE AND BACK LOCATION .............................. 147
6.7 COMPARISON OF DEVELOPED HELMET SHELLS ..................................................... 147
6.8 SUMMARY .................................................................................................................... 149

CHAPTER 7 FINITE ELEMENT ANALYSIS ON SINGLE-PIECE RIOT HELMET SHELL ................................................................. 150

7.1 BRIEF INTRODUCTION OF ABAQUS ............................................................................. 150
7.2 CREATION OF GEOMETRIES FOR IMPACT SIMULATION ........................................ 151
7.2.1 RIOT HELMET SHELL GEOMETRY ......................................................................... 151
7.2.1.1 GENERATION OF POINT CLOUDS ..................................................................... 152
7.2.1.2 SURFACE GENERATION ...................................................................................... 152
7.2.1.3 THICKNESS TO SHELL SURFACE .................................................................... 153
7.2.1.4 MESH GENERATION ........................................................................................... 153
7.2.1.5 MIRROR TO COMPLETE HELMET SHELL SHAPE ............................................. 154
7.2.1.6 CREATION OF INTERNAL AND EXTERNAL FACES ......................................... 155
7.2.2 GEOMETRY OF IMPACTOR SHAPE ....................................................................... 155
7.2.3 GEOMETRIC MODEL OF HEADFORM .................................................................. 156
7.2.4 TRANSVERSE ISOTROPIC PROPERTIES ................................................................. 157
7.3 MESHING AND BOUNDARY CONDITIONS .................................................................. 158
7.4 CREATION OF FE MODELS FOR DIFFERENT IMPACT LOCATIONS ......................... 159
7.5 SIMULATED RESULTS AND VALIDATION WITH EXPERIMENTAL RESULTS ............ 160
7.6 INFLUENCE OF HELMET THICKNESS ....................................................................... 166
### 7.6.1 Effect of Helmet Thickness on Transmitted Force

166

### 7.6.2 Effect of Helmet Thickness on Energy Absorption

167

### 7.7 Summary

169

### Chapter 8 Conclusion and Future Work

170

#### 8.1 Conclusions

170

#### 8.2 Recommendations for Further Research Work

172

### References

174

### Appendices

185

#### Appendix A

186

#### Appendix B

191
LIST OF FIGURES

Figure 2-1 Schematic configuration of vacuum bagging process ........................................ 30
Figure 2-2 Schematic diagram for guidelines according to BS EN ISO 527-4:1997 ........ 31
Figure 2-3 (a) Principle of plate twist method (b) Position of support and loading point . 33
Figure 2-4 Impact damage in a composite laminate ........................................................... 37
Figure 2-5 Multi-piece plate design .................................................................................... 39
Figure 2-6 Sketch of the Instron Dynatup 8200 impact tester ............................................ 42
Figure 2-7 Velocity detector and flag .................................................................................. 43
Figure 2-8 Riot Helmet Assembly ....................................................................................... 45
Figure 2-9 Injection moulding process ................................................................................ 46
Figure 2-10 Half side of a typical multi-piece composite riot helmet shell ....................... 48
Figure 2-11 Reference planes on human head as PSDB Standard .................................... 52
Figure 2-12 Coverage area of the head by the visor and the helmet ................................. 53
Figure 2-13 Headform basic data according to CAN/CSA-Z611-02 ............................... 55
Figure 2-14 A typical motorcycle helmet ........................................................................... 56
Figure 2-15 FEA on military helmet ................................................................................... 57
Figure 3-1 AI-fabric (a) ‘through-the-thickness’ (b) ‘Layer-to-layer’ ............................... 62
Figure 3-2 Lifting plan for 5-layer through-the-thickness AI-fabric ................................. 65
Figure 3-3 5-8-28 Angle-interlock woven fabric ............................................................... 66
Figure 3-4 (a) Steel yarn hook (b) Modified ceramic yarn hook ....................................... 67
Figure 3-5 Paper rolled in warp beam ............................................................................... 67
Figure 3-6 Vacuum bagging setup .................................................................................... 71
Figure 3-7 Resin infused vacuum bag ............................................................................... 71
Figure 3-8 Flat composite panel from the AI-fabric .......................................................... 72
Figure 3-9 MTS RT/100 testing machine .......................................................................... 73
Figure 3-10 Stress-strain curves for tensile test in warp direction ................................. 74
Figure 3-11 Stress-strain curves for tensile test in weft direction ................................. 74
Figure 3-12 In-plane shear testing using Instron 4411 ................................................... 75

Figure 3-13 Equipment used in Acid Digestion (a) Oven (b) Desiccator with crucibles having samples (c) Vessels and their jackets (d) Microwave Oven (e) Washing apparatus of crucibles (f) weighing balance .................................................................................. 77

Figure 4-1 Vacuum bagging of a three dimensional structure (a) wooden mould (b) vacuum bagging setup (c) composite dome-shape composite top view (d) inside view .... 81

Figure 4-2 Tool for helmet mould .................................................................................. 83

Figure 4-3 Normal force (N) between object an surface ................................................ 84

Figure 4-4 Angle of friction .......................................................................................... 85

Figure 4-5 Layout of mould design ................................................................................ 85

Figure 4-6 (a) Side of tool with embedded glass fibres (b) Creating walls of hollow part (c) Cured hollow part of mould (d) Middle part preparation (e) Right, left and middle hollow parts of the nonwoven fibre-glass mould .................................................................................. 86

Figure 4-7 Different views (a) left filled part (b) middle filled part (c) moulded parts inside the helmet shell tool (d) complete fixed mould on a stand ........................................ 87

Figure 4-8 Helmet shell tool with (a) Unfixed moulded parts (b) Fixed moulded parts .... 87

Figure 4-9 Fabric on mould ready for conforming ...................................................... 88

Figure 4-10 Top view of conformed fabric ................................................................... 89

Figure 4-11 Conformed fabric held by clips .................................................................. 90

Figure 4-12 Uncured portions marked at helmet shell edge ......................................... 91

Figure 4-13 Dry fabric on the mould with locked edge by resin ................................... 92

Figure 4-14 Helmet shells edge formation by resin ..................................................... 92

Figure 4-15 Vacuum assisted draping ......................................................................... 95

Figure 4-16 Post VADT views (a) Side (b) Back (c) Front (d) Top ............................... 95

Figure 4-17 Riot helmet shell manufacturing using the vacuum bagging method ........ 97

Figure 4-18 Placement of mould on front edge ............................................................ 98

Figure 4-19 (a) Two inlet valves (b) Single inlet valve ................................................ 98
Figure 4-20 Different varieties of infusion mesh (a) Soft (b) Hard .................................................99

Figure 4-21 (a) Perforated release film having creases (b) Impregnation without perforated release film ..........................................................................................................................99

Figure 4-22 (a) Uniform infusion (b) H-clip ......................................................................................100

Figure 4-23 Bridging of vacuum film .................................................................................................100

Figure 4-24 Mould placed on wooden blocks ..................................................................................101

Figure 4-25 Dismantling of mould ....................................................................................................102

Figure 4-26 (a) Developed single-piece riot helmet shell (b) Finished look of developed single-piece riot helmet shell .................................................................................................102

Figure 4-27 Flow chart of single-piece riot helmet shell manufacturing ........................................104

Figure 5-1 Impact locations on a riot helmet ....................................................................................105

Figure 5-2 Dynatup 8200 drop weight impact testing instrument ................................................106

Figure 5-3 Aluminium headform ....................................................................................................108

Figure 5-4 Headform with helmet shell ............................................................................................109

Figure 5-5 (a) Headform holding rods (b) Foundation for helmet holding assembly ......................109

Figure 5-6 Force sensor model series1203V5 ..................................................................................110

Figure 5-7 Sensor’s groove on the headform ...................................................................................111

Figure 5-8 Different views of the helmet test rig (a) front view (b) side view .................................111

Figure 5-9 Impulse data acquisition system ......................................................................................112

Figure 5-10 LIVM sensor and power unit schematic diagram .........................................................113

Figure 5-11 Low impedance voltage mode system ..........................................................................114

Figure 5-12 Impact force and force transmitted curves at 25.6J impact (without specimen) .........115

Figure 5-13 Force transmitted curve for flat panel composite at 5J impact ......................................118

Figure 5-14 Trapezoidal method to calculate energy absorption ..................................................119

Figure 6-1 Categories of flat panel composite panels ......................................................................121

Figure 6-2 Flat composite panels for impact testing .................................................................121
Figure 6-3 Impact testing on flat composite panel ................................................................. 122
Figure 6-4 Energy absorption for flat composite panels ....................................................... 124
Figure 6-5 Energy absorption of flat composite panels for (a) 5.6J impact (b) 15.6J impact and (c) 25.6J impact .......................................................... 124
Figure 6-6 Force transmitted (normalised) for flat composites ........................................... 125
Figure 6-7 Normalised peak transmitted force of flat composite panels for (a) 5.6J impact (b) 15.6J impact and (c) 25.6J impact .......................... 126
Figure 6-8 Force attenuation factor for flat composites ...................................................... 127
Figure 6-9 Force attenuation factor of flat composite panels (a) for 5.6J Impact (b) 15.6J Impact (c) for 25.6J Impact ............................................. 128
Figure 6-10 Thickness of developed single-piece riot helmet shell ................................. 130
Figure 6-11 Density of developed single-piece riot helmet shell ........................................ 131
Figure 6-12 Schematic model for curvature calculation .................................................. 132
Figure 6-13 Bi-radial curvature at different impact locations ........................................... 133
Figure 6-14 Categories of developed helmet shells and location for impact testing .......... 134
Figure 6-15 Impact on top location at riot helmet shell ..................................................... 134
Figure 6-16 Energy absorption at different helmet locations on single-layer helmet shells ......................................................................................... 135
Figure 6-17 Energy absorption at different locations on single-piece helmet shells (a) for 5.6J impact (b) for 15.6J impact and (c) for 25.6J impact (d) on double-layer helmet shells for 25.6J impact ......................................................... 137
Figure 6-18 Peak transmitted force at different level of impact energy (a) at helmet back location (b) at helmet top location (c) at helmet side location ................................................. 138
Figure 6-19 Transmitted force at different locations (a) for 5.6J impact (b) for 15.6J impact and (c) for 25.6J impact (d) on double-layer helmet shells for 25.6J impact ........................................ 140
Figure 6-20 Force attenuation factor at different impact location on helmet shell .......... 142
Figure 6-21 Force attenuation factor at different locations (a) for 5.6J impact (b) for 15.6J impact and (c) for 25.6J impact (d) on double-layer helmet shells for 25.6J impact........143
Figure 6-22 Energy absorption performance with and without internal padding (a) at side location (b) at back location and (c) at top location..............................................................145
Figure 6-23 Force attenuated factor with and without internal padding at (a) side location (b) back location (c) top location ..................................................................................146
Figure 6-24 Original helmet pieces (a) Thermoplastic helmet shell (b) Multi-piece composite helmet shell.............................................................................................................148
Figure 6-25 Helmet shell comparison for transmitted force ...........................................148
Figure 6-26 Helmet shell comparison for energy absorption...........................................148
Figure 7-1 Half helmet shell nodes .................................................................................152
Figure 7-2 Surface generation of half helmet shell.........................................................152
Figure 7-3 Half helmet shell with thickness 1 mm..............................................................153
Figure 7-4 Half helmet shell shape with individual meshing .............................................153
Figure 7-5 Riot full helmet shell shape in Rhinoceros (a) without render (b) with render .................................................................................................................................154
Figure 7-6 Helmet shell views in ABAQUS (a) front (b) side (c) back (d) top.............154
Figure 7-7 Helmet shell with combined faces....................................................................155
Figure 7-8 Flat impactor ....................................................................................................155
Figure 7-9 (a) Half headform wire structure (b) Complete headform wire (c) Complete solid headform in ABAQUS ..................................................................................156
Figure 7-10 Surface representing force sensor.................................................................156
Figure 7-11 Transverse isotropic plane............................................................................157
Figure 7-12 Tetrahedral shape ..........................................................................................158
Figure 7-13 Simulation showing (a) Boundary conditions (b) Meshed parts...............158
Figure 7-14 Cross-sectional view of the simulated model in Abaqus .........................159
Figure 7-15 Schematic illustration of the FE impact models: (a) Model for Top impact location in assembly form (b) Model for Top impact in meshed form (c) Model for Side impact location in assembly form (d) Model for Side impact in meshed form (e) Model for Back impact location in assembly form (f) Model for Back impact in meshed form......160

Figure 7-16 Energy absorbed by the helmet shell (thickness 1mm) at different locations ............................................................................................................................................................................................................................................................................................................................................................................................................................................................................................................161

Figure 7-17 Percent energy absorption for helmet shell (thickness 1mm) ...............162

Figure 7-18 Comparison of energy absorption results for 1mm thick helmet shells at different helmet locations............................................................................................................................................................................................................................................................................................................................................................................................................................................................................................................162

Figure 7-19 Comparison of percent energy absorption at different locations on 1mm thick helmet shells (a) Top location (b) Back location (c) Side location.........................164

Figure 7-20 Comparison of force transmitted results at different locations on 1mm thick helmet shells (a) Top Location (b) Back Location (c) Side Location.........................165

Figure 7-21 Peak transmitted force at different impact locations of helmet shell (a) Top location (b) Back location (c) Side location............................................................................................................................................................................................................................................................................................................................................................................................................................................................................................................167

Figure 7-22 Energy absorbed at different impact locations of helmet shell (a) Top location (b) Back location (c) Side location............................................................................................................................................................................................................................................................................................................................................................................................................................................................................................................168
LIST OF TABLES

Table 2-1 Guidelines (BS EN ISO 527-4:1997) used for the dimensions of the tensile test specimens (all dimensions are in mm) .......................................................... 31
Table 3-1 Properties of Kevlar®-49 with comparison to Kevlar®-29 ......................... 64
Table 3-2 Tensile properties of 5-8-28 flat Kevlar ............................................... 73
Table 3-3 Fibre and resin contents ...................................................................... 77
Table 5-1 Experimental data (average) for correcting factor ................................. 115
Table 6-1 Thickness of flat composite panels ....................................................... 122
Table 6-2 Tests results for the energy absorption performance ............................ 123
Table 6-3 Experimental results for the force attenuation factor ............................ 127
Table 6-4 Curvature at different impact locations ................................................. 133
Table 6-5 Experimental results for the energy absorption performance ............. 135
Table 6-6 Experimental results for the force attenuation factor at helmet shells .... 141
Table 7-1 Simulated results for helmet shells (thickness 1mm) for energy absorption .... 161
ABSTRACT

The present research aims to develop a novel technique for the creation of composite riot helmet shells with reinforcing fibre continuity for better protection against low velocity impacts. In this research an innovative, simple and effective method of making a single-piece continuous textile reinforced helmet shell using vacuum bagging has been established and discussed. This technique also includes the development of solid collapsible moulding apparatus from nonwoven fibres. Angle-interlock fabric, due to its good mouldability, low shear rigidity and ease of production is used in this research. Several wrinkle-free single-piece composite helmet shells have been manufactured.

Low-velocity impact tests on the continuously reinforced helmet shells have been carried out. For this purpose an in-house helmet shell testing facility has been developed. A test rig has been designed in such a way that the impact test can be carried out at different locations on the riot helmet shell. Low-velocity impact testing has been successfully conducted on the developed test rig. Practical experimentation and analysis revealed that the helmet shell performance against impact is dependent on the impact location. The helmet shell top surface has better impact protection as compared to the helmet shell side and back locations. Moreover, the helmet shell side is the most at risk location for the wearer.

Finite Element models were created and simulated in Abaqus software to investigate the impact performance of single-piece helmet shells at different impact locations. Model parts have been designed in Rhinoceros software. Simulated results are validated by the experimental results which show that the helmet top position is the safest position against an impact when it is compared to the helmet back and helmet side positions.
DECLARATION

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BIOGRAPHICAL

Author
Bilal Zahid

Professional
The author is working as Assistant Professor in the Textile Engineering Department, NED University of Engineering and Technology, Karachi, Pakistan since November 2006. Previous experience includes, working in managerial positions as head of production and ‘marketing and sales’ in denim manufacturing units of Karachi, Pakistan since 2001-2006.

Education


Student Conferences
Characterisation of Riot Helmets with Continuous Textile Reinforcement for Impact Protection, Materials Post Graduate Conference, 21st May 2010, Renold Building, University of Manchester, UK.

Characterisation of Riot Helmets with Continuous Textile Reinforcement for Impact Protection, Materials Post Graduate Conference, 21st and 22nd May 2009, Renold Building, University of Manchester, UK.

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International Conference Publication
Riot Helmet Shell with Continuous Textile Reinforcement for Improved Protection, 3rd World Conference on 3D fabrics and their applications, Wuhan Textile University, Wuhan, PR China, 20th and 21st April 2011.
With Love and Gratitude to My Parents and All Family Members
CHAPTER 1 INTRODUCTION

1.1 Preamble

Helmets are one of the items of protective wear used as military equipment in wars. The need for the helmet at such time is to protect the head, face and sometimes the neck from the swords, arrows, spears and other blunt weapons (Scott, 2005). Currently helmets are used in daily life with the major aim of protection. However, the needs and intensity of protection vary. The protection may be against threats from any chemicals, fire, heat and impact. Currently, helmets are used for head protection in military, police, fire fighting, sports and leisure. The level of protection and the quality of the helmet mainly depend on the type of threats. For example the helmet used for riding a bicycle has a different level of impact protection from that for police riot helmets, and the police riot helmets offer low velocity impact protection while the military anti-ballistic helmets provide protection against impact projectiles travelling at high velocity.

The main purpose of helmets is to protect the wearer from various types of external impact. Injury to the head can cause symptoms such as skull deformation and brain contusions (Ryan, 1992). The inertial effects can also cause problems such as cerebra-concussion, i.e. a small movement of the brain due to a relative movement of skull and fixed membranes and there may be damage to the tissues as well. These effects can lead to loss of function or physical disruption of neural tissues and the victim may suffer traumatic effects. Head protection is one of the most important needs for police officers who are vulnerable to thrown objects.

Riot is a violent disturbance of the peace by a crowd (Oxford Reference Online Premium, 2011). Disturbances caused by disorganised rioters are normally destructive and continuously have created an intense situation. The reasons for and causes of riots are different in nature all around the world. However, police officers have to monitor the riots and have to control the situation. Sometimes while calming down the rioters, police officers also can have direct body contact with the rioters.

In order to control the crowd, the police use different techniques and tactics. These techniques for handling or calming down people may be also different for different regions depending on culture, environment and laws of that particular country or region. Police officers usually wear body armour, helmets, face shields, and limb protectors.
There were approximately 40,000 helmets used throughout the United Kingdom in 2003 (Roedel, 2008). There is an annual demand of approximately 12,000 riot helmets for the police in the United Kingdom (Malbon, 2011). Every tactical officer who is trained for public order duties has a helmet as one of the items of protective equipment. The demand for riot helmets is also increasing in other countries. The requirements for helmets usually include effective protection against impact, light weight, wear comfort and cost effectiveness.

1.2 Background of the research

Riot helmets are currently manufactured based on the use of two technologies, i.e., moulding and textile reinforced composites. Thermoplastic helmets are produced by the injection moulding processes, where a molten polymer is injected into the mould and cured into the helmet shape. Helmets produced by this technique offer reasonable protection, low manufacturing cost and high production rates due to its simplicity. The Hand lay-up technique is used for the manufacture of textile reinforced composite helmet shells. In this technique, several layers of matrix impregnated pre-cut fabric are placed on a negative mould and then cured to the desired helmet shape. Waste of material due to cutting of fabric and time taken in manufacturing are the reasons for high manufacturing cost and low production rates (Roedel and Chen, 2007). During impact loading, the failure mechanism for textile reinforced composite riot helmets is much more complex than for the thermoplastic helmets due to fibre breakage, matrix cracking and delamination. Apart from absorbing energy by deformation, textile reinforced composite riot helmets also absorb energy through these complex mechanisms. This is the reason why riot helmet shells made from textile composites are gaining popularity for better impact protection despite the fact that composite helmets are more expensive than thermoplastic helmets (Anonymous, 2010). However, there is a restrictive feature of discontinuity in the fabric due to trimming and cutting, which seem to be a disadvantage to the current composite helmets.

Roedel and Chen (Roedel, 2008; Roedel and Chen, 2007) researched continuous textile reinforced helmet shells aiming to avoid fibre discontinuity in the helmet shells. They manufactured an optimised 5 layer through-the-thickness angle-interlock Kevlar woven fabric with a construction of 5-8-28 and moulded it into a helmet shape using a positive moulding method without needing to cut the fabric. In addition, numerical studies on impact analysis were reported on multi-piece and single-piece helmet shells. The results
showed that single-piece fabric-reinforced helmet shells have better impact protection than the multi-piece fabric reinforced helmet shells.

The riot helmet shells were produced (Roedel, 2008) using a hand lay-up technique in which matrix material was brushed on the draped fabric. There are always some constraints to composites made from hand painted matrices such as uneven resin content, possibility of air bubbles in the composite and unequal fibre volume fraction within a helmet shell. Therefore, there is a need to develop a new technique for the manufacture of single-piece fabric-reinforced riot helmet shell and the present research will address this problem and will also aim to conduct impact analyses on the single-piece helmet shells for performance characterisation, using experimental and numerical methods.

Two main helmet components are the protective foam padding and the helmet shell. The primary function of the protective foam padding is to absorb most of the impact energy. Whereas, the main function of the helmet shell is to resist penetration of any kind of foreign object touching the head causing direct damage to the skull and to distribute the impact load on a wider foam area in order to increase the foam energy absorption capability (Shuaeib et al., 2002a).

1.3 Research aim and objectives

Based on the research carried out by Roedel and Chen (Roedel, 2008), this present research aims to innovate a novel technique for manufacturing composite riot helmet shells with reinforcing fibre continuity and to evaluate helmet shells for impact protection against low velocity impacts. The study is divided into three main parts.

The first part is the manufacturing of a continuously reinforced riot helmet shell from an industrial technique. The objectives in this part of the work are:

1) to manufacture 5-8-28 angle-interlock fabric for helmet development;

2) to develop flat composite panels from vacuum bagging using the manufactured 5-layer angle-interlock fabric and to determine the major physical and mechanical properties of flat composite panels necessary for the finite element analysis (FEA) needed for the third part of this study;
3) to create a dome shaped prototype from vacuum bagging. This objective is the essence of creating a novel technique for manufacturing riot helmet shells from vacuum bagging and;

4) to establish a procedure for the manufacturing riot helmet shells and also to provide guidance to the future practical production process for the industry. This procedure should allow easy reproduction.

The second part of this study is the low-velocity impact testing of the continuously reinforced riot helmet shells. The objectives in this part are:

1) to develop an in-house riot helmet shell testing facility for low velocity impact test;

2) to designed a test rig in such a way that the impact test can be carried out at different locations at the riot helmet shell;

3) to conduct low velocity impact tests on the riot helmet shells at different locations and with different impact energy levels; and

4) to establish a procedure in order to carry out impact tests on riot helmet shells.

The third part of this study involves the use of the finite element method (FEM) to investigate the impact performance of riot helmet shells. This would also facilitate the comparison between the experimental and FE results. The objectives for the third part of the research are as follows:

1) to re-establish the riot helmet shell geometry;

2) to create FE models in ABAQUS for different impact locations and to analyse the impact performance at different impact locations; and

3) to validate the theoretical results against the experimental results.

1.4 Thesis layout

Chapter 1 is the introductory chapter. The remainder of this thesis is organised as follows:
Chapter 2 presents a review of the literature in the areas of: general information about riot helmets history, construction and manufacturing methods of riots helmets, classification of composites, composite manufacturing and testing for properties evaluation, drop weight impact testing, impact performance of low velocity impact on composite structures, riot helmet testing standards and previous research on riot helmet shells. Further, a methodology will be explained.

Chapter 3 presents the initial study and fabrication of angle-interlock fabric, development and understanding of flat composite panels by the vacuum bagging technique. Further physical and mechanical properties of Kevlar composite panels were also determined for understanding the behaviour of Kevlar composite structures and also these properties were necessary in developing a finite element simulation.

Chapter 4 initially presents the basic understanding towards the development of dome-shape composite structures by the vacuum bagging technique. Afterwards a detailed procedure for the development of a novel technique for the manufacturing of single-piece riot helmet shell will be described. This technique includes the development of a non-woven glass fibre mould with its collapsible mechanism and also vacuum-assisted draping technique (VADT) which provide wrinkle free draped helmet shells. Moreover, a successful method of making single-piece riot helmet shells from angle-interlock fabric using a vacuum bagging process is discussed.

Chapter 5 focuses on the manufacturing of a test rig. Moreover, a detailed procedure for conducting impact tests and data analysis from the developed test rig is explained. Sufficient capabilities have been achieved in order to do the impact testing at different locations on the riot helmet shells.

Chapter 6 presents the impact testing results on flat composite panels and on helmet shells based on the developed test rig. An investigation has been carried out for the overall impact performances of continuous textile reinforced helmet shells.

Chapter 7 starts with a brief introduction to finite element simulation. Furthermore, it explains the creation of a dynamic simulation used for finite element analysis. Moreover, results from the impact simulation have been validated by the experimental test.

Chapter 8 ends the thesis with conclusions and recommendations for future work.
CHAPTER 2  LITERATURE REVIEW AND METHODOLOGY

2.1 Introduction

Helmet shells with continuous reinforcement led to better protection against trauma impact on the head. This is a new area for research and not much direct literature has been published on the theoretical and practical investigations on riot police helmet shells (Roedel and Chen, 2007; Roedel, 2008).

This chapter presents a literature review which provides the building blocks of this research, which include (i) helmet’s history, (ii) introduction and classification of composites, (iii) testing methods for composite structures, (iv) impact phenomenon of composite helmets, (vi) drop weight impact testing instrument, (vii) construction and manufacturing techniques of riot helmet, (viii) helmet test standards, (ix) previous research on composite helmet shells. Further, research methodology has been described in this chapter.

2.2 History of helmets

Warfare has been persistent since the beginning of humanity. There is commonly a need for head protection as well as other parts of the body in personal defence. In the early days protective covering in the form of a shell cap made of wood and leather skins were used to protect the head from the blow of a club (Scott, 2005). Improvement in the protection criteria are directly related to the development of weapons. When mankind did any advancement in weapons then there was always a demand and need for more advanced armour.

