

UC San Diego

UC San Diego Electronic Theses and Dissertations

Title

Experimental and numerical simulations of explosive loading on structural components :
composite sandwich connections

Permalink

<https://escholarship.org/uc/item/35r0x3wn>

Author

Huson, Peter N.

Publication Date

2012

Peer reviewed|Thesis/dissertation

UNIVERSITY OF CALIFORNIA, SAN DIEGO

**Experimental and Numerical Simulations of Explosive Loading on Structural
Components: Composite Sandwich Connections**

A dissertation submitted in partial satisfaction of the
requirements for the degree
Doctor of Philosophy

in

Structural Engineering

by

Peter Huson

Committee in charge:

Professor Robert Asaro, Chair
Professor Gil Hegemier, Co-Chair
Professor Hyonny Kim
Professor Vlado Lubarda
Professor Vitali Nesterenko

2012

Copyright
Peter Huson, 2012
All rights reserved.

The dissertation of Peter Huson is approved, and it is acceptable in quality and form for publication on microfilm and electronically:

Co-Chair

Chair

University of California, San Diego

2012

DEDICATION

To my family.

TABLE OF CONTENTS

Signature Page	iii
Dedication	iv
Table of Contents	v
List of Abbreviations	vi
List of Symbols	viii
List of Figures	x
List of Tables	xviii
Acknowledgements	xix
Vita and Publications	xxii
Abstract of the Dissertation	xxiii
Chapter 1 Introduction	1
Chapter 2 Background	4
2.1 Fundamentals of Blast Loading	4
2.2 Composite Joint Connections	13
2.3 The UCSD Blast Simulator Facility	20
2.4 Numerical Simulation	25
Chapter 3 Structural Tests	34
3.1 Loading Complex Geometries	35
3.1.1 Preliminary 1D Impact Tests	35
3.1.2 1D Impact Tests	41
3.1.3 2D Impact Tests	46
3.1.4 Load Cell Calibration Tests	52
3.1.5 Loading Methods Summary	58
3.2 Joint Tests	58
3.2.1 Surrogate Joint Tests	59
3.2.2 Composite Joint Tests	71
3.3 Summary	116

Chapter 4	Material Tests	118
4.1	Bending Properties	119
4.1.1	Quasi-Static Bend Tests	119
4.1.2	Dynamic Bend Tests	124
4.2	Shear Properties	130
4.2.1	Quasi-Static Shear Tests	130
4.2.2	Intermediate Speed Shear Tests	135
4.2.3	Dynamic Shear Tests	138
4.3	Delamination Properties	143
4.3.1	Delamination Tests	143
4.4	Summary	146
Chapter 5	Numerical Model Development & Calibration: Material Tests . .	147
5.1	Delamination Test Simulations	149
5.2	Bend Test Simulations	154
5.2.1	Quasi-Static Bend Test Simulations	154
5.2.2	Dynamic Bend Test Simulations	158
5.3	Shear Test Simulations	164
5.3.1	Intermediate Speed Shear Test Simulations	164
5.3.2	Core Material Model Discussion	168
5.3.3	Dynamic Shear Test Simulations	175
5.4	Summary	179
Chapter 6	Numerical Model Development & Validation: Composite Joint Tests	181
6.1	Composite Joint Model Setup	181
6.2	Simulation of Composite Joint Test 1	187
6.3	Simulation of Composite Joint Test 4	191
6.4	Simulation of Composite Joint Test 3	194
6.5	Simulation of Composite Joint Test 2	199
6.6	Simulation of Composite Joint Test 5	203
6.7	Summary	207
Chapter 7	Conclusions and Recommendations	208
7.1	Summary and Conclusions	208
7.2	Recommendations for Future Work	210
References		212

LIST OF ABBREVIATIONS

BG	Blast Generator
CMU	Concrete Masonry Unit
EUCLID	European Cooperation for the Long-term In Defence
IS	Intermediate speed
FRP	Fiber reinforced polymer
HSS	Hollow structural section
MTS	Material Testing Systems
QS	Quasi-static
RLC	Reaction load cell
TML	Tokyo Sokki Kenkyujo Co., Ltd
TNT	Trinitrotoluene
UCSD	University of California, San Diego
VARTM	Vacuum Assisted Resin Transfer Molding