The Assyrians and the Persians had helmets made of leather and iron, which were then developed by the Greeks who produced bronze helmets. The Romans further worked on these helmets in 1st and 2nd century AD and started a revolution in helmet manufacturing when they introduced legionary’s and gladiator’s helmets which gave better protection to the head, face and neck. From the Romans to the end of the Middle Ages there was a modernisation in helmet manufacturing which also included flat top skull-cap helmets (Lambert, 2011).
The importance of skull protection was appreciated by every developing nation. China also has a very old civilisation and helmets made from bronze and leather had been used for centuries. In the 11th century BC, Chinese warriors wore body armour made from multiple layers of rhinoceros skin. Similarly in the 13th century AD, Mongols used ox hides. Iron and steel helmets were also very popular due to highly skilled work in Turkey and India.

At the end of the 15th century helmets having hinges or pivots were also introduced to improve protection of the neck and face. There was a decline in helmet usage in the 18th and 19th centuries when there was an abundance of swords and spears. This was due to the innovation of flintlock muskets. In that era only light weight open face helmets were in use. However, in World War I, steel helmets were necessary items for the infantry due to the high velocity metal fragments of the shell (Scott, 2005). Helmets become standard equipment in World War I and more varieties of helmet were seen in World War II.

The human head represents approximately 9% of the body area exposed in combat and receives approximately 20% - 25% of all hits (Carey et al., 2000). This was the reason that helmets at different stages in history were used for protection against different weapons and threats. Nowadays, helmets have been diversified according to their applications i.e. from riding an infant bicycle to a flying combat aeroplane, helmets are used based on their purpose. It has been noted that composite helmets are gaining popularity and importance due to their inherent impact performance including the light weight and protection.

2.3 A brief introduction to composites

In composites, two or more different types of material are bonded together with one serving as the matrix. Composites are developed by emphasising the good properties of different materials while avoiding their drawbacks (Bolton, 1998). In the most commonly used composites, one constituent is known as the reinforcing phase (in the form of fibres, particles, or flakes) and the other serves as a medium which is known as the matrix (in continuous form) (Kaw, 2006).

The term “textile composite” refers to a class of innovative composite materials in which the reinforcement is produced from any of the textile processes (woven, braided, knitted, stitched) (Bogdanovich and Pastore, 1996). In current study an aramid fibre, Kevlar 49®, is
used as reinforcement in the form of an angle interlock woven fabric structure. Kevlar 49® has low density, high tensile strength and high impact resistance (Kevlar, 2011).

2.3.1 Classification of composites

Composites are classified in two ways, either by the geometry of reinforcement for instance, particulate, flake and fibres or by the type of matrix, such as polymer, metal, ceramic and carbon composite (Kaw, 2006). This research deals with fibre composites with a polymer matrix.

A polymer matrix composite (PMC) consists of a polymer as resin reinforced by fibres. Based on the nature of the resin PMC are further classified into two major categories.

1) Thermoplastic composites
2) Thermoset composites

The major difference between the two is that the thermoplastics soften when heated and then they become hard again when cooled back down, whereas the thermosets do not soften when heated (Bolton, 1998). Thermoset polymers are insoluble and infusible after curing because the polymer chains are rigidly joined together with covalent bonds, whereas the thermoplastics are formed at high temperature and high pressure because the bonds are weak and are of van der Waals type (Kaw, 2006; Mallick, 2008). Typical examples of thermoset resins include polyester, phenolics, epoxies and polyamide and those of thermoplastic resins include polyphenylene sulphide, polystyrene, polyether-ether-ketone and polyethylene. Epoxy will be used in this study due to its high strength, low viscosity and low flow rate which causes more wet-ability of fibres. Curing of epoxy can be done at room temperature by the addition of a curing agent commonly known as hardener.

Commonly used composite manufacturing techniques are resin transfer moulding, hand lay–up and vacuum bagging. In using the hand lay-up method there is a possibility of uneven resin impregnation and dry areas especially while painting on thicker fabric layers. In this study, vacuum bagging will be used due to its flexibility and better performance as compared to the hand lay-up technique.
2.3.2 Vacuum bagging

Vacuum bagging is a clamping method that uses atmospheric pressure to hold the resin of lamination in place until the resin cures. For understanding, vacuum bagging is a technique in which the textile or preform are covered with peel-ply, releasing film, breather fabric and vacuum bag film (West System, 2009; Miravete, 2000; Kelly and Zweben, 2000; Eckold, 1994; Long, 2005; Mallick, 2008). The edges of the vacuum bag film are locked with a sealant tape. From one side, air in the bag is extracted by the use of a vacuum pump and from another side resin is infused into the bag using a resin infusion tube. When the vacuum is applied it causes the resin to flow into the textile and proper wetting is achieved. In the laboratory, steel plates are used as the base of the vacuum bagging setup. Figure 2-1 shows a schematic view of the vacuum bagging process. Significant features of vacuum bagging are low void content, high fibre volume fraction and short installation time (Long, 2005).

![Figure 2-1 Schematic configuration of vacuum bagging process](image)

2.4 Testing methods for composite structures

In this section, literature is reviewed for the understanding of different standards in order to determine the physical and mechanical properties of composite panels. These properties have been studied due to their importance and explain the need for finite element software, ABAQUS, in this study.
2.4.1 Method of testing tensile properties

Tensile strength and tensile modulus are the most important measurements for evaluating the strength of a material. In tensile testing, specimens clamped by the jaws of a tensile testing machine were displaced axially at constant speed. For composite specimens, the load due to pulling of the composite, transferred to the matrix and ultimately to the reinforcing fibres. Tensile strength is a measurement of the ability of a specimen to withstand forces that tend to pull it apart before breaking. Tensile modulus is a measure to understand the stiffness of the material and is calculated from the stress-strain graph.

The principle of BS EN ISO 527-4:1997 (British Standard, 1997) is to extend the specimen at its major excess at constant speed until the specimen fractures or the stress value or strain value reaches a certain value.

**Table 2-1 Guidelines (BS EN ISO 527-4:1997) used for the dimensions of the tensile test specimens (all dimensions are in mm)**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Minimum/Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_3$</td>
<td>Overall length</td>
<td>$\geq 250$</td>
</tr>
<tr>
<td>$L_2$</td>
<td>Distance between end tabs</td>
<td>$150 \pm 1$</td>
</tr>
<tr>
<td>$b_1$</td>
<td>Width of specimen</td>
<td>$25 \pm 0.5$</td>
</tr>
<tr>
<td>$L_0$</td>
<td>Gauge length (recommended for extensometer)</td>
<td>$50 \pm 1$</td>
</tr>
<tr>
<td>$L_T$</td>
<td>Length of end tabs</td>
<td>$\geq 50$</td>
</tr>
<tr>
<td>$h_T$</td>
<td>Thickness of end tabs</td>
<td>1 to 3</td>
</tr>
</tbody>
</table>

[Figure 2-2 Schematic diagram for guidelines according to BS EN ISO 527-4:1997]

The stress and strain at the breaking load are calculated by using the following equations:
\[ \sigma = \frac{F}{A} \]  

where,
\( \sigma \) is the tensile stress expressed in megapascals
\( F \) is the measured force in newton
\( A \) is the cross sectional area of the specimen measured in millimetres

\[ \varepsilon_t(\%) = 100 \times \frac{\Delta L}{L} \]  

where,
\( \varepsilon_t(\%) \) is the strain, expressed in percentage %
\( L \) is the distance between the grips, expressed in millimetres
\( \Delta L \) is the increase of the distance between the grips, expressed in millimetres

The tensile modulus of the specimens is calculated by using the following equation:

\[ E_t = \frac{(\sigma_2 - \sigma_1)}{(\varepsilon_2 - \varepsilon_1)} \]  

where,
\( E_t \) is the tensile modulus, expressed in megapascals
\( \sigma_1 \) is the stress, in megapascals, measured at the strain value \( \varepsilon_1 = 0.0005 \)
\( \sigma_2 \) is the stress, in megapascals, measured at the strain value \( \varepsilon_2 = 0.0025 \)

### 2.4.2 Method of testing shear properties

In-plane shear modulus can be calculated in accordance with BS EN ISO 15310:2005 (British Standard, 2005). Under shear loading the resin transfers the load across the composite. Shear stresses are also based on the adhesion of resin and fibre. In this plate-twist method shown in Figure 2-3, a square or rectangular plate is supported on the two corners of one diagonal and the load is applied at a constant rate to the corners of the other diagonal (Hodgkinson, 2000; British Standard, 2005).
In Figure 2-3 (British Standard, 2005) and also according to BS EN ISO 15310:2005, \(a'\) and \(a''\) are the width of the specimen, also \(a' \geq 35h\) (h = thickness of the sample). \(S_1\) and \(S_2\) are the distance between the loading points and the support points. The test machine speed should be 1 mm/min +/- 20%.

The in-plane shear modulus is determined by using the following equation.

\[
G_{12} = \frac{3}{4} \times \frac{\Delta \times a' \times a'' \times K}{1000h^3}
\]  

(2.4)

where,
\(\Delta\) is the slope of the load-deflection curve
\(K\) is the geometric correction factor, \(K = 0.822\)
\(a'\) and \(a''\) are the average specimen width in each direction in millimetres
\(h\) is the average specimen thickness in millimetres
\(G_{12}\) is the in-plane shear modulus expressed in gigapascals

Note: For a span-to-diagonal ratio other than 0.95, the value of \(K\) can be calculated from

\[
K = 3s^2 - 2s - 2(1-s)^2 \ln(1-s)
\]

where,
\(s = S / D\)

\(S\) is the measured mean span in mm and
\(D\) is the length of the diagonal in mm.
2.4.3 Method of calculating density by Immersion technique

Density is one of the most important physical properties of a composite structure which
derives from the variation and uniformity in the composites structure. The immersion
method is used in the industry as per British Standard BS EN ISO 1183-1:2004 (British
Standard, 2004) to calculate the density of composite material.

The density $\rho_S$, can be calculated from the following equation:

$$\rho_S = \frac{(m_{S,A} \times \rho_{IL})}{(m_{S,A} - m_{S,IL})}$$

(2.5)

where,

$m_{S,A}$ is the apparent mass, in grams, of the specimen in air

$m_{S,IL}$ is the apparent mass, in grams, of the specimen in the liquid

$\rho_{IL}$ is the density of the immersion liquid (water)

2.4.4 Method for constituents of composite Specimens

The composition of a composite is one of the important features. The resin and fibre
contents were calculated from the acid digestion procedure BS ISO 14127:2008 (British
Standard, 2008).

The percentage mass of fibre and resin content is calculated by using the following
equations:

$$w_f = \left( \frac{m_2 - m_1}{m} \right) \times 100$$

(2.6)

$$w_r = 1 - w_f$$

(2.7)

where,

$w_f$ is the fibre content (mass %)

$w_r$ is the resin content (mass %)

$m_1$ is the initial mass of the glass filter with the crucible (g)

$m_2$ is the mass of the test specimen and the glass filter with the crucible after digestion (g)

$m$ is the initial oven dry mass of the test specimen (g).
Fibre content and resin content by volume can be calculated from the following equations (Mallick, 2008):

$$v_f = \frac{w_f \times \rho_c}{\rho_f}$$  \hspace{1cm} (2.8)

$$v_r = 1 - v_f$$  \hspace{1cm} (2.9)

where,

- $v_f$ is the fibre content (volume %)
- $v_r$ is the resin content (volume %)
- $\rho_c$ is the density of the test specimen (g/cm$^3$)
- $\rho_f$ is the density of the fibre (g/cm$^3$).

### 2.5 Impact phenomenon of composite riot helmets

The purpose of a riot helmet is different when it is compared with a military helmet. Military helmets have a completely different design in that they have more stiffness due to the greater helmet shell thickness and these helmets are specifically designed for protection against high velocity impacts e.g. bullets or flechettes (Aare and Kleiven, 2005), whereas riot helmets are designed for low velocity impacts.

#### 2.5.1 Low-velocity impacts

A sudden application of an impulsive force to a part or portion of a structure is known as impact (Oxford Reference Online Premium, 2011; Reid and Zhou, 2000). Impact on riot helmets mainly comes from flying objects such as stones, bottles, cans, cricket bats and hockey sticks and is categorised as low velocity impact. It is hard to have a clear boundary defined between a low velocity impact and high velocity impact (Richardson and Wisheart, 1996). According to Abrate (Abrate, 1998), impact resulting in complete penetration of the laminate are often known as ballistic impacts, whereas non-penetrating impacts are called low-velocity impacts. The major difference in nature is of impactor shape, impactor velocity and the response time (Choi and Chang, 1992). Usually, low velocity impacts are caused by high masses and low velocities. For example, low velocity impact would involve flying objects weighing 50 grams to 1000 grams with a velocity of maximum 30 m/s. High velocity impacts would have very low masses and high velocities (Aare and
Kleiven, 2005). A larger mass with low velocity may never cause the same amount of damage as smaller mass with high velocity (Abrate, 1998), even when the impact energy is similar. Ballistic helmets are the common examples for understanding low mass and high velocity. NIJ Standard-0101.04 (National Institute of Justice, 2001) uses mass of 2.6 grams to 10.8 gram with a velocity of 329 m/sec to 878 m/sec (Croft and Longhurst, 2007; Chen and Yang, 2010)

2.5.2 Modes of failure in composite riot helmet shells
Metals absorb energy in elastic and in plastic regions, whereas composite laminates mostly absorb energy in the elastic deformation. Since most composites are brittle in nature they can absorb energy in elastic deformation and damage mechanism and not due to plastic deformation (Richardson and Wisheart, 1996). Further, a riot helmet composite shell suffering a low-velocity impact may contain barely visible impact damage (BVID) and yet this can reduce the structural integrity of the composite helmet shell (Roedel, 2008). It has been earlier stated that not much literature is directly available for the riot helmets. For understanding, modes of failure in composites with respect to low-velocity impacts (Richardson and Wisheart, 1996) are reviewed and discussed.

2.5.2.1 Matrix mode
Matrix cracking is the first type of failure, usually caused by low-velocity impact and occurs parallel to the fibres due to tension, compression and shearing. Shear cracking (inclination of 45°) and bending cracking (vertical inclination) are examples of matrix cracking.

2.5.2.2 Delamination mode
Delamination cracks always develop in the resin-rich area between the overlapping laminar surfaces. Delamination also comes in the presence of matrix cracking when the threshold energy has been reached. Bending cracks and the shear cracks are responsible for delaminations.
2.5.2.3 Fibre failure mode

The fibre failure mode of failure occurs after matrix cracking and delamination. It is due to the locally high stresses and indentation effects by shear forces and also due to high bending stresses on the non-impacted site.

2.5.2.4 Penetration mode

The penetration mode is the last failure mode and it occurs when the fibre failure reaches its critical extent and the impactor is allowed to penetrate the composite material.

There is damage to laminates after an impact which cannot be observed through the naked eye (Barely Visible Impact Damage, BVID) and the strength of the composite will be decreased. Freitas et al (Freitas and Reis, 2000) studied the damage growth of the impacted composite laminates and suggested that the delaminated area depends on the number of interfaces between the composite layers. An illustration of the typical failure modes is shown in Figure 2-4 (Freitas and Reis, 2000):

![Impact damage in a composite laminate](image)

Single-piece riot helmet shells will reduce the delamination due to the absence of multiple fabric layers. The impact properties depend mainly on the location of the impact and since riot helmets have varying curvatures, the impact location plays a vital role in impact performance of the riot helmet (Mills, 1996). Impacts on riot helmets are in the category of low velocity impacts and usually a drop weight impact testing instrument is recommended in the laboratory for appropriate testing.
2.5.3 Factors influencing impact characteristics

2.5.3.1 Impactor shape

Mitrevski et al (Mitrevski et al., 2005; Mitrevski et al., 2006) used a drop weight impact tester with hemispherical, ogival and conical impactor shapes. In their study, specimens with hemispherical shape impact produced barely visible impact damage (BVID) while the conical and ogival shape impactor produced permanent indentation and penetration. They found out that the hemispherical impactor produces the largest damage area, whereas the conical shape impactor produces the most fibre breakage and produces the largest indentation depth.

In an experimental investigation by Zhou et al (Zhou et al., 2001) found out that the damage mechanism is changed by the change of impactor shape. When a hemispherical impactor is used, matrix cracking is initiated followed by fibre fracture. Although, ply shear-out in their study, seems to be the foremost effect with a flat impactor. Also in their study, a flat impactor spreads stresses to a major area in the specimen as compared to hemispherical and nose-shaped impactors.

2.5.3.2 Impactor velocity and laminate thickness

In a study, Aslan et al (Aslan et al., 2003; Aslan et al., 2002) investigated the effect of impactor velocity and thickness of laminates under low velocity impact using a drop weight impact tester. According to them, stiffer specimens have shorter contact durations and higher peak forces as compared to softer specimens. Peak force in a thin plate is smaller as compared to a thick plate composite. Delaminations due to shear stresses are larger in thin plates as compared to thick plates. Under low velocity impact, the in-plane dimensions of laminates influence the mechanical behaviour of composite structures.

2.5.3.3 Single-piece and multi piece laminates

Roedel and Chen (Roedel and Chen, 2007; Roedel, 2008) concluded that the single-piece laminate has better impact protection compared to discontinuous laminates. In their study they initially did FE analysis in MSC Marc Mentat on composite plate structures having single-piece and multi-piece reinforcement. Four multi-piece plate models based on different overlapping lengths and one single-piece plate model were impacted by a circular ball impactor with different energy levels. Their results showed that the single-piece plates had better indentation resistance than multi-piece plates, therefore single-piece plates have
more ability to block the impact force being transmitted to the head than multi-piece plates. Figure 2-5 (Roedel and Chen, 2007) shows multi-piece plate design.

![Multi-piece plate design](image)

**Figure 2-5 Multi-piece plate design**

Roedel and Chen (Roedel and Chen, 2007; Roedel, 2008) suggested that more energy is absorbed by the composite panels having shorter overlapping lengths and in the case of a single-piece where there is no overlapping (due to the single-layer) there is less energy absorption. Due to this reason single-piece laminate structures will block more impact energy as compared to the multi-piece structures. They also found from analysis, higher strain values in multi-piece plates than single-piece plates and suggested that helmet shells from a single-piece of fabric have better impact force blocking properties than multi-piece helmet shells. According to them, single-piece laminates will have better impact absorption properties and these properties are also beneficial in reducing head acceleration in manufactured helmets. They also concluded that single-piece plates performed better impact protection in terms of displacement and residual deformation as compared to multi-piece plates.

### 2.5.3.4 Curvature of laminates

Her et al used finite element analysis in their comparison work of composite laminates and shell structures (Her and Liang, 2004). They suggested that specimens with smaller curvatures result in a large contact force. Structural response of laminates is directly related to the impact velocity.

Mahajan et al did a finite element study to determine the effect of impactor mass, velocity and curvature of shell on cylindrical shells and shell panels (P. Mahajan et al., 2003). Impactor velocity has a greater effect on the contact force as compared to impactor mass. For a particular kinetic energy, impact induced damage is more with high velocity for both varieties of specimen. According to them, low curvature of shell panels has very little
effect on maximum contact force and impact induced damage. Further, contact time and deflection increased with the decrease of curvature. As per their finding, damage in flat shell panels is more than that of cylindrical shell.

2.5.4 Behaviour of textile composites

Park and Jang investigated impact analysis on thick and thin aramid fibre laminates. They recorded large displacement and delamination areas in thin laminates as compared to thick laminates. More impact energy is absorbed in a thin laminate due to its flexibility i.e. without restriction of deformation. According to them, thick laminates did not experience full deformation due to restriction caused by the adjacent aramid composite layer (Park and Jang, 2003).

Hu et al compared plates of textile composite and aluminium and found out that energy absorption of 3-Dimensional textile composites is greater than aluminium. They also did finite element analysis and achieved successful comparison between experimental and virtual results (Hu et al., 2009).

Impact behaviour of composites with different fibre architectures has been investigated (Chen and Hodgkinson, 2009). Their results show that three dimensional woven composites have the best damage resistance and tolerance in low velocity impact as compared to non-crimp fabric reinforced composites. Further they suggested that in high velocity impact three dimensional woven composites absorb less energy.

The drop weight impact apparatus is setup using a semi-spherical indenter dropped with 5J, 15J, 25J energy levels on hand-made preforms of orthogonal and angle-interlock weaves (Padaki et al., 2010). They observed that increases in the interlacement points in a preform, improves the impact resistance of the multilayer textile composite.

Two dimensional (2D) textile composite structures and three dimensional (3D) textile composite structures were compared and 2D plain woven laminates were shown to have less resistance to penetration as compared to 3D orthogonal composites which also dissipated more energy as compared to the 2D systems (Baucom and Zikry, 2004). They also used drop weight impact testing machine for their experiments. 3D composites due to having more interlacement points in the structure can dissipate more energy than 2D
composites and for this reason the area of energy dissipation is smaller in 2D laminates as compared to 3D composites.

2.6 The drop weight impact

Impact testing on composite structures can be done in number of ways as discussed by Abrate (Abrate, 1998), but the major three categories are: Gas gun, Drop weight and Pendulum.

In drop weight testers, a large mass impactor is guided by rails in a free fall motion from a given height. Sensors can detect the velocity and load at the time of impact. Impact energy and velocity are calculated from the following equations.

\[ E = \frac{1}{2} m v^2 \]  
(2.10)

\[ v = \sqrt{2gh} \]  
(2.11)

In the drop weight system the potential energy of the system is converted into kinetic energy during an impact onto the specimen. Friction in the mechanism is supposed to be zero due to the free fall motion of the impactor.

According to Instron® the drop weight system has several advantages over other methods (Instron, 2010):

1) it is applicable to moulded samples, moulded parts;
2) it is unidirectional (vertical) movement has no preference of failure. (Failure originates from the weakest point in the specimen);
3) failure can be defined by deformation, cracking or complete fracture.

2.6.1 Instron Dynatup 8200 drop weight tester - Impact testing instrument

The literature on the Instron Dynatup 8200 drop weight impact tester has been reviewed due to the instrument availability in the University of Manchester. The Instron Dynatup 8200 drop weight impact tester is capable of testing materials at a velocity of up to 4.4 m/sec with a maximum drop height of maximum 1.2 metres. Figure 2-6 shows the sketch of the Instron Dynatup 8200 impact tester (Instron, 2004).
The main assemblies of 8200 drop weight impact testing instruments have been described as follows (Instron, 2004).

2.6.1.1 The drop weight assembly
The drop weight assembly is the core of the Dynatup impact instrument. This assembly consists of three parts, which are the drop weight, tup and flag bracket. Brief descriptions are as follows.

The drop weight consists of the mass for the impact testing. The drop weight assembly is a framework of weights and plates bolted together. The empty mass of the drop weight is approximately 3 kg. The drop weight has an ability to hold more mass; ten extra weights, each weighing approximately 1.1 kg, to give a total test mass of 13.6 kg. These ten weights can be stacked within the drop weight and are retained by a threaded rod and securing hand-knob. Cover plates bolt onto the front and back of the drop weight frame to retain the weights.

The impact force applied on the specimen is measured by the tup of the drop weight assembly. It consists of two parts, the tup: which is a load cell for measuring force, and the
tup insert or impact head which is the impactor that actually strikes the specimen. In the current study a flat rigid impactor made from Tecamid 66 was used as the tup insert (RS Components - Electronic and Electrical components, 2010) which is abrasion resistant, tough and rigid material.

The velocity flag, a double pronged stainless steel piece, is a part of a velocity measuring system and is located at the right hand side of the drop weight. During the free fall of the drop weight assembly the velocity flag passes through the velocity detector and the velocity just before the impact is determined. Figure 2-7 shows the schematic diagram of velocity detector and flag.

![Figure 2-7 Velocity detector and flag](image)

2.6.1.2 The drop weight release mechanism

A mechanical lever (release latch) is provided to manually release the drop weight assembly from a pre-selected drop position. The position, based on the required impact energy, can be adjusted by moving the clamp frame up and down and clamping it to the guide columns using the clamp knobs. The velocity of the drop weight can be adjusted from the drop height by using the Equation 2-2.
2.6.1.3 The drop tower framework

The impactor was dropped precisely onto the specimen with the help of a guiding mechanism. This guiding mechanism consists of two vertical bars (columns), base plate, back and top weldment (support) and table.

The drop weight assembly drops free fall on the guide columns via holes in its upper and lower guide blocks. The two guide columns bolted to the base plate and the top weldment. The back weldment provides rigidity and vertical stability to the drop tower.

2.6.1.4 The anvils

Anvils are fixtures that hold specimens during testing. Different styles of anvil are available to accommodate various test specifications and techniques (Instron, 2004).

The drop weight mechanism also depends on several factors for instance impactor mass, impactor shape, height of the drop weight and also the boundary conditions holding the specimen to be tested.

2.7 Composition of a riot helmet

There is not very much information available on the theoretical and practical understanding of the police riot helmets (Roedel and Chen, 2007).

In 1994 the Police Scientific Development Branch ‘PSDB’ (currently the Home Office Scientific Development Branch, ‘HOSDB’) published a minimum performance specification for riot police helmets which is administered by the British Standard Institution (BSI) in the form of a Product Approval Specification (PAS017) (Malbon and Croft, 2004). The current PSDB/ACPO standard was revised by the PSDB from the old version of PAS017. The riot helmet is a combination of different components of different materials as shown in Figure 2-8 (Helmet Integrated Systems, 2009).
2.7.1 Helmet Shell

The helmet shell is the most important part of riot helmet. This part of the helmet has to absorb, disperse and decelerate the impact in order to minimise the risk of traumatic brain injury (TBI). To protect the head and the skull from impact and penetration of an object to the skull is one of the requirements of a helmet shell. The helmet shell distributes the energy to the foam liner and also it absorbs the impacted energy within itself (Shuaeib et al., 2002a).

Helmet shell material properties have an influence on the impact absorption properties (Spyrou et al., 2000). Currently available riot helmets shells are either thermoplastic or composite shells and both these types of shell have different manufacturing techniques (Shuaeib et al., 2002b).

2.7.1.1 Thermoplastic shells and manufacturing method

Polymers can be classified as thermoplastic or thermostet. Materials used in thermoplastic shells are Acrylonitrile-Butadiene-Styrene (ABS), Polybutylene Terephtalate (PBT), polycarbonate (PC) (Bolton, 1998; Helmet Integrated Systems, 2009; MLA, 2006; Shuaeib et al., 2002b). The Polycarbonate is a tough, stiff and transparent material which has an ability to retain its properties at high temperature. So it is used as a combined material due to its good impact resistance and thermal properties with Polybutylene Terephtalate (PBT) as a blend to increase the chemical resistant properties of the riot helmet shell. Acrylonitrile-Butadiene-Styrene (ABS) has good impact resistance, abrasion
resistance and better thermal properties (Bolton, 1998). Due to its poor chemical resistant
to ketones, esters and concentrated oxidising acid, ABS is usually used as alloys for riot
helmet shell (Helmet Integrated Systems, 2009).

Injection moulding is the moulding technique used for thermoplastics and is widely used
all around the world for producing a variety of useful products (Bolton, 1998; Margolis,
1985; Rosato et al., 2000).

The injection moulding process shown in Figure 2-9 (Tool Craft Plastic, 2011) involves
the heating of the plastic material and then injecting by a plunger or screw, under pressure
into a cold metal mould tool. The mould tool has two parts which are combined to form a
complete mould tool. The gap in between the two parts when they are put together as an
assembly determines the thickness of the shell (moulded part tool). Pressure of the plastic
material in the mould is maintained unless the molten plastic gets cool and hardened or
cured into the required shape, then the mould is opened and the manufactured part is
removed for quality inspection (Bolton, 1998; Margolis, 1985; Tool Craft Plastic, 2011;
Rosato et al., 2000; Shuaeib et al., 2002b).

![Figure 2-9 Injection moulding process](Image)

High production rates can be achieved from this process with minimum scrap losses. The
disadvantage of this process is the high initial investment cost for the equipment.
Nowadays the cost of the thermoplastic shell is cheaper as compared to composite helmets
due to the use of machinery and less labour and other finishing costs (Cops Plus, 2011;
Shuaeib et al., 2002b).

### 2.7.1.2 Composite shells and manufacturing method

Helmet shells produced from composite materials have better impact protection as
compared to thermoplastic helmet shells (Gilchrist and Mills, 1994; Roedel and Chen,
2007; Shuaeib et al., 2002b). The main cost of the helmet is due to its raw material of the
helmet shell. Usually thermoplastic helmets are cheaper than composite reinforced helmets. The main reason behind this is the cost of material and low labour high production rates of thermoplastic helmets.

Composite helmets are usually made by a hand lay-up method, and consequently have a lower production rate with more labour as compared to the thermoplastic helmets. Normally Aramid and glass fibre reinforcement are used due to its good impact protection and economical properties (Shuaeib et al., 2002b) and are commonly known as fibre reinforced composite shells. In composite helmets the Kevlar based helmets are more expensive than glass fibre reinforce composite (Helmet Integrated Systems, 2009; MLA, 2006). Thermoplastic shells are dominating the market due to the lower manufacturing cost.

Composite helmets have definitely had an edge over thermoplastics on the impact resistance properties due to fibre reinforcement. However, there are some de-lamination problems which are always present from the discontinuity of reinforcing laminar layers due to matrix cracking (Hull and Clyne, 1996). There are many ways to create a composite material. However, the crux of the manufacturing technique is to impregnate the low-viscosity resin onto the dry reinforcement material. The wet lay-up method is the simplest method in which the fabric is conformed onto a mould and impregnated by brushing or spraying and then curing is done at room temperature. Another name for this technique is the hand lay-up method. By this technique fabric can be moulded in any shape. Advantage associated with this technique is the ability of the fabric to conform to a shape without having wrinkles in it. Due to this reason riot helmets are commonly produced by the manual hand lay-up method (Malbon, 2008).

2.7.1.3 Multi-piece composite riot helmet shell

There is no published material available on the manufacturing of Riot helmet shells made from composite material (Roedel and Chen, 2007). The reason seems to be the secrecy and confidentiality of the police helmet manufacturing companies. However, manufacturing multi-piece composite riot helmet shells in a simple way can be described as in the next paragraph.

Composite riot police helmets have been manufactured using hand lay-up processes. These helmets are made from trimmed textile reinforcing material due to its low
deformation and low shear properties. These fabrics are used layer by layer in different shapes as reinforcement in a negative mould. Firstly, the inner surface of the mould is coated with the releasing agent. This is done to prevent the sticking of the resin onto the surface of the mould. Secondly, the fabric is impregnated by resin with brush or roller and then gently applied to the inner surface of the mould in such a way that there is no wrinkle formation on the surface. The desired thickness is achieved by curing multiple layers of fabric. After curing, the shell is removed from the mould and the shell edges are trimmed. Sometimes, fabric with different materials is used to increase the impact performance as in Figure 2-10 where Kevlar along with Glass fibres is used for the helmet shell manufacturing.

![Figure 2-10 Half side of a typical multi-piece composite riot helmet shell](image)

Currently multi-piece composite helmet shells are manufactured more or less in the same way as discussed and also it is a costly and labour intensive procedure (Scorpion Sports Europe, 2011; Roedel, 2008).

### 2.7.1.4 Single-piece composite riot helmet shell

The problem with the discontinuous composite helmet shell is uncertainty in respect of the impact resistance of the laminates since de-lamination often occurs when there is an impact. Roedel and Chen significantly identified the fabric that can be draped and moulded to form a single-piece helmet shell and also developed a technique to produce a
single-piece composite helmet shell (Roedel, 2008; Roedel and Chen, 2007). They conducted FE modelling to compare the performance between single-piece helmet shells and multi-piece helmet shells. However, no practical experiments have been done to validate the riot helmet shell design. FEA results indicate that the single-piece helmet shell is better than the multi-piece helmet shell. However, their research has innovated an idea for manufacturing single-piece helmet shells based on fabric that had been made on a conventional loom.

2.7.2 Protective padding

The protective liner (liners / foam) or (internal padding) is the second most important part of a riot helmet. The primary purpose of this padding is to absorb the energy from the shell before transmitting it towards the skull by collapsing the air-filled gaps in the constituent material (Mills, 1996; Malbon and Croft, 2004). The secondary purpose of protective padding is to give a comfortable and close fit (Malbon and Croft, 2004; Mills, 1996) for the wearer. Foam materials are of different types and can be reviewed.

In an study on cricket batting helmets (Stretch, 2000), six helmets were tested with different combination of helmet shell and placement of ethylene vinyl acetate (EVA) linings at different positions. It was found out that along with the impact absorption properties of the helmet shell, the linings also plays an important role in the pass and fail criteria of the helmet. This is also true for riot police helmets.

Different varieties of foam liners will be briefly discussed.

2.7.2.1 Expanded polystyrene foam liners

Expanded polystyrene (EPS) foams are lightweight and have good performance characteristics (Shuaeib et al., 2002b). They are rigid, inelastic with low flexibility and are manufactured by the injection moulding process. Nowadays, high density EPS are the most widely used foam liners (Anonymous, 2010).

2.7.2.2 Polypropylene, Polyethylene, and Polybutylene foams liners

Polypropylene, Polyethylene, and Polybutylene foams have very good resilient properties and are produced through the Bead Moulding process (Shuaeib et al., 2002b).
2.7.2.3 Polyurethane foam liner

Polyurethane foams have decent impact performance and are the alternatives for the EPS foams. The manufacturing of this type of foam is known as “pouring in place” injection moulding (Shuaeib et al., 2002b).

2.7.2.4 Polyvinylidene chloride foam

Polyvinylidene chloride (PVDC) foam has an excellent strength to weight ratio as compared to other helmets and also it has good multi-impact performance. It can also be produced by the bead moulding process which make it a cost effective liner (Shuaeib et al., 2002b).

The foams discussed have different properties due to the different manufacturing method and the material of the foam (Shuaeib et al., 2002b). Basically the foams are porous in nature and their main purpose is to absorb energy per unit volume and restrict the energy transmitted towards the skull (Shuaeib et al., 2002a). Currently high density Expanded Polystyrene (EPS) is used as the liner for police riot helmets (Helmet Integrated Systems, 2009).

2.7.3 Comfort Padding

Cheek pads or sizing pads are installed for the purpose of size fit and to give a feeling of comfort for the wearer (Malbon and Croft, 2004). The common materials used for comfort padding are cotton, leather or polyethylene (PE) (Helmet Integrated Systems, 2009).

Comfort padding also plays a vital role for the psychophysical characteristic for the wearer. G.A. Davis et al (Davis et al., 2001) shows that there is a psychological effect which contributes to the helmet comfort. They also conclude that the helmet weight and fit are the most important parameters for helmet design. The choice of material for the padding should be optimised in such a way that it should not produce harmful effects for instance skin allergies to the wearer (Malbon and Croft, 2004). Some helmet manufacturers are also using cool-max fabric for comfort inside the helmet.

2.7.4 Retention System

Retention systems include a chin cup and chin straps having good tensile and breaking strength for the safety and security of the helmet onto the head of the wearer (Malbon and
Croft, 2004). Nowadays Nomex® straps and polypropylene chin caps are used (Helmet Integrated Systems, 2009).

2.7.5 Visor
The visor is the front part of the helmet and is usually transparent for clear vision for the police officer. It provides protection from the wind, dust and insects to the face of the wearer (Mills, 1996). The visor should not have scratches on its surface and should transmit a high proportion of light and give clear vision to the wearer. Polycarbonate visors are common nowadays with options of anti-mist and anti-scratch coatings (Malbon and Croft, 2004; Helmet Integrated Systems, 2009; Mills, 1996).

2.7.6 Neck Guard
The neck guard is an additional protection mostly provided by the manufacturer. It is made up of high density foam (Helmet Integrated Systems, 2009). Its purpose is to provide additional protection against impact and fluids and is sometimes also has fire extinguishing properties (Malbon and Croft, 2004).

2.7.7 Additional equipment
Nowadays additional equipment such as a communication system and a light/torch are also installed in riot helmets (Helmet Integrated Systems, 2009). Riot helmets should be designed in such a way that the helmet does not reduce the level of sound reaching the wearer with respect to defined limits (Malbon and Croft, 2004). It is very important for police officers to be aware of their environmental noises and also to hear their personal communications.

2.8 Impact performance of riot helmet

2.8.1 Riot helmet test standards
During a riot, helmets are exposed to different types of impact and environmental threat. The protective properties of a riot helmet can be reviewed from the riot helmet test standards. Basic requirements with respect to Impact protection can be viewed from these riot helmets standards which are “National Institute of Justice Standard for Riot Helmets and Face Shields” (US Department of Justice, 1984), CAN/CSA-Z611-02 “Riot Helmets and Face shield Protection” (A National Standard of Canada) (Shanahan, 2003) and the
There are different types of tests in these standards which relate to helmet performance. These tests include impact attenuation testing, chemical and fire resistance testing, helmet retention testing, prismatic testing and visor impact and mist testing (Malbon and Croft, 2004).

A brief discussion of the impact sites on the helmet will be discussed.

2.8.2 Impact site definitions by PSDB Protective Headwear Standard for UK Police (2004)

The human head is divided into two planes: one is known as the mid-sagital plane and other is the mid-coronal plane, which are as shown in Figure 2-11 (Malbon and Croft, 2004). The mid-sagital plane is the one which passes on the central vertical axis and bisects the head into left and right portions whereas, the mid-coronal plane is the one which passes on the central vertical axis and bisects the head into anterior and posterior portions. Position of impacts according to PSDB/APCO (Police Scientific Development Branch / Association of Chief Police Officers) standard is described as follows (Malbon and Croft, 2004).

![Figure 2-11 Reference planes on human head as PSDB Standard](image)
Front: impact area at the front is on the mid-sagittal plane and should be within 50mm above the horizontal plane H1, as shown in Figure 2-12. This H1 plane has the reference dimensions according to the headform and is described in the BS EN 960: 1994 (The European Standard, 2006).

Crown: This is the top most area of the head at the mid-sagittal plane.

Front Left / Right: these two areas represents the front side of the helmet starting from the mid-coronal plane forwards to the H1 plane on the both left and right sides of the mid-sagital plane.

Rear Left / Right: these two areas represent the rear side of the helmet starting from the mid-coronal plane rearwards to the H1 plane on the both left and right side of the mid-sagital plane.

Figure 2-12 Coverage area of the head by the visor and the helmet

In Figure 2-12 (Malbon and Croft, 2004), minimum visor coverage according to PSDB Protective Headwear Standard is marked by V1, V2, V3, V4 and V4’ and also the minimum area for the helmet coverage is marked by H1, H2, H3 and H4.
2.8.3 Impact site definitions: NIJ Standard for Riot Helmets and Face Shields

The NIJ standard is an old standard dated 1984, but is still very popular for riot helmet testing. Impact site definitions by the NIJ Standard are described (US Department of Justice, 1984).

**Front Left / Right:** these areas are at the front side of the helmet and are parallel to the reference plane and 50 mm above the reference plane. These areas are parallel to the mid-sagittal plane and are 50 mm on the both right and left side of the mid-sagital plane.

**Side Left / Right:** these areas are parallel to the reference plane and 50 mm above the reference plane. These areas are parallel to the mid-coronal plane and extend 50 mm on both the right and left side of the mid-coronal plane.

**Back Left / Right:** these areas are at the rear side of the helmet and are parallel to the reference plane and 50 mm above the reference plane. These areas are parallel to the mid-sagittal plane and extended 50 mm to both the right and left side of the mid-sagital plane.

**Top:** this area is at the crown position of the helmet and is situated at the intersection of the mid-sagital and mid-coronal plane within 50 mm of the intersection.

2.8.4 Impact site definitions as per Canadian CAN/CSA-Z611-02 Riot Helmets and Face-shield Protection (2003)

CAN/CSA-Z611-02 is also one more standard for Riot Helmets and Face-shield Protection (Shanahan, 2003). This standard is very close in characteristics and in comparison with the NIJ standard. According to this standard, impact sites on the head protector are anywhere on the helmet shell (which termed a Head Protector) above the test line ABCD as shown in Figure 2-13 (Shanahan, 2003). The impact test should be separated at a distance of at least 100 mm apart.
It must be noted that impact location near to the brain area is focused by the PSDB/APCO Standard (Malbon and Croft, 2004) and the NIJ Standard (US Department of Justice, 1984) whereas, CAN/CSA-Z611-02 (Shanahan, 2003) offers the opportunity to do testing at any point on the helmet shell.

2.9 Previous research on composite helmet shells

(Dionne et al., 2003) explored the overall impact performance of riot helmets by testing six helmets from different manufacturers at the lateral, front side and on the visor. By using a drop test, they measured the energy producing head acceleration of 300g (they range in between 69J to 171J). They compared energy values with the energy values obtained from the experimental study of throwing different objects from 10 metres by healthy male persons. The results shows that the impacts generated from the drop tower are more severe than real life threats. Further, they concluded that the shape and type of impactor also affects a lot on the helmet impact testing.

Mahajan and Pinnoji (Mahajan, 2010) compared the delamination of composite shells with shells made from Acrylonitrile Butadiene Styrene (ABS). They used finite element analysis (FEA) in ABAQUS for their numerical study. They concluded that energy absorbed by helmets made from composite shells during damage and delamination is less as compared to the energy absorbed by plastic deformation of ABS helmet shells. Ideally,
helmets should absorb and distribute impact energy to a wider area of the helmet shell and internal paddings.

![Figure 2-14 A typical motorcycle helmet](image)

(Kostopoulos et al., 2002) also developed a helmet-headform system in LS-DYNA3D, simulation software. They studied different types of motorcycle helmet shells made from different composite materials. According to them Kevlar based helmet shells absorb more energy as compared to other composite helmets made from glass and carbon fibres due to their lower shear strength and stiffness. At higher energy impacts, composite shells show substantial protection due to their complex damage mechanism before final breakage. This is one of the reasons composite helmets are gaining popularity over thermoplastic helmet shells (Anonymous, 2010).

(Kormi and Etheridge, 1992) conduct an impact finite element analysis (FEA) in ABAQUS on multi-layered glass-reinforced plastic (GRP) composite helmet shells. According to them, composite shells made from multilayer can attenuate the transfer of impact energy efficiently and hence the damage intensity to the skull is minimised.

(Tan and Lee, 2007) conduct experiments and also FE analysis in order to study high velocity impact testing. According to them FE simulation is a cheaper way of conducting experiments as shown in Figure 2-15 (Tan and Lee, 2007). Ballistic helmets are of completely different design and the impact requirement is also different. They are made up of several layers of composite material for better impact protection against high velocity impact and due to this the stiffness of the ballistic helmet is far greater than the riot helmet.
The properties of motorcycle helmet shells can be studied for use in riot helmet shells. Mills categorised the purpose of motor cycle helmet shells into roles. Some of the details that can be used for riot helmets are listed below (Mills, 1996).

1. Absorbing energy: this is the primary focus of the helmet shell. Energy absorption depends on the impact site, material, and thickness of the shell and the shape of the impacting object.

2. Distribution of local forces from an impact: helmet shells contribute a lot to the distribution and transmission of an impact to the protective padding. Without the shell there will be maximum damage to the protective padding and to the skull.

3. Supporting equipment: assemblies such as the visor and chin straps are also attached of the helmet shell. If there is no helmet shell then chin straps must be threaded into foam protective padding and it can never withstand the strong forces during the impact. The same is the case for the visor.

The impact energy absorbed by the shell depends on the impact site, the shape of the impactor and mainly the material and stiffness of the shell (Shuaeib et al., 2002a; Mills, 1996). The properties of the helmet shell material are important factors for the impact performance of riot helmets.

In addition to material selection, the shape of the shell also has an importance for the impact analysis. The head is not a completely flat surface neither it is round. The human head is a somewhat spherical surface. The shape of the helmet shell is one of the important criteria while designing a shell.

Figure 2-15 FEA on military helmet

![Figure 2-15 FEA on military helmet](image)
The material of helmet shell should be selected based on the concept of energy absorption. During an impact the helmet shell should dissipate impact energy to a wider area throughout the shell surface. This can be done in single-piece composite shell more efficiently than for a multi-piece riot helmet (Roedel and Chen, 2007). Distribution of impact energy to a wider area corresponds to the wider energy distribution towards the internal protective padding and therefore less energy will be transmitted to the skull. Protective padding should be selected in such a way that it should collapse completely before transmitting energy to the skull. High-density foams are being used in the industry.

The light mass of a riot helmet is one of the characteristics by which the effectiveness and efficiency of a police officer can be improved. This means that the low mass helmet can be worn for long periods. There are major disadvantages of using heavy helmets (Brady, 2003). Firstly the wearer has early neck fatigues specially if additional monitoring equipment is attached on the helmet and secondly a heavy helmet causes hindrance in quick movement of the head. The total weight of a helmet along with its visor and neck guard must not exceed 1.75 kg (Malbon and Croft, 2004). Riot police officers have to wear helmets for long periods therefore helmet mass should be optimised in material selection.

Exposure to burning and chemical attack is one of the threats to riot police officers. Therefore, the use of self-extinguishing materials and chemical resistance are also required. The riot helmet shell has a smooth continuous external surface with a fully closed visor which form a complete liquid tight seal along the top edge of the visor to the shell of the helmet (Malbon and Croft, 2004). The protection may also include protection from exposure to UV light, solvents, caustic and corrosive chemicals and temperature variations. Chemicals used in this regard should be eco-friendly.

2.10 Methodology

This chapter also summarises the general approach to and construction of the study. The current chapter is also designed to provide sufficient information to the reader on how the overall objectives of the research will be achieved.

Research aims and objectives have been described in Section 1.3. Moreover, a literature review has been conducted in order to understand and planned the project in order to
achieve the targeted objectives. The research methodology has been planned and explained in steps.

2.10.1 Production of fabric

In order to develop riot helmet shells there was a need of fabric. It is stated in Section 1.2 that angle-interlock fabric due to its mouldable properties has been optimised by Roedel and Chen (Roedel, 2008). It was planned to use the same construction of 5-8-28 angle-interlock Kevlar fabric for making riot helmet shell. Kevlar is an organic fibre which has high strength, high modulus, toughness and thermal stability (Hearle, 2001). It was developed by DuPont in 1971 by para-orientation of the benzene ring (Dupont, 2011; Hearle, 2001). Kevlar has 30% more impact protection and is less dense than steel (Langston, 1980). Composites developed from Kevlar fibre exhibits better resistance to impact than glass and carbon fibres (Yang, 1993). In current research, due to the non-availability of fabric for helmet shell manufacturing, the production of 5-8-28 angle-interlock fabric was necessary. The fabric was produced in the University of Manchester’s weaving laboratory and discussed in detail in Section 3.3.

2.10.2 Manufacturing of flat composite panels

In the literature review, the vacuum bagging method seems beneficial over the hand lay-up method for making composite panels. Moreover, vacuum bagging was reviewed due to its common usage in industry, easy handling and availability of a composite manufacturing setup in the University of Manchester. In order to find the different physical and mechanical properties of 5-8-28 Kevlar composite structure, it was necessary to develop flat composite panels. Flat composite panels were manufactured and tested for property evaluation and are discussed in section 3.4. For testing composite panels, literature review has been conducted in Section 2.4 and is calculated in Section 3.5.

2.10.3 Creation of single-piece helmet shell

Discontinuity in the multi-piece composite helmet shell is one of the major concerns as confirmed by researchers (Roedel and Chen, 2007) that continuous helmet shells have better impact protection as compared to multi-piece helmet shells. The single-piece helmet shells produced by Roedel and Chen (2007) were developed by a hand lay-up method. Composites manufactured by vacuum bagging have many advantages over the hand lay-up method (McCrary, 2011) which include better layup uniformity, a stronger finished
product and better strength-to-weight ratio. A new method for creating a single-piece riot helmet shell should be designed through industrial processing due to the advantages over hand lay-up techniques. It was planned that a process such as vacuum bagging technique could be used in creating a single-piece riot helmet shells. The development of an innovative procedure for creating a single-piece riot helmet shells using the vacuum bagging technique will be a new era in the creation of single-piece textile reinforced riot helmet shells. A successful method of developing a single-piece riot helmet shell using vacuum bagging has been established and explained in Section 4.6.

2.10.4 Development of a test rig
Impact testing was one of the objectives of this research as discussed in Section 1.3. Furthermore in the literature review, no records on the physical testing of the single-piece riot helmet shell have been reported. In order to full this gap, it was anticipated that physical impact testing will be used for better understanding of impact behaviour of single-piece riot helmet shells. Moreover, in the literature review the location of impact on the helmet shell based on different available standards has been discussed. In the literature review, the drop weight impact testing method found to be significant instrument for the impact testing. It was planned that the University of Manchester’s drop weight impact testing instrument would be modified in order to do impact testing on developed single-piece riot helmet shells. In doing so, a helmet test rig has been manufactured and discussed in detail in Section 5.3.

2.10.5 Creation and simulation of finite element models
The literature review suggests that finite element analysis is a vital tool for the virtual experimentation, since a validated FE model from experimental results will give a deeper understanding. Therefore, it was planned that in addition to the experimental analysis, a finite element (FE) method will be used to model helmet shells and to study the influence of the geometrical parameters on the performance of the helmet shells in FE software ABAQUS. Furthermore, the models will be validated by the experimental results. ABAQUS was suggested for creating a simulation due to its windows interface and also due to availability in University of Manchester. So, designing and simulation of dynamic impact analysis has also been planned. Impact properties at different impact locations on the helmets shells will be investigated physically through the helmet testing instrument and virtually by means of ABAQUS software. Creation of models and their simulations has been discussed in detail in Section 7.4.
2.11 Summary

In this chapter, relevant literature has been reviewed based on the overall needs for this research and in order to grasp the overall understanding of the riot helmet shell performance. These review areas include, an introduction and classification of composites, brief manufacturing of composites from vacuum bagging, composite testing standards, low-velocity impact on composites, modes of failure in composites and drop weight testing instruments. Moreover, the history of helmets, construction, types, manufacturing methods and impact testing standards for riot police helmet were also discussed.

Detailed planning for achieving the aim and objectives of this project has also been discussed. The main purpose was to provide an overall understanding of the project.
3.1 Introduction

Composite structures are made up of two phases of materials, the matrix phase (resin) and the reinforcement phase (fabric). Composite panels manufactured in this study in order to gather physical and mechanical properties of composite structures have 5 layers of through-the-thickness angle-interlock Kevlar woven fabric. In the current study, angle-interlock fabric has been used as the reinforcement, whereas thermoset epoxy resin was used as the matrix. In this chapter manufacturing of angle-interlock fabric and creation of flat panel composites for physical and mechanical testing has been discussed. Furthermore, physical and mechanical testing results were also calculated and discussed. These studies act as building blocks for the riot helmet shell manufacturing.

3.2 Definition and significance of AI-fabric for helmet shell manufacturing

Angle-interlock (AI) fabrics are one of the ways of making 3-dimensional (3D) fabrics. In an angle-interlock fabric, the weft yarns remain straight and the warp yarns travel diagonally through-the-thickness direction of the fabric (Chen and Potiyaraj, 1999).

There are two categories of angle-interlock fabrics. One is ‘through-the-thickness’ angle-interlock fabric and other is ‘layer-to-layer’ angle-interlock fabric as shown in Figure 3-1 (TexEng, 2005).

Many studies have been established for analysing angle-interlock structures. Some of them are highlighted.
Increasing the number of layers in angle-interlock fabric, had little influence on the shear rigidity and the structure became more difficult to bend specially in the weft direction (Chen et al., 1999). The tensile strength of the angle-interlock fabric in the weft yarn direction increases by the increase in the number of layers. In angle-interlock fabric there is more elongation in the warp yarn direction as compared to the weft direction. Chen et al also established angle-interlock structures (Chen, 2008; Chen and Potiyaraj, 1999).

Chen et al worked on 2-layer, 3-layer stitched fabrics and 3-layer interlock fabric and their effects on shearing properties. Angle-interlock fabrics have low shearing properties (Chen et al., 1992). Due to this property angle-interlock structures seem easy to drape without wrinkles.

Gu et al found strong effects on the tensile strength and dimensional stability of the composite due to weave structures. They worked on through-the-thickness fabrics and found that straight yarn arrangements in the fabric have a positive influence on the strength and stiffness of composites (Huang and Zhong, 2002).