LIST OF SYMBOLS

a_0	Speed of sound
α	Non-linear shear stress parameter
α_e	Vent ratio
A_s	Area
b	Waveform parameter
C	FRP compressive strength
δ	Contact penetration depth
E	Young's modulus
G	Shear modulus
F_{comp}	Compressive failure criteria
F_{fiber}	Fiber failure criteria
F_{matrix}	Matrix failure criteria
f_s	Nodal contact force
$G_{fI\parallel}$	Parallel fracture energy in tension
$G_{fII\parallel}$	Parallel fracture energy in shear
$G_{fI\perp}$	Perpendicular fracture energy in tension
$G_{fII\perp}$	Perpendicular fracture energy in shear
I_i	i th tensor invariant
i_s	Specific impulse
K_I	Fracture toughness mode 1
K_{II}	Fracture toughness mode 2
K_c	Contact stiffness
l	length
$NFLS$	Tiebreak normal failure stress
ν	Poisson's ratio
$PARAM$	Tiebreak critical interface failure distance
p_o	Ambient pressure
p_{QS}	Quasi-static pressure
p_s	Incident overpressure

p_{so}	Static overpressure
p_r	Reflected overpressure
Q_e	Specific energy
R	Standoff
ρ	Density
S	FRP tensile strength
$SFLS$	Tiebreak shear failure stress
S_{ij}	Compliance coefficient tensor
$S_{\parallel}$	Shear strength parallel to the grain
$S_{\perp}$	Shear strength perpendicular to the grain
σ	Stress
σ_y	Yield strength
τ	Shear stress
$\bar{\tau}$	Shear stress ratio
t	Thickness
t_a	Time of arrival
t_p	Positive phase duration
t_n	Negative phase duration
V	Volume
W	Charge weight
w	Width
X_C	Compressive strength parallel to the grain
X_T	Tensile strength parallel to the grain
Y_C	Compressive strength perpendicular to the grain
Y_T	Tensile strength perpendicular to the grain
Z	Scaled distance

LIST OF FIGURES

Figure 2.1:	Photo of the shock wave and fireball created during an explosion.	5
Figure 2.2:	Schematic of a free airburst.	7
Figure 2.3:	Characteristic pressure-time history of a free airburst.	7
Figure 2.4:	Schematic of a reflected airburst.	9
Figure 2.5:	Characteristic pressure-time history of a reflected airburst.	9
Figure 2.6:	Schematic on an internal explosion, reproduced from [33].	10
Figure 2.7:	Characteristic pressure-time history of an internal explosion, reproduced from [13].	11
Figure 2.8:	Characteristic pressure-time history of an internal explosion.	11
Figure 2.9:	Composite sandwich structure.	13
Figure 2.10:	Schematic of resin infusion process, taken from [26].	14
Figure 2.11:	Typical composite sandwich joint construction [28].	15
Figure 2.12:	Types of composite sandwich joint manufacturing defects [35].	16
Figure 2.13:	Example of complete joint failure due to overlamine delamination [14].	16
Figure 2.14:	Composite connection utilizing triangular core material stiffeners/fillets.	17
Figure 2.15:	Example of failure in stiffened joint design [17].	18
Figure 2.16:	Photo of composite sandwich material denoting dimensions and grain direction in the balsa core.	19
Figure 2.17:	Photo and dimensions of 90° composite sandwich joint.	19
Figure 2.18:	UCSD Blast Simulator Facility Layout.	21
Figure 2.19:	Schematic of Blast Generator.	21
Figure 2.20:	Photo of a Blast Generator.	22
Figure 2.21:	Urethane impacting pad.	23
Figure 2.22:	Damage evolution of a reinforced concrete column [32].	24
Figure 2.23:	Response of CMU wall retrofitted with polyurea catcher system [27].	24
Figure 2.24:	Severe deformation incurred by a W10x132 steel section under simulated truck bomb loads [34].	25
Figure 2.25:	Stresses in fiber direction, σ_1 , matrix direction, σ_2 , and shear stress, τ_{12}	26
Figure 2.26:	Balsa wood directionality taken from [38].	27
Figure 2.27:	Typical balsa panel construction.	28
Figure 2.28:	Numerical representation of LS-DYNA tiebreak.	31
Figure 2.29:	Graphical representation of tiebreak failure surface.	32
Figure 2.30:	Graphical representation of tiebreak damage formulation applied after initial tiebreak failure.	33
Figure 3.1:	Schematic of 1-D Impact Test setup.	35

Figure 3.2:	Photos of water bladders used for 1D Impact Test 1 (a), Test 2 (b), & Test 3 (c).	36
Figure 3.3:	Sequence of events for 1D Impact Test 1.	36
Figure 3.4:	Target mass acceleration histories for 1D Impact Tests 1, 2 & 3. . .	37
Figure 3.5:	Converted pressure time histories for 1D Impact Tests 1, 2 & 3. . .	38
Figure 3.6:	Impulses for 1D Impact Tests 1, 2 & 3.	38
Figure 3.7:	Photo of typical vertical internal baffles used to control water flow within the bladders and provide additional structural reinforcement. . .	40
Figure 3.8:	Photo of improved bladder design mounted to target mass with ratchet straps.	40
Figure 3.9:	Dynamic load cell and target plate schematic.	41
Figure 3.10:	Sequence of events during 1D Impact Test 7. (a) Before impact, (b) at impact, (c) after impact.	42
Figure 3.11:	1D Impact Test 7 force-time history from embedded load cells. . .	42
Figure 3.12:	Pressure-time history for 1D Impact Test 7.	43
Figure 3.13:	Test 7 impulses recorded from embedded embedded load cells. . .	43
Figure 3.14:	Comparison of pressures from bladder material selection (a) XR5 and (b) U1940.	44
Figure 3.15:	Pressure-time histories for XR5 (a) 6 in and (b) 8 in bladder. . . .	45
Figure 3.16:	Comparison of field test example (left) and Test 9 (right).	46
Figure 3.17:	(a) Schematic of 2D Impact Test setup.	47
Figure 3.18:	Channel dimensions and locations of load cells.	47
Figure 3.19:	Sequence of events of 2D Impact Tests. (a) Before impact, (b) at impact, (c) after impact.	48
Figure 3.20:	Lateral and normal pressure time histories for 2D Impact Test 2. . .	48
Figure 3.21:	Impulses on normal and lateral faces of channel for 2D Impact Test 2.	49
Figure 3.22:	Normal pressure-time histories of 2D Impact Test 6: (a) embedded load cells (b) reaction load cells (c) reaction load cells x (1/.281). .	51
Figure 3.23:	Photos of Load Cell Calibration Test configuration.	52
Figure 3.24:	Schematic of steel load cell housing.	53
Figure 3.25:	Configuration, location and assembly details for Load Cell Calibration Test 1 & 2.	53
Figure 3.26:	Configuration, location and assembly details for Load Cell Calibration Test 3.	56
Figure 3.27:	Bladder mounted pressure gauge.	57
Figure 3.28:	Plywood and structural foam surrogate sandwich specimen.	59
Figure 3.29:	Surrogate Joint Test geometry.	60
Figure 3.30:	Schematic of Surrogate Joint Test setup.	60
Figure 3.31:	Dimensions of bladder for Joint Surrogate Test 1.	61
Figure 3.32:	(a) Embedded load cells and (b) surrogate joint load cell placement. .	61
Figure 3.33:	Joint Surrogate Test 1.	62
Figure 3.34:	Photo of overhead mirror used for live video.	62