Mouldability is dependent on fabric density and the number of layers (Chen et al., 2002). Chen et al used a mouldability tester for calculating the fabric mouldability index. Moreover, their research concluded that by increasing the number of weft layers of angle-interlock fabric becomes more mouldable.

Properties discussed above recommend angle-interlock structures for applications where impact protection is required. Low-shear rigidity is highly advantageous for mouldability of angle-interlock fabric into a desired shape. High stiffness seems also to offer benefits for low-velocity impacts. Furthermore, long floats of warp yarn because of through-the-thickness features in the angle-interlock structure seem to be an optimised way to minimise the delamination problem in composite laminates. These properties seem to be very helpful for the riot helmet shell.

Roedel and Chen used a particular construction of 5-8-28 to manufacture riot helmet shells (Roedel, 2008; Roedel and Chen, 2007). They investigated 21 through-the-thickness AI weaves and optimised the structure for the best weave design for moulding continuous textile reinforced riot helmets. As earlier studies suggested, angle interlock structure is a suitable construction for draping fabric for riot helmet shell manufacturing, the current
study will focus on ‘through-the-thickness’ angle-interlock fabric with a specification of 5-8-28, i.e. with 5 layers of straight warp yarn, 8 ends per cm per and 28 weft yarns per cm.

In the current research the draft and lifting plans are made using ‘Weave Engineer’, a University of Manchester developed software.

3.3 Manufacturing of “through-the-thickness” angle-interlock fabric

In order to develop riot helmet shells there was a need for angle-interlock fabrics. This section will represent the manufacturing process at different manufacturing stages of 5-8-28 angle-interlock woven fabric for this study.

Kevlar roving type 49 supplied by DuPont has been used. The count of the yarn used in this study was 158 Tex. The same yarn and count were used for both warp and weft for the angle-interlock fabric. The properties of Kevlar are shown in Table 3-1 (Kevlar, 2011).

<table>
<thead>
<tr>
<th>Property</th>
<th>Kevlar 29</th>
<th>Kevlar 49</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (g/cm³)</td>
<td>1.44</td>
<td>1.44</td>
</tr>
<tr>
<td>Tensile Modulus (GPa)</td>
<td>70.50</td>
<td>112.40</td>
</tr>
<tr>
<td>Ultimate Tensile Strength (MPa)</td>
<td>2920</td>
<td>3000</td>
</tr>
</tbody>
</table>

Winding of yarn from cones to warp is known as warping (Lord and Mohamed, 1988). A single thread warping machine MS-1800/8 made by Hergeth Hollingsworth GmbH, model 1988 was used. This machine is designed for small patterns of sample length approximately 8 metres. The machine has two drums, one at the top and one at the bottom, which are approximately 4 metres apart and can produce a warp length of 8 metres per revolution. However, the maximum working width of the machine is 1.8 metres. A single roving/cone was wound around the drums until the required number of ends was reached. This machine also has an automatic counter for the required revolutions. The limitations with this sample warping machine are the fixed length of 8 metres and the manual transfer of yarns. In order to reduce the static charges which can cause filamentation during the unwinding process, a humidifier was used. A beam of total 750 ends was produced having a width of 90 cm (the required width for weaving). Weft yarn pirns were prepared on a MSK pirn-winder made by Schweiter Ltd. This winder is specially designed for winding
of continuous synthetic filament yarns. These pirns were later used in shuttles for weft insertion.

The University of Manchester software ‘Weave Engineer’ was used for making lifting patterns of the 5-layer angle inter-lock fabric. The lifting pattern was later punched on the plastic card / sheet by a pattern punching machine as shown in Figure 3-2.

![Figure 3-2 Lifting plan for 5-layer through-the-thickness AI-fabric](image)

The interlacing of warp yarns and weft yarns is known as weaving (Lord and Mohamed, 1988). For weaving AI 5-8-28 fabric, dobby shuttle loom ‘Arbon 100W’ manufactured by Adolphe Saurer has been used. This loom has a maximum working width of 1.2 metres. The maximum machine speed is 260 picks per minute with a single shuttle picking mechanism and it also has a negative let-off mechanism. The straight drawing-in draft was used for easy handling of yarns in the heald frames. For weaving of AI 5-8-28 fabric 6 heald frames having 130 healed wires each were used. A regular reed plan of one end per dent was adopted in a reed a having reed density of 8 dents per centimetre. The fabric width required was 90 cm. Pick adjustments were carried out by means of a regulator. This regulator was connected to a picking lever by a gearing mechanism. The final produced AI 5-8-28 fabric can be seen in Figure 3-3.
3.3.1 Optimisation in producing fabrics

A problem of filamentation occurs during Kevlar fabric making at the warping stage and at the weaving stage. Due to this difficulty the stoppage time also increases and there were problems of making defect-free fabric on the loom. The filamentation was initiated in the warping and then it deteriorated in weaving due to friction in the reed and heddle wires. The problem of filamentation also increased due to static charges within the warp sheet. In order to rectify the problems of filamentation, the following techniques were adopted.

Warping was the first step towards weaving, so efforts were made to minimise the problems of filamentation such as pills and fibre entanglement on the warping machine. It was noticed that as soon as the machine started, the problems of filamentation started. Efforts were made and it was noticed that the yarn hook due to its shape caused friction in the yarn. The steel hook, as in Figure 3-4 (a) seems to be one of the reasons for filamentation creating static charges to the Kevlar 49 yarn in each step. These static charges were causing entanglements in-between the two adjacent yarns. In order to reduce the element of friction between steel and the Kevlar yarn, the yarn steel hook was replaced with the modified circular ceramic eye yarn hook as shown in Figure 3-4 (b). Ceramic yarn guides are used in several textile applications (Ascotex, 2011).
By replacing the hook, it was noticed that static charges in the warped sheet significantly reduced. Furthermore, extra care was taken while handling the yarns during warping. Moreover, paper sheets were rolled with the warp sheet, during making warp beam for weaving shown in Figure 3-5. It was carried out to reduce the stickiness of the warp sheets.

The weaving machine is where the filamentation deteriorates yarn due to high friction between the yarns and the reed. Precautionary measurements were carried out. Firstly, it was ensured that only one type of heald wires were used in the all heald frames. Secondly, care was taken while drawing-in.
Kevlar is a light-sensitive fibre therefore when there was no work on the machine, the yarns have to be covered. In order to minimise filamentation, the weaving machine was covered in such a way that the cover should not touch any of the yarn.

The combination of all the above actions helped to minimise the filamentation in warping and weaving with minimum rejection of faulted fabric.

### 3.4 Manufacturing of Flat panel composites

#### 3.4.1 Need for development

Developments of flat 5-8-28 angle-interlock Kevlar composite structures were required due to two reasons. Firstly, it is difficult to evaluate the mechanical properties like Young’s modulus, tensile and shear strength in the helmet shape structure rather than in flat composite panels. Secondly, properties were required for the finite element analysis. Furthermore, complete understanding of vacuum bagging is necessary for the development of riot helmet shells from this method. Vacuum bagging had been chosen in this study for its better wet-out and resin flow. Easy availability, handling of the equipment and common usage of this method in the industry were the motivation for using this method.

#### 3.4.2 Resin information

Huntsman epoxy resin Araldite® LY 5052 was chosen as the matrix in this study due to easy availability and common usage in the industry. Araldite® LY 5052 has to be mixed with a hardener Aradur® 5052 in the ratio of 100:38 by weight or 100:47 by volume (Huntsman, 2010). In order to obtain optimal properties of the matrix, weighing and mixing should be precisely performed. Moreover, according to the manufacturer (Huntsman, 2010), curing was carried out in two stages: the laminates were initially cured at room temperature for 24 hours and then these laminates were taken off the mould or vacuum bags and were further cured at 100°C for 4 hours. The second stage can also be performed at 50°C for 15 hours.

Significant properties of Araldite® LY 5052 / Aradur® 5052 system which are helpful for the riot helmet shell are discussed (Huntsman, 2010).
Araldite® LY 5052 / Aradur® 5052 matrix has low viscosity due to which it can be easily applied to the reinforcing material. This will make it easy to penetrate the Al-fabric. This matrix has a long pot-life (2hrs for 100ml); this means it has sufficient processing time which allows production of big objects like a riot helmet shell. This property helped in the slow impregnation of the fabric in riot helmet shell manufacturing. This matrix has good mechanical and dynamic properties in matrix form and also laminates produced by this system shows outstanding mechanical and dynamic properties. Moreover, it is a transparent liquid so there is no colouring affect on the produced helmets. This matrix has high temperature resistance make it a good choice for a riot helmet shell.

3.4.3 Precautionary measure

Working with composites always needs precautionary measures due to the curing of resin after activation and hazardous fumes released during mixing. For this reasons, a fume cupboard, safety goggles, protective gloves and a filter mask were used for personal protection in the preparation of the composite.

3.4.4 Experimental method in the laboratory

Vacuum bagging has been discussed in Section 2.3.2. However, the following procedure was executed in the laboratory in order to manufacture flat composite panels:

(1) A 5-6 mm thick square steel plate known as a tool was placed on a vacuum table (a flat surface). This tool was the foundation of the whole setup. A plastic release film was placed on the tool and the film was fixed from all the four edges by means of Sellotape (plastic adhesive tape), in order to prevent the tool damage from the resin. A double sided adhesive tape known as tacky tape was placed in such a way that a half portion of the bottom side of the tape was on the Sellotape and the other half was on the tool. Tacky tape was used to form an air tight seal.

(2) Angle-interlock fabric in the desired quantity was placed on the release film. Nylon pieces known as peel ply were used to cover the entire surface of the Al-fabric. Peel ply can be peeled-off the sample when the resin is cured.

(3) A perforated release film was placed on the peel ply in order to obtain a uniform distribution of resin onto the Al-fabric. To distribute resin evenly throughout the area of perforated release film, an infusion mesh was used. The infusion mesh was placed only to cover the areas where the movement of resin was required on the
tool. This mesh was most important as the resin initially flows in this mesh before being directed to the AI-fabric.

(4) An infusion tube was then placed on the resin infusion mesh on one side of the tool to ensure a constant supply of resin. This tube consists of two portions interconnected in the bag. One portion was placed inside the bag onto the infusion mesh for uniform distribution of resin throughout the length of the bag. The other side of the tube was connected to the spiral tube (in the bag) and the other side sealed airtight by an H-clip outside the bag. This infusion tube was the inlet for the resin flow.

(5) A bleeder cloth, normally a polyester nonwoven fabric was placed at the boundaries of the infusion mesh on all four sides. This was done in order to absorb the excess resin in the bag. This may work similarly to a breather whose purpose was to provide a gas flow path over the laminates and ensure uniform vacuum pressure across the tool.

(6) Usually at the opposite side of the inlet tube zone an outlet zone had been created by putting a vacuum valve sealed in a release film to draw air out of the bag by means of vacuum pump. The vacuum pump and vacuum valves were connected through vacuum pipes.

(7) Finally, the bagging film commonly known as the vacuum bag was placed at the tool and formed a precisely airtight seal by means of the tacky tape top surface which was already placed on the edges of the tool. This procedure was repeated for all the sides of the tool.

(8) The vacuum was then applied in order to check air leakage. Araldite® LY 5052 was mixed with a hardener Aradur® 5052 in the ratio of 100:38 by weight (Huntsman, 2010) in a cup. By the application of a vacuum, the mixture of resin and hardener was infused in the bag and the AI-fabric was impregnated.

(9) The vacuum bag was kept under vacuum for approximately 14-16 hours. Samples were further cured in a drying oven for 4 hours at 100°C as per recommendations (Huntsman, 2010).

The vacuum bagging process is illustrated in Figure 3-6 and Figure 3-7.
A flat panel produced using the vacuum bagging method is shown in Figure 3-8. Physical and mechanical properties were evaluated to understand the performance of the AI-fabric reinforced composite for a helmet and to provide data for the finite element analysis, which will be described and discussed in Section 7.2.
3.5 Properties of 5-8-28 Kevlar flat composite panels

In this section, the physical and mechanical properties of the 5-8-28 Kevlar flat composite panels produced are calculated. Relevant literature has been discussed in Section 2.4. These properties were necessary for understanding the behaviour of a 5-8-28 Kevlar composite panel and were also required for the finite element simulation.

3.5.1 Tensile properties

Tensile testing was carried out in order to calculate the modulus of elasticity. British standard BS EN ISO 527-4:1997 (British Standard, 1997) was used to find out the tensile properties in the warp and in the weft directions of the 5-8-28 Kevlar/Epoxy composite panels. Specimens were cut by diamond blade cutter to the required size. An MTS Alliance RT/100 machine was used for the testing. The jaws of the MTS RT/100 were unable to tightly grip the composite panels directly, so an alternative tabbing arrangement was carried out according to standard BS EN ISO 527-4:1997 (British Standard, 1997). The reason for using tabs was to prevent the failure at the jaws. Metallic pieces were attached with the help of resin and hardener (the same as used for making composite panels). The samples were cut in the warp direction and also in the weft direction. Five samples from each of the two categories i.e. warp and weft, having length of 250 mm each was prepared as discussed in Section 2.4.1, according to BS EN ISO 527-4:1997 (British Standard, 1997).
The MTS RT/100 testing machine was used to do the tensile test. The extensometer used has a gauge length of 50 mm and a 50 KN load was applied at a constant crosshead speed of 2mm/minute. The Young’s modulus, the tensile stress and the tensile strain at breaking point were calculated. Average results of the tensile properties in the warp and weft directions of the Kevlar composite structure are shown in Table 3-2. Detailed results of the specimens cut along the warp and weft directions are shown in Appendix A (Table A-1 and Table A-2). Stress-strain curves of composite specimens in the warp and weft directions are shown in Figure 3-10 and in Figure 3-11, respectively.

**Table 3-2 Tensile properties of 5-8-28 flat Kevlar**

<table>
<thead>
<tr>
<th>Specimen Category</th>
<th>Tensile stress at break (MPa)</th>
<th>Tensile strain at break (%)</th>
<th>Young’s modulus (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Warp direction</td>
<td>131.60</td>
<td>2.73</td>
<td>7793.70</td>
</tr>
<tr>
<td>Weft direction</td>
<td>538.06</td>
<td>1.79</td>
<td>36938.30</td>
</tr>
</tbody>
</table>
In 5-8-28 angle-interlock Kevlar composite panels, larger numbers of wefts were dominating in the results. In Table 3-2, the percent strain at break was 1.52 times more in the warp direction composite samples as compared to the weft direction composite samples due to de-crimping of the warp in the composite samples. Crimps in the warp direction are the inherent property of through-the-thickness angle-interlock fabric. In Table 3-2, stresses at break in the weft directional samples are 4.1 times higher in the weft direction samples than in the warp direction composite samples. This was due to the toughness of the weft yarns in angle-interlock fabric. Greater load was required to break the composite specimens in the weft direction samples.
The Young’s moduli in the warp and in the weft direction of the Kevlar composite were approximately 7793.70 megapascals and 36938.30 megapascals respectively. It can be observed that the modulus of elasticity in the weft direction was 4.7 times more as compared to the warp direction composite specimens. This was due to the greater population of weft yarns as compared to warp yarns in the weft direction cutting of the specimen. These properties can be used very effectively in procedures where multiple layers of 5-8-28 AI-fabric properties were required. The combined effect on the composite made from multiple orientated layered 5-8-28 AI-fabrics will enhance the tensile properties.

3.5.2 Results of In-plane Shear Modulus

For in-plane shear modulus testing, square specimens with dimensions 45 mm × 45 mm were cut from a composite sheet having a thickness of 1mm. The samples were deflected up to 0.5 times the thickness as suggested by the standard test method BS EN ISO 15310:2005 (British Standard, 2005).

![Figure 3-12 In-plane shear testing using Instron 4411](image_url)

In-plane shear testing on a laboratory scale can be shown in Figure 3-12. The in-plane shear modulus calculated as per the plate-twist method BS EN ISO 15310:2005 (British Standard, 2005) found to be 1379.26 MPa. Detailed results are shown in Appendix A (Table A-3).
**3.5.3 Result of 5-8-28 flat panel density – Immersion technique**

Density was calculated based on the standard BS EN ISO 1183-1:2004 (British Standard, 2004). Apparatus used in the density measurement included a physical balance which can do weight measurement in air and as well as in water, beaker and corrosion resistant wire, and a physical balance.

Specimens of 5-8-28 Kevlar flat panel composite having dimensions of 2 cm by 2 cm were cut precisely from larger samples with the help of ceramic scissors. These samples were cut from different places on the flat composite panels. Cutting was carefully carried out since damage in the specimen can have a direct effect on density.

A corrosion resistant wire having less than 0.5 mm diameter was suspended in air and its mass was determined. The wire was then immersed in a beaker with water and weighed. Both the readings i.e. the mass of wire in air and in water were measured. Water was used as an immersion liquid and the average density was taken as 0.99823 g/cm$^3$. The mass of the specimen in air was calculated by subtracting the mass of the wire in air from the measured reading of the mass of the wire with the specimen in air. Specimens were later hung in water by suspending them with the same wire in the beaker filled with water. The mass of the specimen in water was calculated by subtracting the mass of the wire in water from the measured reading of the mass of the wire with the specimen in water. Care was taken that the specimen should not touch the walls of the beaker and there should be no air bubbles in the water. Appendix A (Table A-4) illustrates the density of composite specimens. The average density $\rho_S$ of the flat 5-8-28 Kevlar composite structure was calculated as per Equation (2.5) was found to be 1.229 g/cm$^3$.

**3.5.4 Constituents of Kevlar composite specimens**

In composite manufacturing, fibres are used as reinforcement to increase the mechanical properties of the composite. It is desirable to have high fibre volume fractions. In order to calculate the constituents of the composite, it is necessary to separate the reinforcement and the matrix. The standard BS ISO 14127:2008 (British Standard, 2008) is for carbon fibres but due to the non-availability of standards on Aramid fibre, BS ISO 14127:2008 was used to calculate the fibre and resin weight fractions.

The desiccated dry mass of the specimen was determined before and after the resin digestion. The composite specimens were soaked in a hot bath in the microwave oven to
digest the resin. Nitric acid digestion is applicable to almost all epoxy resins. Crucibles, filter paper, desiccators and nitric acid were used in this experiment. First the samples were dried in the oven at 100°C and then they were held in desiccators for half an hour. The specimens were weighed and put in the plastic vessels along with concentrated Nitric Acid (60%). These plastic vessels were held in jackets also sealed with valves. After this the whole setup was then heated in the microwave oven to digest the resin in the Nitric acid. After resin digestion the specimen were washed with water and then dried in the oven, desiccated and weighed. Different steps of the procedure can be viewed in Figure 3-13.

![Figure 3-13](image-url)  
Figure 3-13 Equipment used in Acid Digestion (a) Oven (b) Desiccator with crucibles having samples (c) Vessels and their jackets (d) Microwave Oven (e) Washing apparatus of crucibles (f) weighing balance

<table>
<thead>
<tr>
<th>Table 3-3 Fibre and resin contents</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fibre Content (mass %)</td>
</tr>
<tr>
<td>------------------------</td>
</tr>
<tr>
<td>w_f (%)</td>
</tr>
<tr>
<td>75.292</td>
</tr>
</tbody>
</table>

The results obtained using Equation (2.6), Equation (2.7), Equation (2.8) and Equation (2.9) are summarised in Table 3-3. The detailed results are tabulated in Appendix A.
Results show a high volume of fibre content which seems to be due to the 3-dimensional weave. Composites made from angle-interlock fabric usually have a high fibre volume fraction as reported by several research groups (Yang and Liu, 2011; Sheng and Hoa, 2003).

3.6 Summary

In this chapter, three objectives of the research have been successfully achieved.

Firstly, 5-8-28 angle-interlock fabric has been manufactured and discussed in detail. The necessary arrangements to eliminate the filamentation problem in the fabric manufacturing process have been described.

Secondly, fabrication of 5-8-28 angle-interlock Kevlar composite panels has been discussed in detail. Successful fabrication helps to understand the vacuum bagging procedure so that this procedure can be modified and adopted for riot helmet shell manufacturing. Moreover, the composite panels were manufactured for the physical and mechanical testing which were necessary for the finite element simulation.

In the third part of the chapter, the physical and mechanical properties of 5-8-28 Al Kevlar composite panels have been calculated using standard testing procedures and will be used in developing a finite element simulation close to reality.
CHAPTER 4 INNOVATIVE FABRICATION OF RIOT HELMET SHELL

4.1 Introduction
To make a 3-Dimensional (3D) shape using vacuum bagging is difficult and different in procedure. Based on the understandings developed in Chapter 3 for making composite panels, a few basic guidelines have to be developed, before finalising a procedure for manufacturing single-piece helmet shells using vacuum bagging.

Firstly, a 3D solid mould was required: resin flows where it has the least resistant. In the case of a hollow mould the resin might accumulate inside the mould and can damage the mould. Furthermore, the outer dimensions of the mould should be the same as that of the required 3D composite structure. Moreover, the mould should be effortlessly removed after composite manufacturing.

Secondly, a draping technique was required: in the case of flat composite panels the fabric can be placed directly on the flat mould and the vacuum sticks the fabric on the mould without any shearing of the fabric. However, for a 3D composite structure, the fabric has to be draped on the mould according to the shape required. Moreover, the placement of fabric on the mould should be carried out in such a way that after vacuum bagging, the mould can be removed from the 3D composite structure.

Thirdly, complete fabric impregnation was necessary: the placement of a resin inlet valve is one of the constraints. In case of flat composite panels, the inlet valve is normally placed in one side of the fabric and the resin impregnating the fabric travels to the other side of the fabric where usually a vacuum valve is placed. The main purpose was to place the inlet valve in such a position that the fabric should be impregnated completely on a 3D mould.

4.2 Manufacturing of three dimensional dome-shape composite structure
The procedure discussed in Section 3.4 was repeated. Precautionary measures have been taken based on the considerations as discussed above. For a trial, a 3D dome-shaped structure has been manufactured and is discussed in several steps.
• Three dimensional mould: the riot helmet shell is a doubly curved structure. For a trail, it was decided to make a single curvature dome-shaped structure. A wooden solid-shaped semicircle was selected as a mould due to easy availability as shown in Figure 4-1(a).

• Draping and covering of preform: angle-interlock fabric produced in section 3.3 having construction 5-8-28 was draped manually, by shearing the fabric on the semi-circular wooden block. Nylon peel ply, perforated release film and infusion mesh were placed on the mould. Precautions were carried out to minimise wrinkles while covering the preform. A released film was also used between the mould and the fabric. Moreover, the wooden mould was completely covered with the release film to have no contact with the resin.

• Covering with bagging film: bagging film plays a vital role in making the surface of composite structure. Unlike flat composite panels, the AI-fabric was draped on a mould having a certain height. The vacuum bag was sealed in such a way that excess loose bagging film was present to stretch and properly cover the vacuum bag setup. “Tuck-in” is commonly used to describe the technique of sealing the vacuum bag where loose bagging material is required on the mould. Tacky tape tucks can be seen in Figure 4-1(b).

• Top infusion technique: in order to develop dome-shaped 3D hollow composite structures, there were limitations of resin flowing from the base of the mould to the top of the mould due to the height constraint. To solve this constraint, infusion in the bag was carried out from the top of the wooden mould as shown in Figure 4-1b. Araldite® LY 5052 was mixed with a hardener, Aradur® 5052, in the ratio of 100:38 by weight (Huntsman, 2010) and infused from the top the mould. This method of infusion helped the proper wet-out of the angle-interlock fabric and also even resin distribution was carried out from the top of wooden mould.

• Pre-curing of dome-shape structure: the vacuum bag was kept under vacuum for approximately 14-16 hours (Huntsman, 2010). After 24 hours the samples were taken out.

• Removal of dome-shape off the mould: after curing, the vacuum bag is peeled off. Since the wooden mould was in the shape of a half sphere with similar curvature at
every location on the surface, so the mould was simply removed by pulling back from the developed dome-shaped composite structure.

- Post-curing of dome-shape structure: samples were further cured in a drying oven for 4 hours at 100°C (Huntsman, 2010). Cured dome-shape structures can be viewed in Figure 4-19(c) and Figure 4-1(d).

![Image](image.png)

**Figure 4-1** Vacuum bagging of a three dimensional structure (a) wooden mould (b) vacuum bagging setup (c) composite dome-shape composite top view (d) inside view

### 4.2.1 Importance of dome-shape structure

The dome-shape structure has a certain height and the results from the top infusion technique showed promising properties in respect of the development of a riot helmet shell that has no dry areas on the dome shape. Angle-interlock fabric shows mouldable properties under vacuum. Apart from the few wrinkles that appeared at the bottom edge of the dome due to improper edge formation, there were no wrinkles found at the dome top surface due to this, the idea of making an innovative technique for helmet shells from vacuum bagging was further reinforced. In the view of the fabric mouldability, the infusion of resin and the vacuum bagging technique showed significant signs that riot
helmet shells can be created by using vacuum bagging. Due to the vacuum bagging benefits over the hand lay-up method, a helmet shell developed using vacuum bagging should be of better quality and should have benefits over a helmet shell developed using a hand lay-up method.

4.3 Creation of single-piece helmet shell from vacuum bagging

Following the investigation in Chapter 3, a dome-shape composite structure was developed. No reports have been published on making single-piece riot helmet shells by vacuum bagging. This chapter describes the innovative technique of creating single-piece helmet shells using vacuum bagging. According to the understanding developed from dome-shape manufacturing in Section 4.2, the following necessary requirements were required in order to create single-piece helmet shells using the vacuum bagging technique.

(1) A mould was required.
(2) A method of fabric draping was necessary.
(3) A procedure for the manufacturing of single-piece helmet shells had to be developed.

4.4 Fabrication on nonwoven glass fibre mould

4.4.1 Required characteristics of a mould

Based on the technique developed for a dome-shape structure, the mould for making helmet shell should have the following characteristics.

(1) Solid mould: in vacuum bagging, resin flows wherever it has the least resistance. So for making helmets shells the mould should be a solid structure. Otherwise, there will be an accumulation of resin inside the hollow mould causing difficulties in removing the helmet shell off the mould.

(2) Correct dimensions of mould: the dome-shape structure developed had a single curvature since it was made from a solid wooden mould which had equal radius at all points on it surface. However, riot helmet shells are composite structures with variable curvatures. So, the desired helmet shell inner curvature should be exactly similar to the mould outer surface curvatures.
(3) Draping processes and edge formation: fabrics should be able to be draped over the mould without difficulty. The necessary arrangement should be carried out in order to form a proper edge for the helmet shell on the mould.

(4) Removal of a cured helmet shell off the mould: the mould should be developed in such a way that after curing, the helmet shell should be removable easily in a single-piece. Therefore, a collapsible mechanism has to be designed for the mould.

4.4.2 Material of mould
Currently riot helmet shells are normally produced by pasting trimmed fabric on a concave mould. However, present research seems to mould fabric onto a convex (positive) mould. Chopped glass fibres were used due to easy availability and good embedding properties compared to yarn or fabric form. Araldite LY5052 and Aradur 5052 were mixed together as epoxy and hardener in the ratio of 100:38 by weight (Huntsman, 2010). Special care was carried out while manufacturing under the guidance of safety regulations such as gloves, a dust respirator, protector glasses and lab coat.

4.4.3 Mould designing
In order to develop a riot helmet shell having variable surface curvatures, there was a need to produce a mould having similar curvatures. The mould should have the capability for easy removal of the cured helmet shell from the mould. If a riot helmet is assumed to have six sides like a cube shape, then the mould can be removed off the developed shell from only two sides i.e. front and bottom sides of the helmet shell only provide space for the removal of the mould as can be shown in Figure 4-2.

![Figure 4-2 Tool for helmet mould](image)
As discussed in section 4.4.1 regarding the collapsible mechanism, it was planned to develop a mould in a minimum of three solid pieces (non-hollow) which can be removed from the helmet shell. The mould parts should be constructed in such a way that they all can be stacked inside the helmet shell. The mould was planned to be made in three parts namely, left side, middle part and the right side of the mould. The fixing mechanism was one of the important features since limited working space was available for dismantling the mould. The middle part was designed to have less thickness from the top as compared to the bottom due to two reasons. Firstly, for the easy removal of the middle part from the other two parts i.e. to reduce the friction between the parts while dismantling. Secondly, it was planned due to the fixing bolts which run through the middle part to the aluminium plates inside the other two parts. The force applied to remove the middle part should be greater than the frictional forces. A typical illustration can be seen in Figure 4-3 (Beardmore, 2010).

\[
F_{\text{net}} = F_{\text{applied}} - F_{\text{friction}}
\]  
\[
F_{\text{friction}} = \mu \, N
\]

where, 

N is the normal force action on the middle piece of the mould.

In order to reduce the frictional force an angle has been placed while making the mould parts. The helmet mould piece will exert weight ‘N’ on the middle part while dismantling. The forces acting are shown in Figure 4-9.

Force acting down = N sin θ  
Force pressing middle piece on to the slope = N cos θ  
The coefficient of friction = force pressing surfaces together / force moving the middle piece = N sin θ / N cos θ = tan θ
4.4.4 Creating wall and filling part technique

A technique for making parts was designed and named as ‘Creating Wall and Filling Part’ (CWFP). By this technique the inner curvatures of the helmet shell were archived. In CWFP, first the walls of the parts were created and after curing the space was filled with the mixtures of resin and glass fibres to make it a solid part.

To create the mould surface geometry, a riot helmet shell was used as a tool for the creation of the mould. The matrix along with chopped glass fibre was amalgamated and applied by hand on the inner side of the helmet shell tool which was covered with release film as in Figure 4-6 (a). After curing the mould left portion is shown in Figure 4-6 (b). By a similar method, the right side of the mould was developed. As per the name of the
technique the walls of the parts were created. A metal sheet cut and ground with the exact inner diameter of the helmet shell was placed on the inner side of the helmet touching the already developed nonwoven fibre-glass mould. The purpose of using a plate was only to restrict the flow of glass fibre while embedding and making walls of the side parts. C-clips were used in order to hold the part and the plate to get the exact dimensions of the inner side of the original tool. In a similar way, both the hollow side portions of the mould were manufactured as in Figure 4-6 (c). An angle of around 10 degrees was introduced while making the second wall of each side part. This was carried out only to give more thickness to the top portions of the side parts for easy removal of the middle part from the other two parts after helmet shell manufacturing as discussed in Section 4.4.3. The manufacturing of the middle part of the mould was carried out in two steps by creating separately two walls of the middle part as shown in Figure 4-6 (d). All the three hollow parts of the mould have been manufactured and shown in Figure 4-6 (e). The second part of CWFP is described in the next section.

Figure 4-6  (a) Side of tool with embedded glass fibres (b) Creating walls of hollow part (c) Cured hollow part of mould (d) Middle part preparation (e) Right, left and middle hollow parts of the nonwoven fibre-glass mould

4.4.4.1 Fixing mechanism and mould edge formation

The second part of the CWFP i.e. the filling part is discussed in this section and shown in Figure 4-7. A mechanical fixing mechanism was produced in order to connect the three
moulded parts together to form a mould. The parts created were hollow structures and for use as a mould in a vacuum bagging setup, there was a need to make them solid. They were filled with the mixture of resin and glass fibre along with the aluminium pieces so that the three pieces of the mould can be fastened together with the help of bolts. Extra care has been taken while filling the moulded parts to obtain proper edge formation. The edge on the mould was necessary for holding the helmet shell in the subsequent vacuum bagging processes. A metallic stand was also manufactured in order to fix the mould on a stand. A bolt was used to hold the mould firmly on the stand’s rod. The tube at the bottom of the middle part was used to hold the mould on the stand.

Figure 4-7 Different views (a) left filled part (b) middle filled part (c) moulded parts inside the helmet shell tool (d) complete fixed mould on a stand

4.4.4.2 Mould surface finish

There was a need to finish the mould smoothly since an uneven surface can cause entanglement of yarns while draping. By using plastic padding as filler, a smooth even surface was obtained. The glass fibre mould was then painted to give an attractive appearance as can be viewed in Figure 4-8.

Figure 4-8 Helmet shell tool with (a) Unfixed moulded parts (b) Fixed moulded parts
4.5 Draping process

In the current study, the helmet shell fabrication technique involves a series of steps namely: fabric draping, edge formation, vacuum infusion and removal of the shell off the mould. The prime objective was to constrain the fabric over the mould without any wrinkle formation and to use vacuum bagging to form a cured single-piece helmet shell.

The helmet shell was made in mainly two stages: firstly, the draping process and secondly, vacuum bagging. For optimal results these two stages are related to each other in such a way that the careful measures adopted in the draping process ends up with better results in the vacuum bagging.

4.5.1 Initial setting

The moulded parts were fixed together and then the fibre-glass mould was completely covered with release agent. This was carried out in order to keep the resin away from the mould while making the composite.

Minimisation of fabric usage is important. For that purpose an exact outer perimeter from the front edge to the back bottom edge of the mould was measured and the desired amount of fabric length was cut in the warp direction. The trimmed fabric and the edge were fixed with adhesives in order to prevent ripping off the yarns. The fabric placed on the mould is shown in Figure 4-9.

![Fabric on mould ready for conforming](image)

Figure 4-9  Fabric on mould ready for conforming
4.5.2 Primary draping technique

5-8-28 Al-fabric has good mouldability as discussed in Section 3.2. The fabric was draped onto the mould surface by decreasing the fabric area to a maximum extent through shearing and allowing the fabric to be sheared and conformed to the mould surface with no wrinkles.

The mould surface was subdivided into four sections as shown in Figure 4-10. The fabric in each section was draped. The fabric was fixed at the front top edge and back edge of the middle part of the mould with the help of fold-back clips. In the process draping, the Al-fabric was kept tensioned in the warp direction on the mould surface. First the fabric on the mould was draped by giving maximum shear at any position of the fabric to conform on the mould surface. Fold-back clips were used in order to constrain the fabric on the edges of the mould. Similarly, fabric in all the mould sections was draped using the same procedure.

![Figure 4-10 Top view of conformed fabric]

The intention while draping was to have a smoothly draped fabric. Although, wrinkles were produced due to excessive fabric shearing and these wrinkles were removed by realigning the yarn paths in the fabric and directing them toward the non-conform portions. The conformed AI-fabric over the mould surface is shown in Figure 4-11.
4.5.3 Edge control

The objective of draping was to obtain a wrinkle-free single-piece helmet shell having proper edges. A challenge in vacuum bagging was to hold the fabric until curing was completed, on the developed mould inside the vacuum bag. In order to achieve this, two edge controlling techniques were practiced and later optimised in order to hold the wrinkle free fabric on the mould.

4.5.3.1 Edge control by clips

For vacuum bagging, the mould along with the draped fabric has to be placed inside the vacuum bag. In this first technique, fold-back clips were used to hold the fabric on the mould edges while in the vacuum bag. The whole setup was sealed in the bagging film. Each fold-back clip was sealed separately by a release film as shown in Figure 4-11. This was carried out in order to prevent the fold-back clips sticking to the fabric during resin infusion and curing. The extra fabric was trimmed off. However, there were difficulties in trimming the fabric since the fabric was in tension and in a sheared position. Complete trimming by means of ceramic scissor at the edges of sheared fabric was nearly impossible due to the space availability around the edges of the mould. The mould with fabric clipped on its edge was sealed in the vacuum bag and resin infused.

Details of helmet manufacturing by means of vacuum bagging will be described later in section 4.6.

Advantages and disadvantages were observed from this “locking edge with clips” technique. In this attempt at vacuum bagging, a helmet shell shape has been developed.
The major disadvantage with this technique was the uncured edges, which were not properly cured since the resin was unable to impregnate the area beneath the clips. The marked ellipse portions can be seen clearly in Figure 4-12. It was concluded that holding the fabric edges by clips was not suitable for this way of making a helmet shell by vacuum bagging. Furthermore, it was difficult to remove the helmet shell off the mould due to the presence of cured fabric on the edges developed by improper trimming. Excess cured resin near the edge due to the fold-back clips was also present. There are a few uncured areas. Moreover, wrinkle formation near the shell edge was also one of the concerns. These wrinkles were due to the presence of uneven tension on the draped fabric held by the fold-back clips under vacuum.

![Image](image.png)

**Figure 4-12 Uncured portions marked at helmet shell edge**

### 4.5.3.2 Edge control by resin

A second preparation of locking the fabric on the mould edge was carried out by holding the draped fabric by clips while painting the edge with a mixture of resin and hardener. After draping, one by one all the fold-back clips were removed and the area underneath the fold-back clips was painted with the mixture of resin and hardener. The clips were then placed again on the same locations to hold the fabric on the edge on mould. Curing time (14-16 hrs) was given in order to cure the resin (Huntsman, 2010). After curing the fold-back clips were removed and the extra fabric was trimmed by ceramic scissors. The draped fabric on the mould edge, locked with resin, is shown in Figure 4-13.
The vacuum bagging was carried out as discussed in Section 4.6. The helmet shell as developed seemed better in comparison with the first technique (section 4.5.3.1). There were no dry patches at the edge and also no excess resin accumulation has been observed. Further, the helmet shell was simply removed from the mould due to proper edge formation. Two types of fault emerge in this way of making helmet shells. Firstly, there were a few dry patches on the top surface of the helmet shell. These dry patches were later solved and discussed in section 4.6.2. Secondly, there were a few wrinkle formations near to the locked edge of the helmet shell. These dry patches and wrinkles were similar to those found in section 4.5.3.1. The helmet shell edge developed by this technique can be viewed in Figure 4-14.

Figure 4-13 Dry fabric on the mould with locked edge by resin

Figure 4-14 Helmet shells edge formation by resin
4.5.4 Secondary vacuum assisted draping technique

Sections 4.5.3.1 and 4.5.3.2 were the basic foundation for the AI-fabric draping on a solid nonwoven mould. Repeated experiments and observations were gathered and it was found that vacuum pressure in the vacuum bag was the primary reason for creating wrinkles in the developed helmet shells. After locking the edge either by fold-back clips or by resin, uneven tension by the clips was causing the moulded fabric to be a bit loose and also the draped fabric was then compressed towards the mould surface due to the vacuum pressure in the vacuum bag. This caused wrinkles which ultimately end near the locked edge of the helmet shell. These wrinkles were suggested to be due to the improper locking of the edges before vacuum bagging and then further shearing of the fabric caused by the vacuum in the vacuum bag.

In order to stop the formation of wrinkles during vacuum bagging, there was a need to maintain similar shearing conditions while draping the fabric on to the mould, as it was happening during vacuum bagging. The uneven pressure of the fold-back clips was the reason for the problem. In other words, shearing of the fabric due to vacuum pressure must be required during the formation of the shell edges and locking the fabric at the mould surface. By adopting vacuum draping of the fabric there will be no wrinkle formation in the vacuum bagging.

For this reason discussed above a new technique for impregnating textile composites with curved surfaces, named as ‘Vacuum Assisted Draping Technique’ (VADT) was developed. In VADT, the fabric was draped onto the mould and the shell edge was resin impregnated and then cured under vacuum.

The detailed procedure is described as follows:

1. first the fabric was draped over the positive mould as discussed in section 4.5;
2. Araldite® LY 5052 was mixed with hardener Aradur® 5052 in the ratio of 100:38 by weight (Huntsman, 2010) in a cup. With the help a small paint brush the AI-fabric at the edge of the mould was painted. The application of the resin was carried out in such a way that the fold-back clips were removed one by one and the small area underneath the resin was painted and the fold-back clips were replaced again in the same locations;
3. draped, clipped and resin impregnated edges of AI-fabric on the mould fixed on the stand was ready to be draped under vacuum;
(4) a vacuum bag was created from a bagging film whose three sides were sealed with tacky tape. The whole setup was covered with a bag placed from the top of the mould. The setup was covered with bagging film (made of nylon) for two reasons. Firstly, due to the non-stickiness of the film with Araldite® LY 5052 and hardener Aradur® 5052 and the film can work as a release film. Secondly, bagging film has elastomeric properties which can withstand the atmospheric pressure that impinges upon the specimen once the vacuum is applied;

(5) a vacuum pump was connected on the fourth side of the vacuum bag and the bag was then sealed properly with tacky tape. The whole setup was covered with airtight sealed bagging film and the back-fold clips were unclipped from the edge one by one. The vacuum pump was then turned ON during unclipping. The vacuum produced in the bag, further sheared and draped the Al-fabric properly on the mould;

(6) proper curing of the edges along with wrinkle free draping was achieved by leaving the setup under vacuum for approximately 14-16 hours;

(7) after curing the vacuum pump was disconnected. The bagging film was peeled off;

(8) extra fabric on the front portion of the mould was trimmed off with the help of ceramic scissors and a precise helmet shell edge was produced.
The complete setup of the VADT is shown in Figure 4-15. Figure 4-16 shows post VADT views of draped dry AI-fabric on the mould. Due to the vacuum assisted draping technique (VADT), the edges of the draped fabric were locked exactly in the same conditions as happened in the vacuum bag. It was observed that there was no wrinkle formation while the resin was infusing at the edge of the complete helmet shell. VADT furnish a proper shell edge which can be shaped before putting the mould in the vacuum bag.

Figure 4-16 Post VADT views (a) Side (b) Back (c) Front (d) Top
4.6 Novel technique for the creation of single-piece riot helmet shells

Vacuum bagging is an inexpensive and versatile process which is also known as the bag moulding process. In vacuum bagging, suction is applied to the bag to remove excess air and to improve impregnation of the fabric through resin infusion. Based on the author’s knowledge, no-one has previously used vacuum bagging for making single-piece riot helmet shells.

In order to hold the AI-fabric in the desired shape on the glass fibre mould, the VADT draping technique was developed as discussed in Section 4.5. The procedure adopted specifically for riot helmet shell manufacturing was a combination of two processes described in the manufacturing of flat panel composites and dome-shaped composite structures by vacuum bagging. The importance of the dome-shape has been discussed in Section 4.2.1 which leads to the development of single-piece riot helmet shells by vacuum bagging.

The technique for the manufacturing of single-piece riot helmet shells using vacuum bagging is described. The draped fabric on the glass fibre mould with locked edge was ready to vacuum bagged (as discussed in section 4.5.4). Safety precautions as discussed in Section 3.4.3 were adopted. The necessary steps were performed in order to manufacture helmet shells from this method.

4.6.1 Setup for vacuum bagging

Preparation of the vacuum bagging setup was the first step.

AI-fabric draped on a mould completely covered and sealed with release film was placed at the centre of the tool as described in section 3.4.4, step 1. Peel ply, perforated release film, infusion mesh and breathers were placed according to steps 2 and 3 (section 3.4.4). Due to the shape of the mould there were some wrinkles that formed on the infusion mesh while wrapping it on the mould. The excess infusion mesh was cut by scissors and placed in patches for the smooth flow of resin.

The inlet zone and the outlet zones were created. For uniform distribution of resin and for controlling resin speed, H-clips were used at the inlet zones. In the end the whole setup was covered with a vacuum bag having an air tight seal made by tacky tape. The whole
setup was sealed with excess bagging film due to the height constraint. This was necessary for easy resin flow on the mould and also restrains bursting of the bagging film during vacuum application. The complete setup of vacuum bagging achieved in the laboratory is shown in Figure 4-17.

![Figure 4-17 Riot helmet shell manufacturing using the vacuum bagging method](image)

**Figure 4-17 Riot helmet shell manufacturing using the vacuum bagging method**

### 4.6.2 Optimisation in making helmet shell through vacuum bagging

Araldite® LY 5052 was mixed with a hardener Aradur® 5052 in the ratio of 100:38 by weight (Huntsman, 2010). The different parameters optimised for achieving fully impregnated cured helmet shells are discussed.

1. Placement of inlet valve: the position of the inlet valve was one of the most important factors in the creation of riot helmet shells by vacuum bagging. Impregnation of the AI-fabric was performed by infusing resin from the top of the mould. The purpose was to impregnate the fabric on the mould and also due to the mould geometry, the mould was placed in the vacuum bagging tool on the front mould edge instead of the bottom mould edge as shown in Figure 4-18.
(2) Uses of multiple inlets: in order to cover the area of mould surface, two inlet valves were implanted. It was observed that one inlet valve can impregnate the fabric completely as with many infusion inlets for this particular size of mould as shown in Figure 4-19 (a) & (b). One inlet valve was used to impregnate the draped fabric.

(3) Use of different infusion meshes: two varieties of infusion meshes were used (soft and hard) as shown in Figure 4-20 (a) & (b) respectively. Soft infusion mesh has better drape-able qualities. Therefore, the softer infusion mesh was used and recommended due to the better mouldable properties than with the hard infusion mesh.
(4) Use of peel ply and perforated release film: resin can simply flow through the peel ply which was nylon 1/1 plain weave fabric. The perforated film used in making flat panel composites work successfully along with peel ply. However, after observation it was found that the perforated release film was the main reason behind the uncured patches on the helmet shells (as discussed in Section 4.5.3). Since it was impossible to drape a plastic layer on a curved part such as a helmet shell mould, without having wrinkles as can be seen in Figure 4-21 (a). These wrinkles block the flow of resin towards the nylon peel ply and ultimately to the AL-fabric causing un-impregnated patches on the helmet shells. Therefore in making helmet shells, perforated release film was not used in the later stages. Figure 4-21 (b) shows the complete impregnation of the helmet shell without using perforated release film.

Figure 4-20 Different varieties of infusion mesh (a) Soft (b) Hard

Figure 4-21 (a) Perforated release film having creases (b) Impregnation without perforated release film
(5) Flow of resin: long pot-life Araldite® LY 5052 and Aradur® 5052 matrix makes it more feasible to use this approach for manufacturing big objects (Huntsman, 2010). In order to take advantage of long pot-life matrix, the infusion was carried out in such a way that small quantities of matrix per minute were fed into the vacuum bag. The flow of resin was controlled by an H-clip as can be seen in Figure 4-22 (a). In this way complete impregnation of the draped fabric from top to bottom of the mould was achieved. The reason for infusing the matrix from the top of the mould was that it allows even distribution throughout the helmet mould as can be seen in Figure 4-22 (b).

![Figure 4-22 (a) Uniform infusion (b) H-clip](image)

(6) Base of mould: the maximum area of the mould having preform and vacuum bagging film should stick to the mould otherwise while bridging wrongly, wet out at those areas will not occur. Bridging of the vacuum film is shown in Figure 4-23.

![Figure 4-23 Bridging of vacuum film](image)
Improper bridging initially was observed when the mould was placed on the tool on its front top mould edge. Small wooden blocks were made and used to lift the mould from the tool for about 2.5 cm. By raising the mould, the mould was then placed on the wooden blocks instead of on its edge. Due to the space created beneath the mould, the vacuum bagging film firmly stuck to the bottom edge of the mould with the correct bridging as shown in Figure 4-24.

![Mould placed on wooden blocks](image)

**Figure 4-24 Mould placed on wooden blocks**

### 4.6.3 Removal of shell off the mould

As discussed in Section 4.4.3 and 4.4.4, about the significance of the thickness of the middle part of the mould, helmet shells produced in this way can be removed off the mould. After 14-16 hours of initial curing at room temperature (Huntsman, 2010), the vacuum bag was peeled off and the Al-fabric resulting in a stiff composite structure. The bolts used to connect the three pieces of the mould were removed in order to collapse the mould. The middle part of the mould was pulled out with no trouble from the mould and then the other two parts of the mould were collapsed and removed. A riot helmet shell was made. Dismantling of the mould can be viewed in Figure 4-25.
4.6.4 Curing of riot helmet shell

To further enhance the shell stiffness, helmet shells were further cured in the drying oven for 4 hours at 100°C as suggested by the resin manufacturer (Huntsman, 2010). The complete riot helmet shell can be seen in Figure 4-26.

(a) (b)

Figure 4-26 (a) Developed single-piece riot helmet shell (b) Finished look of developed single-piece riot helmet shell
4.7 Summary

The successful trial for the manufacturing of the desired dome-shape composite structure has been carried out. Resin infusion from the top of the mould was a vital practice helpful for complete impregnation of the composite structure. Successful infusion, flow and distribution of resin from the top of the mould to the bottom in a vacuum bagging apparatus make it possible to develop a composite structure with a significant height. Based on the understanding developed in making a dome-shape structure, needs and requirements for the single-piece riot helmet shell were highlighted and then in later stages of the chapter, riot helmet shells have been created.

The important achievement related this chapter is the development of a successful method for making single-piece riot helmet shell from Al-fabric using the vacuum bagging process. A non-woven glass fibre mould has been developed by creating a wall and filling part technique (CWFP). The mould contains a collapsible and fixable mechanism for easy removal of the shell from the mould. Further, vacuum assisted draping techniques (VADT) have been established which provide wrinkle free draping of Al-fabric on the helmet mould. This technique can be used to drape mouldable fabric onto a mould for vacuum bagging. Finally, composite riot helmet shells were successfully produced. A detailed procedure for making single-piece riot helmet shells has been discussed.

The technique developed for the manufacturing of single-piece riot helmet shells can be used for the development of different varieties of bi-curvature composite structures e.g. with the combination of CWFP, VADT and vacuum bagging almost any shape of composite helmet shells can be developed.

A flow chart summarises the sequence for making riot helmet shells as shown in Figure 4-27.
Figure 4-27 Flow chart of single-piece riot helmet shell manufacturing:

1. Assemble mould pieces
2. Primary draping technique
3. Edge control
4. Secondary vacuum assisted draping technique
5. Vacuum bag preparation
6. Resin infusion from the top of mould
7. Initial curing of helmet shell
8. Removal of shell from the mould by collapsible mechanism
9. Final curing of helmet shell
10. Cutting of helmet shell edges
CHAPTER 5  TEST RIG FOR HELMET IMPACT TESTING

Impact testing of the developed helmet shells was one of the objectives in this research. In order to fulfil this objective there was a need for a helmet test rig. This chapter describes the development of an impact test rig for helmets based on an Instron drop weight impact tester, Dynatup 8200. In drop weight impact testing, an impactor with a known mass is dropped in free fall from a known height. The potential energy of the impactor before dropping should be equal to the kinetic energy of the impactor just before hitting the specimen, assuming no frictional loss. In this study, the Instron Dynatup 8200 drop weight impact tester was used and modified for helmet testing.

5.1 Location of impact at helmet shell

The location of impact testing was one of the most important factors for designing a helmet testing assembly. For this purpose the US NIJ standard and the Police Scientific Development Branch’s (PSDB) Protective Headwear Standard for UK Police (2004) were reviewed and discussed in Section 2.8. From the review of the three popular standards, testing was considered based on the review analysis conducted in Section 2.8. It seems that the PSDB/APCO Standard (Malbon and Croft, 2004) and the NIJ Standard (US Department of Justice, 1984) are more reluctant to do the impact testing closer to the brain area and the CAN/CSA-Z611-02 (Shanahan, 2003) has provided the opportunity for testing any point on the helmet shell. Two different side views are shown in Figure 5-1, displaying impact locations based on the NIJ standard (marked as N) and the PSDB/APCO standard (marked as B).

![Figure 5-1 Impact locations on a riot helmet](image.png)
The impact points on the continuous textile reinforced helmet have been planned in-between the area of testing surrounded by the international standards (Malbon and Croft, 2004; Shanahan, 2003; US Department of Justice, 1984). Based on this fact, it was decided that impact testing would be conducted on at least three locations on the helmet shell i.e. the side, back and top locations. The testing assembly has been planned to be constructed in this way so that it should have the option to do impact testing at the side, back and top of the developed continuous textile reinforced helmet shell.

5.2 Requirement of test rig

Based on the aim of this research, one of the main objectives of this research is to develop an in-house testing facility for testing helmet shells. For this purpose, some modifications have been carried out to the Dynatup 8200 at the University of Manchester. The Dynatup 8200 drop weight impact testing machine at the University of Manchester can be seen in Figure 5-2. This instrument is used for low velocity and low energy impact testing.

![Dynatup 8200 drop weight impact testing instrument](image)
For impact testing on the designed helmet shells, there was no anvil available to hold the helmet shells on the 8200 Instron drop weight impact instrument. Moreover, there was a need to determine the transmitted force underneath the helmet shell (or at the top of the anvil). For that purpose force sensors had to be implanted. In other words, a test rig was required which could be used as an anvil in the Instron Dynatup 8200 drop weight impact tester.

In order to develop the test rig for helmet testing, there was ample space available in the bottom portion of the Instron Dynatup 8200 drop weight impact tester as can be seen in Figure 5-2. Utilisation of this bottom portion (having dimensions of 38 cm wide, 43 cm deep and 51 cm height) as the working space was aimed for the helmet holding assembly.

To do impact testing on developed helmet shells, modifications have to be carried out on the Dynatup 8200 drop weight impact tester. The test rig for the helmet testing should have certain requirements.

Firstly, there was a need of a headform for holding the helmet shells during an impact. Secondly, helmet shells should be held firmly during the impact, so there was a need to develop a headform holding assembly. Thirdly, impact testing has to be carried out on the back, top and side of the helmet shell. So there was a need to develop a mechanism by which helmet shells could be rotated with the headform without resetting the whole setup. Lastly, the Instron Dynatup 8200 drop weight impact tester can give the impact data from the top of the specimen. In order to find the force transmitted through the helmet shell, a force sensor was a required for the evaluation of force blocking effectiveness. For this purpose, a force sensor was installed on the headform which could calculate the transmitted force.

5.3 Development of test rig

Based on the requirements discussed above, the test rig was manufactured in three steps namely:

1. manufacturing of headform;
2. manufacturing of headform holding assembly and assembly foundation;
3. placement of force sensors at the headform.
5.3.1 Headform manufacturing

In order to hold the helmet shell there was a need for a headform which could serve the purpose of helmet holding. An ideal headform is the one which should be able to stay firm at low velocity impacts and also force sensors can be mounted on the headform for measuring the transmitted force.

In this study, spherical headform coordinates with 525 mm circumference from the British headform standard ‘Headform for use in the testing of protective helmets’ (BS EN 960:2006) (The European Standard, 2006) was selected due to the fact that it is one of the lowest headform sizes and this size was suitable for the developed helmet shells. Moreover, the same coordinates were later used in FE Simulation in Chapter 7.

A polypropylene made headform which has a circumference of 525 mm was cast from aluminium and is shown in Figure 5-3. Headforms made of aluminium are commonly used by several authors (Becker, 1997; Mills, 2011; Mills and Gilchrist, 2008).

![Figure 5-3 Aluminium headform](image)

5.3.2 Headform holding assembly

The headform should be held firmly with the helmet shell for impact testing. Moreover, the helmet shell has to be impacted on three different impact positions. There was limited space available for holding the headform with the helmet shell. This limited space was only located on the front (face) and the bottom (neck) of the headform as can be seen in Figure 5-4.
There were three basic objectives while designing the helmet holding assembly. Firstly, impact testing has to be carried out on at least three sides of the helmet shell i.e. the top, side and back of helmet shell. Secondly, the whole helmet holding assembly should be able to rotate for different impact locations without resetting the whole setup. Thirdly, a force sensor should be installed on the headform at the exact position of impact.

Based on the requirement it was planned that the headform should be drilled and steel rods would be fixed in the drilled portions at the bottom (neck) and the front (face). The purpose of these steel rods was to hold the headform and can be rotated to the required impact location.
The drilled headform with steel rods can be seen in Figure 5-5(a). The purpose of these steel rods was to hold the headform on a specially designed foundation as can be seen in Figure 5-5(b). In this way the headform along with helmet shell on it can be swing simply to the required direction without removing and resetting the whole helmet holding assembly. The helmet holding assembly foundation was bolted to the main base foundation of the Dynatup 8200 Impact testing instrument. The steel rods were bolted on to the upper part of the helmet holding assembly. Anti-vibration pads were also used in the bottom of the steel rod connecting to the foundation to reduce vibration caused by the reaction on the impact.

5.3.3 Force sensors and mounting at headform

The Dynatup 8200 impact testing instrument has the ability to provide the impact force, but in order to evaluate the force received underneath the helmet shell, a force sensor was installed at the headform.

A Dytran ring type model series 1203V5 force sensor was selected due to its inbuilt form of thin ring with through holes and also its high compression range. These sensors are designed to measure dynamic forces in machines. The mounting of this type of sensor is fairly easy since it has a hole similar to a washer as shown in Figure 5-6 (Dytran Instrument Inc., 2010b).

![Figure 5-6 Force sensor model series1203V5](image-url)
The output signal of these sensors is a voltage mode signal scaled directly in millivolts per newton. The selected sensor has the sensitivity of 0.5 millivolts per newton (i.e. $1V = 8896.44$ N). Sensor information sheet can be viewed in Appendix B. The headform was cut, drilled and tapped as per the sensor’s dimensions at the selected impact locations. The groove prepared for the sensor can be seen in Figure 5-7. The force sensor was held on the aluminium head by means of a steel bolt.

![Figure 5-7 Sensor’s groove on the headform](image)

The developed test rig can be viewed in Figure 5-8.

![Figure 5-8 Different views of the helmet test rig (a) front view (b) side view](image)
5.4 Development of method for data collection and data processing

During an impact two separate systems were used simultaneously for data recording and processing.

(1) Impulse data acquisition system
(2) Low impedance voltage mode system

5.4.1 Impulse data acquisition system

The Instron uses the Dynatup Impulse™ data acquisition system which can collect and analyse the data both graphically and numerically (Instron, 2009; Instron, 2004). The impulse data acquisition system (IDAS) with the Dynatup 8200 drop weight impact testing instrument have been used to record impact testing results. IDAS consists of the following (Instron, 2004):

- impulse software;
- national instrument data acquisition board;
- signal conditioning unit;
- cables;
- velocity detector block;
- velocity flags.

The data acquisition system consists of hardware to amplify and capture the dynamic transducer output from an impact event and software to analyse, display, report and store these data (Instron, 2004). This is a built-in system with the Dynatup 8200 impact testing instrument and Figure 5-9 shows the system composition. The load cell has a maximum range of 2224 N (5000lbs).

![Figure 5-9 Impulse data acquisition system](image)

112
5.4.2 Low impedance voltage mode system

A system has been developed for data collection at the headform. This low impedance voltage mode system (LIVMS) consists of the following (Dytran Instrument Inc., 2010a):

- Dytran force sensor;
- coaxial cable;
- the DC power source;
- NI USB data acquisition device (DAQ);
- Lab View signal express software.

The force sensor model 1203v5 (as discussed in 5.3.3) contains quartz crystals which after produces an output voltage exactly analogous to the dynamic force. This voltage mode signal is directly scaled in millivolts per newton. The schematic diagram of the setup from the manufacturer (Dytran Instrument Inc., 2010b) is shown in Figure 5-10.

![Figure 5-10 LIVM sensor and power unit schematic diagram](image)

Lab View Signal Express software was used to collect and analyse data both graphically and numerically (National Instrument, 2010). The manufactured system in the laboratory is shown in Figure 5-11.
There was no option available for simultaneous triggering of both the software (IDAS and LIVMS), therefore LIVMS was turned ON before the impact and turned OFF after the impact. This is how the data were extracted from the LIMVS, whereas the IDAS processed the data automatically from the impulse software during an impact.

5.4.3 Calibration of the system

The IDAS and LIVMS were manually triggered and the separate data were extracted and exported to Microsoft Excel. Calibration of the two different systems was necessary. The easiest way to calibrate the two was to perform an impact on the anvil without any specimen and compare the forces detected by the two different systems.

Ideally in an impact without any specimen, the peak impact force measured using IDAS should be equal to the transmitted peak force (reaction force) measured by LIVMS. Figure 5-12 shows an impact directly on the anvil without a specimen. The two curves follow the same path but the peaks do not match to a certain value. This seems to be due to the different responsivities of the two sensors and also due to the developed test rig setup as they are subjected to different impact conditions. Several impact test results without specimen shows that test rig geometry has an influence on the magnitude of transmitted force (reaction force). Due to this method a little energy is absorbed by the test rig and causing less reaction force (transmitted force) in impact test without specimen. In order to overcome this problem, the reading of the transmitted force was corrected.
according to the reading of the impact force. Correcting factors have been introduced. In order to obtain the correcting factors at three different locations on the anvil (top, side and the back), a multiple series of impact tests (without a specimen) at three different impact energy levels (around 5J, 15J and 25J) were carried out, and the correcting factors were calculated accordingly. These impact energies were selected due to the responsivities of the IDAS system otherwise the peaks having greater than 25kN force will be limited of by the system. Table 5-1 shows the average impact test results without a specimen. A Detailed experimental data for the correcting factor can be viewed in Appendix A (Table-A6).

![Graph showing impact force and force transmitted curves at 25.6J impact (without specimen)](image)

**Figure 5-12** Impact force and force transmitted curves at 25.6J impact (without specimen)

<table>
<thead>
<tr>
<th>Energy Joules</th>
<th>Impact location</th>
<th>Impact Force</th>
<th>Transmit Voltage</th>
<th>Base Voltage</th>
<th>Delta Transmitted Voltage</th>
<th>Transmitted Force</th>
<th>Correcting Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.6</td>
<td>Top</td>
<td>9.463</td>
<td>1.990</td>
<td>1.223</td>
<td>0.768</td>
<td>6.828</td>
<td>1.386</td>
</tr>
<tr>
<td>15.6</td>
<td>Top</td>
<td>15.875</td>
<td>2.578</td>
<td>1.223</td>
<td>1.355</td>
<td>12.056</td>
<td>1.317</td>
</tr>
<tr>
<td>25.6</td>
<td>Top</td>
<td>20.381</td>
<td>2.962</td>
<td>1.223</td>
<td>1.739</td>
<td>15.470</td>
<td>1.317</td>
</tr>
<tr>
<td>5.6</td>
<td>back</td>
<td>9.176</td>
<td>2.069</td>
<td>1.223</td>
<td>0.846</td>
<td>7.528</td>
<td>1.219</td>
</tr>
<tr>
<td>15.6</td>
<td>back</td>
<td>15.564</td>
<td>2.677</td>
<td>1.223</td>
<td>1.454</td>
<td>12.934</td>
<td>1.203</td>
</tr>
<tr>
<td>25.6</td>
<td>back</td>
<td>19.843</td>
<td>3.084</td>
<td>1.223</td>
<td>1.861</td>
<td>16.558</td>
<td>1.198</td>
</tr>
<tr>
<td>5.6</td>
<td>Side</td>
<td>9.242</td>
<td>2.007</td>
<td>1.223</td>
<td>0.785</td>
<td>6.979</td>
<td>1.324</td>
</tr>
<tr>
<td>15.6</td>
<td>Side</td>
<td>15.513</td>
<td>2.568</td>
<td>1.223</td>
<td>1.345</td>
<td>11.967</td>
<td>1.296</td>
</tr>
<tr>
<td>25.6</td>
<td>Side</td>
<td>19.666</td>
<td>2.942</td>
<td>1.223</td>
<td>1.719</td>
<td>15.292</td>
<td>1.286</td>
</tr>
</tbody>
</table>

* sensitivity of force sensor (1V = 8896.443 N)
5.4.4 Testing procedure

The two systems, IDAS and LIVMS used in the impact testing have been explained in section 5.4. The following procedure was established in the laboratory for impact testing.

1. Pre-test preparation

Few actions were necessary before conducting the test namely, adjusting the drop weight height, setting selection of drop weight mass, and velocity detector. The drop weight mass and the drop weight height determine the impact energy just before the impact.

2. Conducting a test

As discussed earlier that there is no mechanism available for simultaneous triggering of IDAS and LIVMS, the following sequence was carried out before dropping the mass on to the specimen. First the ‘Impulse Data Software’ was switched ON and necessary data were input such as mass of drop weight assembly, then the ‘Lab View Signal Express Software’ was switched ON. The impact test was then carried out by releasing the drop weight from the release button. The data from the Lab View Signal Express reads continuous signals so, after the impact, Lab view signal express was switched OFF.

3. Capturing the data and analysis

Two separate sets of data were captured: one from the ‘Instron Dynatup data acquisition system’ and other from the ‘Low impedance voltage mode system’. After the impact, raw data has been exported to Microsoft Excel and analysed.

5.4.5 Prerequisite of data processing

The following discussions will be focused on the fundamental data processing procedures from IDAS and LIVMS, which include the fundamentals of the drop weight impact test, the concept of force attenuation and its evaluation, the behaviour of the transmitted force and the estimation of energy absorption.

5.4.5.1 Fundamentals of drop weight impact test

The Drop weight impact testing procedure has been already discussed in Section 2.6. The conversion of potential energy into kinetic energy depends on the impactor’s drop height and mass. The velocity of the impactor when the impactor head first touches the specimen
can be calculated as per Equation (2.1). The ratio of the energy absorbed by the specimen to the impact energy carried by the impactor is used as the measure of the specimen’s energy absorption performance.

5.4.5.2 Force attenuation and evaluation

The embedded sensor in the headform is capable of detecting the force transmitted \( F_t \) and the load cell in the Instron drop tester weight provides the impact force \( F_i \). Force-blocking effectiveness, which is commonly expressed as the attenuation factor, \( f_{att} \), for each impact can be calculated using the equation:

\[
f_{att} = \left(1 - \frac{F_t}{F}\right) \times 100
\]

(5.1)

where,

\( F_t \) is the transmitted force collected from the inner surface of helmet shell;

\( F \) is the impact force acting directly on the anvil without any specimen.

Force attenuation has been studied by many (Maach et al., 2004; Robinovitch et al., 2009; Dionne et al., 2002; Gong, 2010). A higher value of attenuation factor corresponds to less force being transmitted through the specimen, and a lower value of attenuation factor indicates that much of the impact force has been transmitted through the specimen (100% means no force transmitted and 0% means all forces transmitted).

5.4.5.3 Behaviour of transmitted force

Figure 5-13 shows the result when impacting on a single-layer flat composite with an input energy of 5J. The data were collected from the LIVMS. The first peak reflects the impact and the rest of the curve indicates the rebounding of the impact head.
5.4.5.4 Computation of energy absorption

The impact force (contact force or load) follows Newton’s second law of motion, which is expressed as follows:

\[ F = m a \]  \hspace{1cm} (5.2)

where, \( m \) is the mass of the impactor assembly and \( a \) is the measured deceleration of the impactor assembly during the impact process.

Energy absorption can be calculated by integrating the closed area of the load deflection curve (Gong, 2010). Graphically, the area beneath the load displacement curve gives the absorbed energy as in Figure 5-14.

In the current study, the trapezoidal method was used. In doing this, the curve upto the maximum load was divided into many smaller trapezoids. The total sum of the areas of the small trapezoids gives the energy absorption value of a particular curve.

\[ E = \sum S_i = \frac{1}{2} \sum_{i=0}^{n} (F_i + F_{i+1})(Y_{i+1} - Y_i) \]  \hspace{1cm} (5.3)

where, \( E \) is the absorbed energy, \( S_i \) is the trapezoidal area, \( F_i \) is the contact force applied on the specimen which can be calculated from Equation (5.3) and \( Y_i \) is the displacement increment at each time-fixed interval caused by the impact force.
5.5 Summary

In this chapter a detailed procedure for manufacturing a test rig for helmet testing has been described. Successful manufacturing of a test rig provides sufficient capability for the impact testing of the developed helmet shells.

A procedure for conducting impact testing using IDAS and LIVMS simultaneously has been established.

Helmet testing can be carried out on the side, back and top locations of the helmet shell. Riot helmet shells have double curvature surfaces. Due to the sufficient capabilities of testing helmet shells at different impact position, force blocking effectiveness at the different locations can be calculated and the behaviour of the transmitted force at different impact locations can be understood. Furthermore, energy absorption at different impact location can also be studied.

The next chapter will comment on the impact analysis conducted on developed riot helmet shells.
6.1 Introduction

A development of the helmet testing assembly and testing procedure was one of the objectives of the research which has been achieved and discussed in Chapter 5. The current chapter describes the evaluation of the developed helmet shells using the developed test rig. In this chapter, the low velocity impact test is discussed and this is carried out on the developed continuous textile reinforced helmet shells at different positions and with three different energy levels. For preliminary understanding, low velocity impact testing was carried out on 5-8-28 Kevlar flat composite panels. These impact tests were performed in order to understand the behaviour of the composite structure and for better understanding of the developed instrumental setup for data analysis. Impact testing was carried out on single and double piece helmet shells for analysing impact performances at different locations on the helmet shells. In the end, the influence of internal paddings is also highlighted.

6.2 Development of 5-8-28 Kevlar composite flat composite panels

Kevlar 5-8-28 angle-interlock fabric was used as the reinforcing phase in the flat composite panels, where the matrix was a combination of epoxy (Araldite LY5052) and hardener (Aradur 5052) mixed in the ratio of 100:38 (Huntsman, 2010). Three types of flat composite panel were manufactured from the woven fabrics, which are a one-layer composite, a two-layer composite and a three-layer composite. The two-layer and three-layer composites were further sub-divided in two categories according to the stacking orientation of the Kevlar fabric layers. The types of flat composite panel are shown in Figure 6-1.
In the 0/0 orientation two-layer flat panel composite, two pieces of angle-interlock fabric were stacked together in such a way that the warp of the second piece of AI-fabric was in the same direction as the warp of the first piece of AI-fabric. However, in the 0/90 orientation the warp of the second piece of AI-fabric was in a direction parallel to the weft of the first piece of AI-fabric. As similar stacking procedure was repeated for the 0/0/0 and 0/90/0 categories of three-layer composites in which three AI-fabric layers were stacked to produce composites. The composite specimens developed were further cut into 6cm by 6cm pieces for impact testing by means of a water-jet diamond cutter and can be shown in Figure 6-2.
6.3 Evaluation and results of flat panel testing

A mass of 4.66 Kg was dropped on to the flat composite panels with three different impact energies of 5.6J, 15.6J and 25.6J approximately. The impact testing was carried out on the developed test rig (shown in Figure 6-3) in order to understand the behaviour of flat composite panels.

![Figure 6-3 Impact testing on flat composite panel](image)

For this preliminary testing, flat composite panels were manufactured in such a way that the effect of laminate thickness due to layering and orientation can be studied based on energy absorption and force attenuation. The thicknesses of the laminates were measured and are shown in the following table.

**Table 6-1 Thickness of flat composite panels**

<table>
<thead>
<tr>
<th>Serial Number</th>
<th>One-layer composite</th>
<th>Two-layer composite</th>
<th>Three-layer composite</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0/90 Orientation</td>
<td>0/0 Orientation</td>
<td>0/90/0 Orientation</td>
</tr>
<tr>
<td></td>
<td>mm</td>
<td>mm</td>
<td>mm</td>
</tr>
<tr>
<td>1</td>
<td>0.97</td>
<td>1.88</td>
<td>1.98</td>
</tr>
<tr>
<td>2</td>
<td>0.96</td>
<td>1.89</td>
<td>1.8</td>
</tr>
<tr>
<td>3</td>
<td>0.95</td>
<td>1.92</td>
<td>1.99</td>
</tr>
<tr>
<td>4</td>
<td>0.97</td>
<td>1.84</td>
<td>1.92</td>
</tr>
<tr>
<td>5</td>
<td>0.94</td>
<td>1.93</td>
<td>1.8</td>
</tr>
<tr>
<td>6</td>
<td>0.98</td>
<td>1.86</td>
<td>1.94</td>
</tr>
<tr>
<td>Avg.</td>
<td>0.962</td>
<td>1.887</td>
<td>1.905</td>
</tr>
<tr>
<td>St. Dev.</td>
<td>0.015</td>
<td>0.034</td>
<td>0.085</td>
</tr>
<tr>
<td>CV%</td>
<td>1.53</td>
<td>1.83</td>
<td>4.48</td>
</tr>
</tbody>
</table>
6.3.1 Effect of laminate stacking and orientation on energy absorption

Four specimens from each of the five categories of flat composite panels were impacted with different impact energies. The absorbed energies have been converted to normalised energy absorbed. The average results have been tabulated in Table 6-2.

Table 6-2 Tests results for the energy absorption performance

<table>
<thead>
<tr>
<th>Sample</th>
<th>Impact energy (J)</th>
<th>Energy Absorbed (J)</th>
<th>Normalised Energy Absorbed (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>K</td>
<td>E</td>
<td>$E_N$</td>
</tr>
<tr>
<td>FS</td>
<td>5.59</td>
<td>3.825</td>
<td>3.978</td>
</tr>
<tr>
<td>FDS</td>
<td>5.56</td>
<td>4.020</td>
<td>2.110</td>
</tr>
<tr>
<td>FDD</td>
<td>5.53</td>
<td>4.037</td>
<td>2.140</td>
</tr>
<tr>
<td>FTS</td>
<td>5.58</td>
<td>4.026</td>
<td>1.472</td>
</tr>
<tr>
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<td>5.63</td>
<td>4.162</td>
<td>1.498</td>
</tr>
<tr>
<td>FS</td>
<td>15.62</td>
<td>9.961</td>
<td>10.358</td>
</tr>
<tr>
<td>FDS</td>
<td>15.58</td>
<td>9.946</td>
<td>5.221</td>
</tr>
<tr>
<td>FDD</td>
<td>15.53</td>
<td>9.946</td>
<td>5.272</td>
</tr>
<tr>
<td>FTS</td>
<td>15.51</td>
<td>9.976</td>
<td>3.648</td>
</tr>
<tr>
<td>FTD</td>
<td>15.47</td>
<td>9.953</td>
<td>3.582</td>
</tr>
<tr>
<td>FS</td>
<td>25.61</td>
<td>16.597</td>
<td>17.258</td>
</tr>
<tr>
<td>FDS</td>
<td>25.61</td>
<td>17.016</td>
<td>8.933</td>
</tr>
<tr>
<td>FDD</td>
<td>25.59</td>
<td>16.771</td>
<td>8.889</td>
</tr>
<tr>
<td>FTS</td>
<td>25.52</td>
<td>16.705</td>
<td>6.108</td>
</tr>
<tr>
<td>FTD</td>
<td>25.41</td>
<td>17.839</td>
<td>6.421</td>
</tr>
</tbody>
</table>

In the table, FS is the term for the average of single-layer or one-layer flat composite panels, FDS is the term for the average of double-layer or two-layer flat composite panels with the same orientation (0/0), FDD is the term for the average of two-layer flat composite panels with different orientation (0/90), FTS is the term for the average of triple-layer or three-layer flat composite panels with the same orientation (0/0/0), FTD is the term for the average of three-layer flat composite panels with different orientation (0/90/0), K is the impact energy just before the impact and is extracted from the IDAS’s velocity detector ($\frac{1}{2}mv^2$) at the time of impact, E is the absorbed energy and is calculated using the trapezoidal method, $E_N$ is the normalised energy absorbed and is obtained by dividing the absorbed energy of the laminates by the thickness of the respective laminates.
Figure 6-4 shows that the energy absorption is directly proportional to the impact energy. Further, it can be observed that the layering has a significant effect on the normalised energy absorption values. The composite panels having one fabric layer absorb the most energy compared with specimens having multiple layering. However, there is no significant difference observed in the energy absorption due to different orientations as
shown in Figure 6-5 (a), (b) and (c). The amount of material seems to be one of the important factors while designing riot helmet shell. The higher the thickness the less will be the energy absorption by the laminates. Further, the one-layer composite panel seems to be more flexible due to less thickness than the multi-layer composite panels. This seems one of the reasons why the one layer composite absorbs more energy.

6.3.2 Effect of laminate stacking and orientation on force attenuated factor

During an impact the force detected beneath of the specimen by the low impedance voltage mode system (LIVMS) is known as the transmitted force. It can be seen in Figure 6-6 and Figure 6-7 that the peak transmitted force increases with the increase of impact energy. The single-layer flat composite always transmits a higher force as compared to the other thicker four categories. Normalised transmitted force ($F_{\text{trans}}$) for each laminate type is obtained by dividing the transmitted force of the laminates by the thickness of the respective laminate.

Figure 6-6 Force transmitted (normalised) for flat composites
Figure 6-7 Normalised peak transmitted force of flat composite panels for (a) 5.6J impact (b) 15.6J impact and (c) 25.6J impact

In Figure 6-7, orientation has caused no significant trend as shown in the two-layer and three-layer composite panels irrespective of the impact energy. However, the higher the number of layers in a composite the smaller is the transmitted force. It must be noted that there is a significant difference between the one-layer composite and the two-layer composite results as compared to the two-layer and three-layer composite transmission impact testing results. This may be due to the fact that a one-layer composite is more flexible and unable to resist as compared to the multi-layer composites.

Table 6-3 shows the average force attenuation factor for all the five categories of flat composite panel for different impact energy levels. The Normalised attenuation factor ($f_{Natt}$) is obtained by using the normalised force transmitted in the calculations. The normalised force transmitted is obtained by dividing the force collected by the Dytran force sensor divided by the thickness of the laminates.
Table 6-3 Experimental results for the force attenuation factor

<table>
<thead>
<tr>
<th>Sample</th>
<th>Impact energy (J)</th>
<th>Impact Force without Specimen (kN)</th>
<th>Force Transmitted (kN)</th>
<th>Normalised Force Transmitted (kN)</th>
<th>Normalised Attenuation factor (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>K</td>
<td>F</td>
<td>(F_{\text{trans}})</td>
<td>(F_{\text{Ntrans}})</td>
<td>(f_{\text{Natt}})</td>
</tr>
<tr>
<td>FS</td>
<td>5.59</td>
<td>9.242</td>
<td>8.253</td>
<td>8.737</td>
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</tr>
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<td>9.242</td>
<td>7.643</td>
<td>4.080</td>
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</tr>
<tr>
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<td>7.613</td>
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<td>55.600</td>
</tr>
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<td>7.643</td>
<td>2.842</td>
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</tr>
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<td>7.584</td>
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</tr>
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<td>FDS</td>
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<td>13.721</td>
<td>7.170</td>
<td>53.784</td>
</tr>
<tr>
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<td>13.692</td>
<td>7.224</td>
<td>53.435</td>
</tr>
<tr>
<td>FTS</td>
<td>15.51</td>
<td>15.513</td>
<td>13.544</td>
<td>4.929</td>
<td>68.224</td>
</tr>
<tr>
<td>FTD</td>
<td>15.47</td>
<td>15.513</td>
<td>13.397</td>
<td>4.800</td>
<td>69.061</td>
</tr>
<tr>
<td>FS</td>
<td>25.61</td>
<td>19.666</td>
<td>18.649</td>
<td>19.214</td>
<td>2.300</td>
</tr>
<tr>
<td>FDS</td>
<td>25.61</td>
<td>19.666</td>
<td>18.088</td>
<td>9.379</td>
<td>52.311</td>
</tr>
<tr>
<td>FDD</td>
<td>25.59</td>
<td>19.666</td>
<td>18.000</td>
<td>9.423</td>
<td>52.083</td>
</tr>
<tr>
<td>FTS</td>
<td>25.52</td>
<td>19.666</td>
<td>18.038</td>
<td>6.522</td>
<td>66.837</td>
</tr>
<tr>
<td>FTD</td>
<td>25.41</td>
<td>19.666</td>
<td>18.029</td>
<td>6.410</td>
<td>67.408</td>
</tr>
</tbody>
</table>

Figure 6-8 Force attenuation factor for flat composites

For every type of flat panel composite developed, the percent force attenuated factor decreases with the increase of impact energy as shown in Figure 6-8, which seems due to more force being transmitted in the higher energy impacts. In Figure 6-8 and Figure 6-9, the force attenuation factor of single-layer composites is always less than for the multi-
layer composites irrespective of the impact energy. Three-layer composites, due to large amount of material, block more impact force as compared to the two-layer composites. Orientation in the samples showed no major trends in the two-layer and three-layer composite specimens in respect of the attenuation factor.

One of the important findings is that the percent force attenuation factor remains in very close range for the 5.6J, 15.6J and 25.6J impacts i.e. for one-layer composites it is between 2.30% to 5.47%, for two-layer composites it is between 52.08 % to 55.86% and in three-layer composites it is between 66.84% to 69.97%. This means that by increasing the number of Al-fabric layers in composite manufacturing, a significant amount of force can be attenuated.

Figure 6-9 Force attenuation factor of flat composite panels (a) for 5.6J Impact (b) 15.6J Impact (c) for 25.6J Impact
6.3.3 Summary of results for 5-8-28 Kevlar flat panel composites

The flat composite panels were manufactured in order to understand the behaviour of the fabric layering effect on the composite properties and secondly the effect of layering orientation in the multilayer composites.

The experiments were conducted in a particular range of impact energies from 5.6 Joules to 25.6 Joules and it can be seen that in this particular range of low velocity impacts, the one fabric layer composite shows different behaviour as compared to the multi-layer counter parts. The one-layer composite being more flexible in nature as compared to the two-layer composites and the three-layer composites and it absorbs more impact energy and more force transmits to the headform as compared to the two-layer and three-layer composite panels. It can be seen that the orientation of fabric in the composites is not an influential factor for this particular range of impacts.

Furthermore, the single-layer flat composite panel exhibits lower force attenuation factor when compared with multi-layer flat composite panels. It can be noted that the increase of a single-layer in the composite structure can increase the force blocking performance.

Riots helmets are usually used in combination with expandable polystyrene foam as and internal paddings. Suitable material thickness can effectively enhance the impact properties of single-piece riot helmet shells.

6.4 Characteristics of helmet shell laminates

Flat composite panels prepared in section 6.2 and the helmet shells developed in section 4.5.4 have distinguishing inherent properties, namely; density, thickness and curvature intensity. Both varieties of laminate were developed using the vacuum bagging technique. The shape of the composite structure and shearing of fabric in the vacuum-assisted draping technique for helmet shells seems to be responsible for these parameters. Before analysing impact testing results on the helmet shells, understanding of these parameters is necessary. These parameters have been measured and discussed in next sections.
6.4.1 Thickness of shell at different locations

For measuring the change of thickness throughout the developed single-piece helmet shell, three different sections based on the impact location were focused i.e. the helmet top, the helmet side and the helmet back. Samples from these locations were extracted by cutting a helmet shell into small pieces. Thicknesses are measured from different locations of the helmet shell by micrometer screw gauge and the results are shown in Appendix A (Table A-7).

![Figure 6-10 Thickness of developed single-piece riot helmet shell](image)

It can be seen from Figure 6-10 that the helmet top location has significantly less thickness as compared to the other two locations. The fundamental reason for this change of thickness was the shearing of the angle-interlock fabric while the vacuum-assisted draping technique was followed by vacuum bagging. The top helmet location is the non-sheared area of the draped fabric, whereas the side helmet location and the back helmet location have the shearing phenomenon while draping. Further, during the vacuum bagging process a non-sheared portion of angle-interlock fabric has more space available to be compressed and this can reduce the thickness of the composite panels.

6.4.2 Density of shell at different locations

Thickness measurement of the pieces in section 6.4.1 was followed by density measurement. The density was calculated according to BS EN ISO 1183-1:2004 (British Standard, 2004) as discussed in section 3.5.3 and the results can be seen in Appendix (Table A-8).
In Figure 6-11, no significant change in density has been shown at different impact locations and the densities of the developed helmet shell at different locations are similar to each other. It seems that the densities at different locations are in a similar range. This result is a positive sign towards the manufacturing of helmet shell by the vacuum bagging technique since the density of the helmet shell seems similar at different locations of the helmet shell. This result also indicates that helmet shells produced by vacuum bagging have an edge over the hand resin painted helmet shells. However, the density near to the edge where the fabric shearing effect is visible, must be higher than the rest of the helmet.

![Figure 6-11 Density of developed single-piece riot helmet shell](image)

**6.4.3 Helmet shell curvatures at impact locations**

Riot helmet shells have doubly curved surfaces and these bi-curvatures are important factors in impact analysis. A study has been carried out similarly to Roedel (Roedel, 2008) in order to find the curvatures at the different impact locations.

A geometric model was used in order to approximate the curvature at different locations on the helmet shell. In the current study, the bi-curvatures of the surfaces were estimated by designing the helmet shell in Rhinoceros, a 3-D modelling program for Microsoft Windows. The designing of a helmet shell is discussed in the Section 7.2. Figure 6-12 schematically illustrates the geometric model used for the curvature evaluation.
The shell curvature is approximated by calculating the bi-radial curvature at individual impact locations. The curvature is defined by the inverse of the radius \( R \) as in the equation.

\[
C = \frac{1}{R} \tag{6.1}
\]

In Figure 6-12,
- \( d \) is the height of the arc
- \( l \) is the chord length
- \( R \) is the radius
- \( C_1 \) and \( C_2 \) are the bi-radial curvatures
- \( P \) is the point where the two arcs that are perpendicular to each other intersect (shown dotted)

The radius is calculated by using the Pythagoras theorem is expressed in following equation.

\[
R = \left( \frac{d}{2} + \frac{l^2}{8d} \right) \tag{6.2}
\]
The height of arc d and the arc length l were measured at the approximate impact locations in Rhinoceros. Table 6-4 shows the calculated curvatures of the different impact positions. It can be observed that the helmet top has the highest curvatures and the helmet side has the lowest curvatures in both the directions.

**Table 6-4 Curvature at different impact locations**

<table>
<thead>
<tr>
<th>Location</th>
<th>Shell Curvatures (mm⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C₁</td>
</tr>
<tr>
<td>Side</td>
<td>0.00558</td>
</tr>
<tr>
<td>Top</td>
<td>0.00856</td>
</tr>
<tr>
<td>Back</td>
<td>0.00643</td>
</tr>
</tbody>
</table>

Figure 6-13 shows the relationship between the approximated $C_1$ and $C_2$ curvatures for individual impact locations. The intersection point P represents the bi-radial curvature of the particular impact position. $P_1$, $P_2$ and $P_3$ represent the intersection points at side location, back location and the top locations respectively. It can be observed that $P_3$, which represents helmet shell top location, shows the highest bi-radial curvature, whereas $P_1$ provides the lowest bi-radial curvature at the helmet shell side.

6.5 Experimental results of helmet shell testing

The developed riot helmet shells were impacted at three different locations namely; the helmet top, the helmet side and the helmet back with three different impact energies of
5.6J, 15.6J, 25.6J approximately. Testing conditions were kept similar to the flat composite panel testing. Two different categories of helmet shell were developed. One was the single-layer helmet shell developed from a single-layer of 5-8-28 angle-interlock woven fabric as discussed in Chapter 5. The second variety of helmet shell developed was the double-layer helmet shell. This variety was produced by doubling the number of fabric layers in the vacuum assisted draping technique. Furthermore, due to the limitations (availability) of the double-layer helmet shells only 25.6J impact tests were conducted at different locations. The helmet shell categories along with the impact locations can be seen in Figure 6-14.

![Diagram showing helmet shell categories and impact locations](image)

**Figure 6-14 Categories of developed helmet shells and location for impact testing**

![Image showing impact on top location at riot helmet shell](image)

**Figure 6-15 Impact on top location at riot helmet shell**
6.5.1 Energy absorption

Helmet shells were placed on the developed test rig and were impacted with three different impact energies at different impact locations. For each set of experiments for a particular energy level, at least three helmet shells were used. The results were extracted using the Impulse data acquisition system and Low impedance voltage mode system. The average results of each set of experiments have been tabulated in Table 6-5 for energy absorption.

Table 6-5 Experimental results for the energy absorption performance

<table>
<thead>
<tr>
<th>Type of helmet shell</th>
<th>Location</th>
<th>Impact energy (J)</th>
<th>Energy Absorbed (J)</th>
<th>Energy Absorption Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single-layer helmet shell</td>
<td>Back</td>
<td>5.60</td>
<td>3.59</td>
<td>64.12%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15.59</td>
<td>9.45</td>
<td>60.59%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>25.64</td>
<td>16.40</td>
<td>63.96%</td>
</tr>
<tr>
<td>Double-layer helmet shell</td>
<td></td>
<td>25.62</td>
<td>18.19</td>
<td>70.97%</td>
</tr>
<tr>
<td>Single-layer helmet shell</td>
<td>Side</td>
<td>5.54</td>
<td>3.43</td>
<td>61.98%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15.59</td>
<td>9.45</td>
<td>60.59%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>25.64</td>
<td>15.77</td>
<td>61.49%</td>
</tr>
<tr>
<td>Double-layer helmet shell</td>
<td></td>
<td>25.63</td>
<td>16.04</td>
<td>62.57%</td>
</tr>
<tr>
<td>Single-layer helmet shell</td>
<td>Top</td>
<td>5.60</td>
<td>3.91</td>
<td>69.81%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15.53</td>
<td>10.24</td>
<td>65.89%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>25.61</td>
<td>17.07</td>
<td>66.65%</td>
</tr>
<tr>
<td>Double-layer helmet shell</td>
<td></td>
<td>25.58</td>
<td>18.36</td>
<td>71.76%</td>
</tr>
</tbody>
</table>

Figure 6-16 Energy absorption at different helmet locations on single-layer helmet shells
Figure 6-17 Energy absorption at different locations on single-piece helmet shells (a) for 5.6J impact (b) for 15.6J impact and (c) for 25.6J impact (d) on double-layer helmet shells for 25.6J impact

Where, in Figure 6-17, HB is the term for the average of the results from the back impact location of the one-layer helmet shells, HS is the term for the average of results from the side impact location of the one-layer helmet shells, HT is the term for the average of the top impact location of the one-layer helmet shells, DHB is the term for the average of results from the back impact location of the double-layer helmet shells, DHS the is term for the average of results from the side impact location of the double-layer helmet shells, DHT is the term for the average of the top impact location of the double-layer helmet shells. E/K is the ratio of the absorbed energy to the impact energy.

Figure 6-16 shows that the energy absorption is directly proportional to the impact energy. The top location of the helmet shell irrespective of the impact location absorbs more energy with the increase of impact energy. A significant trend amongst the different locations of helmet shells is shown in Figure 6-17. In single-piece helmet shells, more energy is absorbed at the top impact location whereas, the helmet side impact location absorbs the least amount of energy during an impact. This may be due to the fact that energy is dissipated over a wider area since the helmet shell top position is at a longer distance from the shell edge. Table 6-5 also highlights the higher energy absorption performance at the top impact location as compared to the other two locations under the same impact. However, in both varieties of helmet shell, the side location absorbs the least amount of energy as compared to the other two locations. It should be noted, as discussed
In Section 6.4.3, the helmet top location has the maximum curvature intensity. It seems that curvature intensity is also influencing in energy absorption at the top location. In general the helmet shell is a dome-shape structure. Dome-shape structures are normally used in construction due to their inherent characteristics of supporting both in tensile as well as in compressive loads. Experimentation shows that in single-piece helmet shells, energy absorption performance at the helmet shell top location is always higher followed by the back location and the side location. This phenomenon seems to be also true for the double-layer helmet shells.

### 6.5.2 Peak transmitted force

In Figure 6-18, it can be observed that the peak transmitted force is directly proportional to the impact energy. The peak transmitted force is measured using low impedance voltage mode system.

![Figure 6-18 Peak transmitted force at different level of impact energy (a) at helmet back location (b) at helmet top location (c) at helmet side location](image-url)
Figure 6-19 shows that the helmet shell top location transmits significantly less peak force. For double-layer helmets, the helmet shell top location also transmits significantly less force as compared to the other two locations. In Table 6-6, double-layer helmets at a similar impact energy of 25.6 Joules transmits less force to the headform than the single-piece helmet shells. Moreover, the double helmet shells have more material at the impacted sites as compared to the single-layer helmet shells. If these results are normalised with respect to the thickness, the double-helmet shells will show less force is transmitted compared with the single-piece helmet shells.
6.5.3 Force attenuated factor

Table 6-6 shows the force attenuation factor at the three locations due to different impact energy levels.

<table>
<thead>
<tr>
<th>Type of helmet shell</th>
<th>Location</th>
<th>Impact Energy</th>
<th>Force on anvil without specimen</th>
<th>Transmitted Force</th>
<th>Attenuation factor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>E (Joules)</td>
<td>(F_{\text{trans}}) (kN)</td>
<td>(F) (kN)</td>
<td>(f_{\text{att}}) (%)</td>
</tr>
<tr>
<td>Single-layer helmet shell</td>
<td>Back</td>
<td>5.60</td>
<td>9.176</td>
<td>7.809</td>
<td>14.895%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15.57</td>
<td>15.564</td>
<td>13.887</td>
<td>10.777%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>25.64</td>
<td>19.843</td>
<td>18.354</td>
<td>7.503%</td>
</tr>
<tr>
<td>Double-layer helmet shell</td>
<td></td>
<td>25.62</td>
<td>19.843</td>
<td>17.956</td>
<td>9.510%</td>
</tr>
<tr>
<td>Single-layer helmet shell</td>
<td>Side</td>
<td>5.54</td>
<td>9.242</td>
<td>7.842</td>
<td>15.151%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15.59</td>
<td>15.513</td>
<td>13.942</td>
<td>10.127%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>25.64</td>
<td>19.666</td>
<td>18.148</td>
<td>7.720%</td>
</tr>
<tr>
<td>Double-layer helmet shell</td>
<td></td>
<td>25.63</td>
<td>19.666</td>
<td>17.915</td>
<td>8.905%</td>
</tr>
<tr>
<td>Single-layer helmet shell</td>
<td>Top</td>
<td>5.60</td>
<td>9.463</td>
<td>6.994</td>
<td>26.087%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15.53</td>
<td>15.875</td>
<td>13.292</td>
<td>16.269%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>25.61</td>
<td>20.381</td>
<td>18.028</td>
<td>11.544%</td>
</tr>
<tr>
<td>Double-layer helmet shell</td>
<td></td>
<td>25.58</td>
<td>20.381</td>
<td>17.431</td>
<td>14.473%</td>
</tr>
</tbody>
</table>

In Figure 6-20, it can be observed that the force attenuation factor decreases with the increase of impact energy. This is due to the fact that more force is being transmitted through the material in higher energy impacts. It has been observed that there has been no significant difference in the force attenuation factor at the side and back impact locations. Moreover, the force attenuation factor at top of the helmet shell is always higher than at the side and back impact locations as shown in Figure 6-20 and Figure 6-21. This may be due to the continuity of the helmet shell at the top impact location, where due to longer distances from the shell edge helmet shell the top location provides a larger volume of shell material, so enhances the ability of having greater blocking of impact force. Further, the highest curvature intensity of the top impact location seems to have an influence on the force attenuation factor and less force is transmitted in the high curvature region of helmet shell. The double-layer helmet shell also behaves in the same way as the single-piece helmet shells with a higher force percentage attenuation factor due to the greater amount of fabric in these helmet shells as shown in Figure 6-21. Moreover, double-layer helmet
shells show a greater force attenuation factor as compared to the single-layer helmet shells with similar 25.5 Joules impacts.

Figure 6-20 Force attenuation factor at different impact location on helmet shell
6.5.4 Helmet shell with internal padding

In order to study the influence of padding inside a single-layer helmet shell, impact testing was carried out at different locations on the helmet shell with approximately 25.6 Joules of impact energy. Due to its easy availability, expanded polystyrene foam (EPS) was used as internal padding for the helmet shells. EPS is commonly used in energy management for protective helmets (Liu et al., 2003). The results of these experiments are also discussed.
6.5.4.1 Influence of internal padding on energy absorption

The results for the energy absorption are shown in Figure 6-22. Three individual tests at each impact location were conducted by using around 25.6 Joules of impact energy. It can be observed that the percentage energy absorption increases with the use of internal padding (expanded polystyrene foam) at all the impact locations. On average, there is an increase in the results of energy absorption performance by 1.3 times at the side location, 1.3 times at the back location and 1.2 times at the top helmet location due to the use of internal padding. Internal padding always enhances the energy absorption in the protective helmets.
6.5.4.2 Influence of internal padding on force attenuated factor

The results for the force attenuation factor are shown in Figure 6-23. The force attenuation factor increases many times at all the impact location by the use of expanded polystyrene foam. It can be observed on average there is an increase in the force attenuation factor at the side location by 10 times, at the back impact location by 8.9 times and at the top impact location by 6.2 times the value as compared to the same location without the use of padding. This result shows the importance of internal padding in a riot police helmet shell. The helmet shell coupled with internal padding provides vital force attenuation.
Figure 6-23 Force attenuated factor with and without internal padding at (a) side location (b) back location (c) top location

6.6 Suggestions for helmet shell improvement

6.6.1 Optimisation of helmet shell top location

Impact performance of the continuous textile reinforced helmet shells is influenced by the impact location. The Helmet top position seems to be the least vulnerable impact position on the helmet shell. This may be due to the two reasons: firstly the distance of the impact top location from the shell edge is greater than the other two locations. Due to fact the impact is distributed to a wider area thus increasing the impact performance. Secondly, the helmet top location has the greater shell bi-curvature. Due to this reason, the helmet top surface requires more impact force to deform and due to this reason usually less force will be transmitted to the head. The helmet shell top position was found to be the least
threatening impact position and it is very difficult to offer any further suggestions for the improvement in impact properties.

6.6.2 Optimisation of helmet shell side and back location

The helmet side and back impact locations attract more attention compared to the top location for better impact protection. Improving the helmet shell stiffness could result in better impact performance. Overall helmet stiffness can be increased by three different methods.

Firstly, an increase in the curvature intensity at the helmet shell side and back impact locations. Force attenuation factor suggests that the impact top location due to higher curvature intensity results in better impact protection.

Secondly, more protection can be achieved by adding more layers of fabric particularly at these impact locations. However, the major disadvantage of doing this will be the increase of helmet shell mass. According to PSDB Protective Headwear Standard for UK Police (Malbon and Croft, 2004), complete helmet mass should not exceed to 1.75 kg.

Thirdly, by selecting suitable high density foam as protective padding which can absorb a greater amount of impact energy per unit volume. Discussion of various varieties of internal padding has been carried out in Section 2.7.2 and Section 6.5.4 and shows that uses of internal padding greatly influence the properties, for instance, the energy absorption and the force attenuation factor.

6.7 Comparison of developed helmet shells

A brief comparison of the developed helmet shells has been carried out with the helmet shell pieces. Due to the non-availability of enough testing material, the testing has been shortened to only 25.6 Joules impacts at the helmet shell top position. Figure 6-24 (a) shows the thermoplastic helmet and Figure 6-24 (b) shows the multi-piece composite helmet shells.
Figure 6-24 Original helmet pieces (a) Thermoplastic helmet shell (b) Multi-piece composite helmet shell

Figure 6-25 Helmet shell comparison for transmitted force

Figure 6-26 Helmet shell comparison for energy absorption
The results have been extracted using IDAS and LIVMS. Further, the average thicknesses at the top of the thermoplastic and multi-piece helmet shells were 4.46 mm and 3.32 mm respectively. The average results have been normalised by thickness and shown in Figure 6-25 for the force attenuation factor and in Figure 6-26 for energy absorption. The normalised results show that developed single-piece helmet shells show better energy absorption capabilities than the original specimens.

6.8 Summary
The fabricated riot helmet shell test rig has been fully utilised for the impact testing. In this chapter, physical impact testing has been carried out on flat composites panels (developed in Chapter 3) and on the continuous textile reinforced developed helmet shells (innovated and manufactured in Chapter 5).

Impact performance of 5-8-28 Kevlar flat composite panels has been summarised in section 6.3.3. A single-layer flat composite panel absorbs more energy and also transmits more force as compared to the other multilayer flat composite panels. The reason behind this is the amount of material. Thicker material transmits less force to the headform and causes less damage to the head.

One of the important findings is that the helmet shell impact properties have been greatly influenced by the curvature intensity. Helmet top impact location is less vulnerable to impact than the helmet shell side and back surfaces. Moreover, in this chapter, suggestions have been made for further improvements of the overall impact properties of riot helmet shells.

Protective padding significantly affects the impact properties of riot helmet shells. It can be seen that a single-layer helmet shell with EPS foam effectively blocks the impact force and enhances the force attenuation factor. Selection of the appropriate thickness should be based on the overall impact properties of the riot helmet. Moreover, the thickness of single-piece helmet shells should be such that it can absorb and distribute the impact energy to a wider area of the protective padding.

A brief comparison with original helmet shell pieces also recommends the trend for better energy absorption capabilities of the developed helmet shell.
7.1 Brief introduction of ABAQUS

ABAQUS is engineering software that provides the facility to create ABAQUS models, to run and monitor the progress of analyses, and to evaluate the results from ABAQUS simulations (The University of Manchester, 2009). In this study the ABAQUS/Explicit product was used which has three stages namely pre-processing, simulation and post processing. One of the advantages of ABAQUS/Explicit as used is that it can translate or import geometries into the ABAQUS/CAE environment. Further, ABAQUS/Explicit is used for simulating impact problems (The University of Manchester, 2009). Pre-processing is creating an input file for ABAQUS simulation in the ABAQUS/CAE environment. Simulation is run as a background process in which the ABAQUS/Explicit solves the numerical problem defined in the simulation. Post-processing is usually carried out by using a visualisation module of the ABAQUS/CAE processor. Results are calculated and analysed in post-processing.

In finite element analysis actual geometries of the structures have to be first discretised by using finite elements. Each element represents a particular portion of the physical structure. Finite elements are joined together by nodes and the collection of nodes and elements are known as a mesh. The ABAQUS/CAE environment is divided into many different functional units known as modules.

In each module a specific modelling task has to be assigned (The University of Manchester, 2009). In the part module, parts are created either by sketching or by importing the geometry of the structure into ABAQUS/CAE environment. In the property module, a section is created and assigned to the parts. These sections contain material definitions for a particular region or part as required. An ABAQUS model has only one assembly and in the assembly module all the parts are positioned, instances (the replica of the parts) are created and positioned according to the global coordinate system to form an assembly. A step is a sequence for capturing change in a model. In the step module, steps are created and configured for analysis. These steps are directly related to the output request. There can be a number of steps in an ABAQUS model. In the interaction module, interactions within an assembly are created based on its mechanical properties. The
behaviour of two different surfaces for instance, constraints and contacts are created in the interaction module. Loads, boundary conditions and predefined fields are applied in the load module. Loads and boundary conditions affect a lot of the results of the analysis and also they are step dependent. The mesh module is one of the most important modules by which finite element meshes are created onto the assembly. Mesh size and shape also has an effect on the analysis. Jobs are submitted for analysis and monitoring in a job module. The visualisation module provides a graphical display of the finite element models and results.

In ABAQUS Lagrangian, material is used in dynamic analysis, due to this the elements remain attached to the meshes throughout the analysis and do not flow out of the element boundaries (The University of Manchester, 2009). ABAQUS uses the central difference rule to integrate the equation of motion explicitly through time. It uses the kinematic condition of one increment to calculate the kinematic condition of the next increment.

7.2 Creation of geometries for impact simulation

7.2.1 Riot helmet shell geometry

To create the mould surface in Chapter 4, a helmet shell tool was used for the creation of a fibre-glass mould. This was the same helmet shell tool as used by Roedel and Chen in their research (Roedel, 2008) for FE mould design and carried out finite element analysis in the MSC Marc Mentat software. In the current research, ABAQUS was preferred over MSC Marc Mentat due to its easy Windows-user interface. It is impossible to convert the MSC Marc Mentat output file extension (*.mud) into ABAQUS (*.iges) (Anonymous, 2008). For this purpose, it was necessary to convert and redesign the helmet shell geometry based on the helmet shells developed in Chapter 4. Cartesian coordinates were required for the input in Abaqus software. Different options were planned and finally the Marc Mentat (*.mud) file extension is converted into (*.dat) file format by the Marc Mentat itself. This file is then opened as a text file (*.txt) in Microsoft WordPad. The file contains nodal coordinates in exponential form in file format (*.txt). These coordinates were then imported into Microsoft Excel and transformed into a Cartesian coordinate system (X, Y, Z).

The re-creation of the riot helmet shell geometry based on the developed helmet shells has been described in steps.
7.2.1.1 Generation of point clouds

Half helmet shell coordinates in form of (X, Y, Z) were entered into the Rhinoceros software one by one, as point clouds. In this process, half helmet shell coordinates were inserted in 3D space and are shown in Figure 7-1.

![Figure 7-1 Half helmet shell nodes](image)

7.2.1.2 Surface generation

Points were joined together horizontally and vertically to form a half helmet shape. After these joining processes, surface generation was carried out individually in all the rectangles of the half head form. The reason for doing this individually was the curvature of the helmet shell which varies at different locations as shown in Figure 7-2.

![Figure 7-2 Surface generation of half helmet shell](image)
7.2.1.3 Thickness to shell surface

The next step was to give thickness to the half shell. The helmet shell manufactured in Chapter 5 has an average thickness of 1mm. A scaling command was used to give thickness to all squares having surface generated as 1 mm of the shell as in Figure 7-3. This method of giving thickness can be used in future for doing analysis based on any desired helmet thickness.

Figure 7-3 Half helmet shell with thickness 1 mm

7.2.1.4 Mesh generation

The next stage was the generation of mesh in each rectangle of the half helmet shell shape. Individual surfaces were generated in the top and on the bottom layer of the helmet shape and not in between the layers. Figure 7-4 shows the surface generated helmet shell shape.

Figure 7-4 Half helmet shell shape with individual meshing
7.2.1.5 Mirror to complete helmet shell shape

In the last stage another half of the helmet was mirrored in the Rhinoceros software to achieve a full riot helmet shell shape with a uniform thickness of 1 mm as in Figure 7-5. After this, the complete helmet shape was exported in *.iges format and imported to ABAQUS as a solid part shown in Figure 7-6.

![Figure 7-5 Riot full helmet shell shape in Rhinoceros (a) without render (b) with render](image)

![Figure 7-6 Helmet shell views in ABAQUS (a) front (b) side (c) back (d) top](image)
7.2.1.6 Creation of internal and external faces

The helmet shell developed in Figure 7-6 was imported in *.iges format as a solid part with a large number of faces which were developed during the creation of the geometry of this shape. Every face was joined precisely with the neighbouring ones leaving the impact position and the edge of the helmet shell (shown in Figure 7-7). The edges were left in order to have nodes on the edge which can be used for applying boundary conditions.

![Helmet shell with combined faces](image)

Figure 7-7 Helmet shell with combined faces

The creation of internal and external faces is one of the most important aspects of the work carried out in order to have homogeneous meshing. In Figure 7-7, a portion is left on the internal and the external faces at the site of impact. At this particular area, high density meshing can be obtained on the contact position and uniform meshing elsewhere on the helmet shell geometry. This technique of meshing has been used in all the models developed for this study.

7.2.2 Geometry of impactor shape

The impactor was designed in ABAQUS as in Figure 7-8, as a flat rigid cylindrical impactor. The dimensions of the impactor were 67.5 mm height and 25 mm diameter, similar to the impactor used in test rig.

![Flat impactor](image)

Figure 7-8 Flat impactor
7.2.3 Geometric model of headform

The headform coordinates were taken from EN 960:2006 (The European Standard, 2006) and also discussed in Section 6.4.2. The headform standard is also used in the British riot helmet shell standard (Malbon and Croft, 2004), where the helmets are also placed on the headform for impact testing. Headform coordinates were entered via Rhinoceros software and the steps discussed in section 7.2.1 were repeated. The headform was made as a solid material. Different views of the developed headform are shown in Figure 7-9.

![Figure 7-9](image)

**Figure 7-9** (a) Half headform wire structure (b) Complete headform wire (c) Complete solid headform in ABAQUS

Further, a small part was created and attached on the top of the headform by means of a tied command in ABAQUS. This was a replica of the force sensor. In the actual impact test, a force sensor was tied by a steel bolt beneath the helmet shell and attached to the headform. A force sensor having a thickness 25 mm, similar to the force sensor was designed and is shown in Figure 7-10.

![Figure 7-10](image)

**Figure 7-10** Surface representing force sensor
7.2.4 Transverse isotropic properties

Transverse isotropy is a sub-class of the orthotropic property of materials in which materials have one plane as an isotropic plane (Kaw, 2006; Mallick, 2008; The University of Manchester, 2009). Due to the geometry of the Kevlar composite angle-interlock fabric 5-8-28, it was decided to assume the material as being transversely isotropic. In the current study, the thickness of the helmet shell was assumed to be as an isotropic plane. Figure 7-11 shows plane 2-3 as a transverse isotropic plane.

![Figure 7-11 Transverse isotropic plane](image)

In the transverse isotropic class of orthotropic material there are only 5 independent constants. The properties obtained from Chapter 4 and were calculated according to the method used by several authors (The University of Manchester, 2009; Kaw, 2006; Mallick, 2008).

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density of Kevlar Composite Material</td>
<td>$\rho = 1.229 \text{ gm/cm}^3$</td>
</tr>
<tr>
<td>Weft Modulus, $E_1$</td>
<td>$36938.301 \text{ MPa}$</td>
</tr>
<tr>
<td>Warp Modulus, $E_2 = E_3$</td>
<td>$7793.701 \text{ MPa}$</td>
</tr>
<tr>
<td>Poisson Ratio (weft to warp), $v_{12}$</td>
<td>$0.356$</td>
</tr>
<tr>
<td>Poisson Ratio (warp to weft), $v_{21}$</td>
<td>$0.075$</td>
</tr>
<tr>
<td>Poisson Ratio (warp to thickness), $v_{23}$</td>
<td>$0.108$</td>
</tr>
<tr>
<td>Inplane Shear Modulus, $G_{21} = G_{12} = G_{13}$</td>
<td>$1379.255 \text{ MPa}$</td>
</tr>
<tr>
<td>Inplane shear warp to thickness, $G_{23}$</td>
<td>$3516.808 \text{ MPa}$</td>
</tr>
</tbody>
</table>

Where,

- $v_{12} = (\nu_f \times V_f) + (\nu_r \times V_r)$
- $v_{21} = (E_2 / E_1) \times v_{12}$
- $v_{23} = v_{12} \times ((1 - v_{21}) / (1 - v_{12}))$
- $G_{23} = [(E_2) / (2 \times (1 + v_{23}))]$
\( V_f \) is Poisson ratio of the fibre material, Kevlar 49 = 0.36 (Kevlar, 2011)

\( V_r \) is Poisson ratio of the matrix material, Araldite LY5052 and Aradur 5052) = 0.35 (Huntsman, 2010)

The above calculated results were necessary for the impact simulation.

### 7.3 Meshing and boundary conditions

In this model a tetrahedral shape of mesh is used because it is the most suitable mesh shape for three dimensional complex parts and almost every three dimensional part can be made by this mesh shape (The University of Manchester, 2009). Further, Encastre boundary conditions were given at the neck and helmet shell edge as shown in Figure 7-13.

![Figure 7-12 Tetrahedral shape](image)

**Figure 7-12 Tetrahedral shape**

![Figure 7-13 Simulation showing (a) Boundary conditions (b) Meshed parts](image)

**Figure 7-13 Simulation showing (a) Boundary conditions (b) Meshed parts**

A complete layout of the simulation can be viewed in Figure 7-14.
Creation of FE models for different impact locations

The impact energy levels were set to be 5.5 Joules, 15.5 Joules and 25.5 Joules with the flat cylindrical impactor having a mass of 4.66 kg. These levels of energy were set in order to compare the model with the experimental results obtained in Chapter 7. Furthermore, the helmet shell was impacted at three different locations i.e. the top location, the side location and at the back location. From the test simulation it was noted that a 3ms analysis time is sufficient to investigate the impact performance of developed shell models. Impact locations can be shown at three different models in Figure 7-15.
Figure 7-15 Schematic illustration of the FE impact models: (a) Model for Top impact location in assembly form (b) Model for Top impact in meshed form (c) Model for Side impact location in assembly form (d) Model for Side impact in meshed form (e) Model for Back impact location in assembly form (f) Model for Back impact in meshed form

7.5 Simulated results and validation with experimental results

In this section, the simulated results are put together with the corresponding experimental results to look for similarities between them. FE simulation has been executed with three different impact energies 5.5J, 15.5J and 25.5J. Impact was conducted at three different locations on the developed helmet shells namely, the top location, the back location and
the side location. In this way 9 models have been simulated and the results for the percentage energy absorption are illustrated in Table 7-1.

Table 7-1 Simulated results for helmet shells (thickness 1mm) for energy absorption

<table>
<thead>
<tr>
<th>Impact Location</th>
<th>Energy of Impactor (J)</th>
<th>Absorbed Energy by the helmet (J)</th>
<th>Energy Absorption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Helmet Top</td>
<td>25.5</td>
<td>21.038</td>
<td>82.502%</td>
</tr>
<tr>
<td>Helmet Back</td>
<td>25.5</td>
<td>19.485</td>
<td>76.411%</td>
</tr>
<tr>
<td>Helmet Side</td>
<td>25.5</td>
<td>19.108</td>
<td>74.932%</td>
</tr>
<tr>
<td>Helmet Top</td>
<td>15.5</td>
<td>12.270</td>
<td>79.161%</td>
</tr>
<tr>
<td>Helmet Back</td>
<td>15.5</td>
<td>11.941</td>
<td>77.039%</td>
</tr>
<tr>
<td>Helmet Side</td>
<td>15.5</td>
<td>11.826</td>
<td>76.296%</td>
</tr>
<tr>
<td>Helmet Top</td>
<td>5.5</td>
<td>4.613</td>
<td>83.871%</td>
</tr>
<tr>
<td>Helmet Back</td>
<td>5.5</td>
<td>4.389</td>
<td>79.791%</td>
</tr>
<tr>
<td>Helmet Side</td>
<td>5.5</td>
<td>4.305</td>
<td>78.266%</td>
</tr>
</tbody>
</table>

Figure 7-16 shows that with higher energy impacts, helmet top surface absorbs more impact energy. The helmet shell side absorbs the least amount of energy. At every location energy absorption is increased with the increase of impact energy. Moreover, the percentage energy absorption in Figure 7-17 also shows similar trends at each energy level. These results show that the helmet top location is the least vulnerable position against impact. More importantly, these results are very similar to the results obtained from the experimental test data.

Figure 7-16 Energy absorbed by the helmet shell (thickness 1mm) at different locations
Figure 7-17 Percent energy absorption for helmet shell (thickness 1mm)

Figure 7-18 Comparison of energy absorption results for 1mm thick helmet shells at different helmet locations

Figure 7-18 shows that the simulated energy absorption has similar trends as compared to the experimental results discussed in Section 6.5.1. The side location seems to absorb less impact energy as compared to the other two locations. This may be due to the same reasons (as discussed in Section 6.5.1) and the curvature intensity is influencing the energy absorption properties.
It can be observed that simulated and experimental percentage energy absorption shares similarities. Simulated results have greater values than experimental results, and simulated trends are near and similar to the experimental results. Furthermore, the results for percentage energy absorption in Table 7-1 and in Section 6.5.1 are compared and shown in Figure 7-19.
The transmitted force at different helmet locations has been obtained and compared with the experimental results. Transmitted force has been obtained from the top surface of the force sensor which touches the inside surface of the helmet shell.

In Figure 7-20, it can be observed that the force transmitted also has a similar trend. However, there is difference in the magnitude of the peak force transmitted. This seems to be true being due to the fact that in simulations the helmet shell has been taken as one composite entity with a solid surface whereas, in reality the composite structure is made-up from Al-fabric which transfers the load throughout its inherent weave structure. Moreover, the reason to explain this kind of difference could be that FE simulation is a much simpler approach to the real situation, therefore, an ideal match between experimental and simulation in the results will not be justifiable due to high complexity of the experimental setup.
Figure 7-20  Comparison of force transmitted results at different locations on 1mm thick helmet shells (a) Top Location (b) Back Location (c) Side Location
7.6 Influence of helmet thickness

Helmet shells developed in section 7.2.1 have a thickness of 1 mm, the same as the helmet shells developed in Section 4.6. In order to understand the influence of helmet thickness on the energy absorption and force transmission, 18 more impact models have been designed using the method discussed in section 7.2.1. The difference between these models and the 1 mm shell thickness simulated models discussed in section 7.5 is the thickness of the helmet shell i.e. 2 mm and 4 mm thickness of helmet shells are impacted with 5.5 Joules, 15.5 Joules and 25.5 Joules at the helmet Top, Side and Back locations. The results from the impact simulations for the helmet shell thickness are discussed in the next section.

7.6.1 Effect of helmet thickness on transmitted force

In Figure 7-21 peak transmitted force has been plotted according to the thickness of the helmet shell. Firstly, peak transmitted force increases with the increase of impact energy irrespective of the location at the helmet shell. Secondly, 1 mm thick helmet shells transmit more force transmitted as compared to the 2 mm and 4 mm thick helmet shells. This may be due to a smaller amount of material present to block the force. Thirdly, 4 mm thick helmet shells block the force more effectively. These results suggest the trend regarding peak transmitted force can be reduced by the increase of shell thickness. The change of helmet shell thickness from 1 mm to 2 mm significantly reduces the transmitted force value.
Figure 7-21 Peak transmitted force at different impact locations of helmet shell (a)
   Top location (b) Back location (c) Side location

7.6.2 Effect of helmet thickness on energy absorption

In Figure 7-22, it can be observed that the 4 mm thick helmet shell absorbs higher impact energy as compared to 1mm and 2 mm thick helmet shells. Further, energy absorbed is directly proportional to the impact energy and also to the thickness of the helmet shell. The higher the thickness, the more energy will be absorbed at any location on the helmet shell.

In a riot helmet, internal padding is used to absorb most of the impact energy. The results in combination with the results of internal padding as discussed in section 6.5.4 will significantly affects the percentage energy absorption. In designing riot helmet shells,
selection of the shell thickness should be based on the combined protection of the helmet shell and the internal padding.

Figure 7-22 Energy absorbed at different impact locations of helmet shell (a) Top location (b) Back location (c) Side location
7.7 Summary

One of the objectives in this research was to develop an impact simulation and its validation through practical testing. In this chapter, successful riot helmet shell models have been generated and impact simulations have been developed. Creation of models in Abaqus has shown an effective way of analysing the impact properties of a riot helmet shell in terms of energy absorption and force transmission.

The simulated models were validated by the experimental data. The results revealed that the simulation generally correspond and shows the same trends as the experimental results although there are some inaccuracies due to the simplification of the simulated model compared to the real impact on the developed helmet shells.

Impact simulation shows similar energy absorption trends as compared to the experimental results. The helmet top impact has been to be the safest position in respect of an impact if compared to the helmet back and the helmet side locations. Moreover, thicker helmet shells absorb more energy and transmit lower peak force values as compared to the thinner helmet shells. The force blocking effectiveness of the riot helmet shells depends on the thickness of the helmet shell which can be optimised while designing the complete riot helmet.
CHAPTER 8  CONCLUSION AND FUTURE WORK

8.1 Conclusions
The aim of the research was to develop a new technique for the manufacturing of riot helmet shells reinforced by single-piece continuously woven fabric and to evaluate them by testing using the newly developed test rig. Alongside the experimental investigations, finite element models have been created and simulated.

The objectives set out for this PhD research include (1) to produce 5-8-28 angle-interlock fabric, manufacture flat composite panels using the same fabric as reinforcing fabric and to determine the physical and mechanical properties of flat composite panels; (2) to create a prototype dome-shaped structure using vacuum bagging which can lead and give guidance for the manufacturing of single-piece riot helmet shells; (3) to develop a technique and establish a procedure for the manufacturing of single-piece riot helmet shells by vacuum bagging; (4) to design and manufacture a test rig in such a way that impact tests can be carried out at different locations on the riot helmet shell; (5) to conduct and establish a procedure for low velocity impact testing of the developed single-piece riot helmet shells using a developed test rig; and (6) to create finite element models in ABAQUS for different impact locations, to analyse the impact performance of riot helmet shells at different impact locations and validate the simulated results against the experimental results.

The research has led to the following conclusions:

(a) Development and establishment of a manufacturing procedure for creating single-piece helmet shells
The new method of making helmet shells has been established and this leads to the possibilities that any other shape of helmet shell can be developed using this method. The idea of making a dome-shaped composite structure was the essence of this technique. A total number of 12 fabric wrinkle-free single-piece riot helmet shell prototypes have been manufactured throughout the study. The thickness of the helmet shell top location is less as compared to the helmet side and helmet back location.

Manufacturing of double-layered helmets was also one of the achievements. Three helmet shells were also made from double-layered fabrics in this study.
(b) Design and manufacturing of a test rig and low velocity impact testing for the developed single-layer and double-layer helmet shells

Another achievement of this research was the design and establishment of a helmet test rig on the basis of the Instron Dynatup 8200. The establishment of a testing procedure is also another achievement and it provides the ability and facility to conduct impact tests on the riot helmets. From the test rig, the transmitted force beneath the helmet shell can be calculated and force attenuation factors can be worked out.

Physical impact testing was carried out on the developed single-layered helmet shells and double-layered helmet shells. Experimental data were extracted which indicates successful manufacturing of the test rig.

Useful information for helmet engineering has been recorded based on the geometric features of the riot helmet shells. Findings are specified as follows:

1. Helmet top location seems to be the least vulnerable position against impact due to its higher curvature and longer distances from the helmet shell edge;
2. Helmet side and helmet back location need more attention while helmet manufacturing as compared to the helmet top;
3. Curvature intensity seems to affect the impact properties of the riot helmet shells. The helmet shell top impact location, due to the higher curvature and longer distances from the edge transmits less force to the headform;
4. Internal padding or protective padding greatly influence the energy absorption and force attenuation;
5. Double-layers helmet shells provide better force attenuation as compared to the single-layer helmet shells.

(c) Property evaluation of 5-8-28 Kevlar composite flat panels

Manufacturing and property evaluation of 5-8-28 Kevlar composite flat panels is also one of the achievements. Composites developed from angle-interlock fabric show different and far better tensile properties in the weft direction as compared to the warp direction. It is much harder to break the fibres in the weft direction than in the warp direction. This behaviour of composites can lead to better products while layering 5-8-28 angle-interlock fabric for multi-single layered helmet shells.
(d) Simulation of single-piece riot helmet shells

One more achievement of the present work is the creation of an impact simulation in Abaqus. The simulation has been validated with experimental results. Similar trends have been recorded in experimental and simulated results. By increasing the helmet thickness, helmet shell energy absorption properties can be increased. Moreover, from impact performance results, the helmet top position is the safest position against impact as compared to the helmet back and side locations.

8.2 Recommendations for further research work

Future research directions remain to enhance the functionality, commercial viability and research contribution of the work describe in this thesis.

Only one type of matrix i.e. Araldite LY5052 and Aradur 5052 as epoxy and hardener was used in this research. The use of different varieties of resin with less curing time would reduce the composite manufacturing lead time and would increase the quality of helmet shells. Suitable selection of matrix based on the combined impact performance with Kevlar fabric will be the key for better impact protection.

The developed test rig would be modified for high energy impacts. Moreover, testing should be extended to complete riot helmet assemblies with protective paddings and comfort paddings instead of just the helmet shell. This would allow comparison of the developed continuous textile reinforced helmet shells with the present helmet shells used by riot police on the developed test rig. Further, developed helmet shells should be converted to complete helmets with protective padding and would need to be tested according to riot helmet standards (Malbon and Croft, 2004). This would allow judging developed helmet shells based on the present safety standards.

FE analysis has been conducted to validate the experimental results. For deeper investigations the FE models can be optimised by setting the material properties to anisotropic. Further, helmet shells would be structured according to the weave geometry to investigate impact performance at different impact locations on the helmet shell. Moreover, future work could use the present FE models in order to conduct parametric studies to analyse the impact performance of helmet shells with different material types and with different impact shapes.
In the present research, double-layer helmet shells have been developed using the newly developed technique for making single-layer helmet shells. This is one of the significant features of the novel technique due to which multiple layers of wrinkle free angle-interlock fabric can be draped and such helmets can be produced which can lead to the manufacturing of continuous textile-reinforced riot helmet shells for high velocity impact protection. Alternatively, this technique can be inherited for the manufacturing of military helmets in which there is a need of several layers of draped fabric.
REFERENCES


Malbon, C. (2011). *RE: Private communication with program manager - Centre for applied science and technology (former HOSDB).*


Appendices
## APPENDIX A

### Table A-1 Tensile properties of 5-8-28 flat Kevlar composites in warp direction

<table>
<thead>
<tr>
<th>Specimen Number</th>
<th>Tensile stress at break (MPa)</th>
<th>Tensile strain at break (%)</th>
<th>Young’s modulus (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>128.87</td>
<td>2.81</td>
<td>8119.20</td>
</tr>
<tr>
<td>2</td>
<td>124.33</td>
<td>2.51</td>
<td>7467.80</td>
</tr>
<tr>
<td>5</td>
<td>136.12</td>
<td>2.77</td>
<td>7729.00</td>
</tr>
<tr>
<td>4</td>
<td>135.09</td>
<td>2.78</td>
<td>7991.01</td>
</tr>
<tr>
<td>5</td>
<td>133.57</td>
<td>2.79</td>
<td>7661.50</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>131.60</strong></td>
<td><strong>2.73</strong></td>
<td><strong>7793.70</strong></td>
</tr>
<tr>
<td><strong>Std. dev.</strong></td>
<td><strong>4.92</strong></td>
<td><strong>0.13</strong></td>
<td><strong>261.13</strong></td>
</tr>
<tr>
<td><strong>CV%</strong></td>
<td><strong>3.74</strong></td>
<td><strong>4.61</strong></td>
<td><strong>3.35</strong></td>
</tr>
</tbody>
</table>

### Table A-2 Tensile properties of 5-8-28 flat Kevlar composites in weft direction

<table>
<thead>
<tr>
<th>Specimen Number</th>
<th>Tensile stress at break (MPa)</th>
<th>Tensile strain at break (%)</th>
<th>Young’s modulus (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>553.02</td>
<td>1.91</td>
<td>35793.72</td>
</tr>
<tr>
<td>2</td>
<td>472.81</td>
<td>1.88</td>
<td>34146.24</td>
</tr>
<tr>
<td>5</td>
<td>595.90</td>
<td>1.78</td>
<td>41047.54</td>
</tr>
<tr>
<td>4</td>
<td>488.57</td>
<td>1.62</td>
<td>37716.18</td>
</tr>
<tr>
<td>5</td>
<td>579.98</td>
<td>1.75</td>
<td>35987.83</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>538.06</strong></td>
<td><strong>1.79</strong></td>
<td><strong>36938.30</strong></td>
</tr>
<tr>
<td><strong>Std. dev.</strong></td>
<td><strong>54.85</strong></td>
<td><strong>0.12</strong></td>
<td><strong>2622.02</strong></td>
</tr>
<tr>
<td><strong>CV%</strong></td>
<td><strong>10.19</strong></td>
<td><strong>6.45</strong></td>
<td><strong>7.10</strong></td>
</tr>
</tbody>
</table>

### Table A-3 In-plane shear modulus of 5-8-28 Kevlar composite panels

<table>
<thead>
<tr>
<th>Specimen Number</th>
<th>In-plane shear modulus (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1293.55</td>
</tr>
<tr>
<td>2</td>
<td>1292.25</td>
</tr>
<tr>
<td>3</td>
<td>1412.51</td>
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<tr>
<td>4</td>
<td>1436.64</td>
</tr>
<tr>
<td>5</td>
<td>1461.33</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>1379.26</strong></td>
</tr>
<tr>
<td><strong>Std. dev.</strong></td>
<td><strong>72.18</strong></td>
</tr>
<tr>
<td><strong>CV%</strong></td>
<td><strong>5.23</strong></td>
</tr>
</tbody>
</table>
Table A-4  Density of 5-8-28 Kevlar composite single-layer flat specimens

<table>
<thead>
<tr>
<th>Specimen Number</th>
<th>weight of wire in air g</th>
<th>weight of wire in water g</th>
<th>weight of specimen with wire in air g</th>
<th>weight of specimen with wire in water g</th>
<th>weight of specimen in air g</th>
<th>weight of specimen in water g</th>
<th>density of specimen* g/cm³</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.188</td>
<td>0.183</td>
<td>0.822</td>
<td>0.289</td>
<td>0.635</td>
<td>0.107</td>
<td>1.200</td>
</tr>
<tr>
<td>2</td>
<td>0.188</td>
<td>0.183</td>
<td>0.790</td>
<td>0.306</td>
<td>0.603</td>
<td>0.123</td>
<td>1.254</td>
</tr>
<tr>
<td>3</td>
<td>0.188</td>
<td>0.183</td>
<td>0.795</td>
<td>0.293</td>
<td>0.607</td>
<td>0.111</td>
<td>1.221</td>
</tr>
<tr>
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Average (g/cm³) 1.229
Standard deviation 0.029
Coefficient of variation (%) 2.343

*Average density of water was taken as 0.99823 g/cm³.

Table A-5  Fibre and resin contents

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<th>Resin Content (mass %) wᵣ (%)</th>
<th>Fibre Content (volume %) vᵢ (g/cm³)</th>
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* sensitivity of force sensor (1V = 8896.443 N)
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# APPENDIX B

Specifications of dynamic force sensor model 1203V

## SPECIFICATIONS, MODEL SERIES 1203V DYNAMIC FORCE SENSOR

### SPECIFICATIONS BY MODEL

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<th>SENSITIVITY (mV/Lb)</th>
<th>COMPRESSION RANGE (Lbs)</th>
<th>MAXIMUM COMPRESSION (Lbs)</th>
<th>DISCH. TC (Sec)</th>
<th>RESOLUTION (Lb, RMS)</th>
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### COMMON SPECIFICATIONS

- **STIFFNESS**: 20.0 Lb/μin
- **MOUNTED RESONANT FREQUENCY, UNLOADED**: 75 kHz
- **LINEARITY [1]**: ±1 % F.S.
- **F.S. OUTPUT VOLTAGE, NOM.**: 5 Volts
- **MAX SHOCK, UNLOADED**: 10,000 g’s
- **MAX. VIBRATION, UNLOADED**: ±5,000 g’s, PEAK
- **COEFFICIENT OF THERMAL SENSITIVITY**: .03 %/°F
- **TEMPERATURE RANGE**: -100 to +250 °F
- **ENVIRONMENTAL SEAL**: HERMETIC WELDED, GLASS-TO-METAL SEAL
- **SUPPLY CURRENT / VOLTAGE RANGE [2]**: 2 to 20 / +18 to +30 mA / VDC
- **OUTPUT IMPEDANCE**: 100 OHMS
- **MATERIAL, LOAD BEARING SURFACES**: 17-4PH, HARDENED STAINLESS STEEL
- **MATERIAL, HOUSING AND CONNECTOR**: 310L STAINLESS STEEL
- **WEIGHT**: 50 GRAMS
- **SIZE (O.D. X I.D. X THICKNESS)**: Ø1.1 X Ø400 X .500 INCHES
- **MOUNTING PROVISION**: Ø400 THRU HOLE AT CENTER
- **ELECTRICAL CONNECTOR**: RADIAL MOUNTED, WITH 10-32 MICRO COAX CONNECTOR

---

[1] Percent of full scale or of any lesser range, zero based best fit straight line method.
[2] Power these instruments only with constant current type power units. Do not connect to a source of voltage without current limiting. This will destroy the integral IC amplifier.