Figure 3.35: Sequence of events during Surrogate Joint Test 1.	63
Figure 3.36: Force-time histories for Surrogate Joint Test 1.	63
Figure 3.37: Pressure-time histories for Surrogate Joint Test 1.	64
Figure 3.38: Impulse histories for Surrogate Joint Test 1.	65
Figure 3.39: Post test photo of bladder from Surrogate Joint Test 1.	66
Figure 3.40: Dimensions of bladder for Joint Surrogate Test 2.	67
Figure 3.41: Dimensions of impacting mass for Joint Surrogate Test 2.	67
Figure 3.42: Joint Surrogate Test 2.	68
Figure 3.43: Sequence of events during Joint Surrogate Test 2.	68
Figure 3.44: Force-time histories for Surrogate Joint Test 2.	69
Figure 3.45: Pressure-time histories for Surrogate Joint Test 2.	70
Figure 3.46: Impulse histories for Surrogate Joint Test 2.	70
Figure 3.47: Post test photo of bladder from Surrogate Joint Test 2.	71
Figure 3.48: Plan view of south Blast Simulator facility configuration.	72
Figure 3.49: Side view of south Blast Simulator facility configuration.	72
Figure 3.50: Reaction block configuration.	73
Figure 3.51: Gripping fixture web and connection assembly.	73
Figure 3.52: Gripping fixture Z assembly and structural foam placement.	74
Figure 3.53: Gripping fixture assembly (a) side view (b) top view.	74
Figure 3.54: Load cell locations for Composite Joint Tests.	75
Figure 3.55: Strain gauge locations for Composite Joint Tests.	76
Figure 3.56: Composite Joint Test 1.	77
Figure 3.57: Sequence of events for Composite Joint Test 1.	78
Figure 3.58: Recorded force-time histories for Composite Joint Test 1.	79
Figure 3.59: Averaged pressure-time histories for Composite Joint Test 1.	80
Figure 3.60: Measured impulses for Composite Joint Test 1.	80
Figure 3.61: Strain-time histories for Composite Joint Test 1.	81
Figure 3.62: Composite Joint Test 2.	82
Figure 3.63: Sequence of events during Composite Joint Test 2.	82
Figure 3.64: Force-time histories for Composite Joint Test 2.	83
Figure 3.65: Pressure-time histories for Composite Joint Test 2.	84
Figure 3.66: Impulses for Composite Joint Test 2.	84
Figure 3.67: Strain-time histories for Composite Joint Test 2.	85
Figure 3.68: Damage progression in Composite Joint Test 2 @ t= 74.75 ms.	86
Figure 3.69: Damage progression in Composite Joint Test 2 @ t= 78.25 ms.	86
Figure 3.70: Damage progression in Composite Joint Test 2 @ t= 86.5 ms.	87
Figure 3.71: Post test photo of breached joint.	88
Figure 3.72: Pull off of Z assembly from concrete reaction block.	89
Figure 3.73: Schematic of layout for Composite Joint Tests 3, 4 and 5.	89
Figure 3.74: Reaction block layout for Composite Joint Tests 3, 4 and 5.	90
Figure 3.75: Top down section views of reaction block design for Composite Joint Tests 3, 4 and 5.	90

Figure 3.76: Hydrocode calculation (a) and proposed experimental simulation (b).	91
Figure 3.77: Geometry and dimensions of impact mass for Composite Joint Tests 3, 4, and 5.	91
Figure 3.78: Load cell locations for Composite Joint Tests 3, 4, and 5.	92
Figure 3.79: Composite Joint Test 3.	93
Figure 3.80: Comparison of bladders for Composite Joint Test (a) 3 and (b) 2 . .	94
Figure 3.81: Sequence of events during Composite Joint Test 3.	94
Figure 3.82: Force-time histories for Composite Joint Test 3.	95
Figure 3.83: Close up of force-time histories for Composite Joint Test 3.	95
Figure 3.84: Averaged pressure-time histories for Composite Joint Test 3. . . .	96
Figure 3.85: Impulses for Composite Joint Test 3.	97
Figure 3.86: Strain-time histories for Composite Joint Test 3.	98
Figure 3.87: Photo of post test damage in Composite Joint Test 3.	99
Figure 3.88: Photo of post test damage in Composite Joint Test 3.	99
Figure 3.89: Photo of post test damage in Composite Joint Test 3.	100
Figure 3.90: Water shield used for Composite Joint Test 4 and 5.	101
Figure 3.91: Water bladder with rotated baffles used for Composite Joint Test 4. .	102
Figure 3.92: Sequence of events during Composite Joint Test 4.	103
Figure 3.93: Force-time histories for Composite Joint Test 4.	104
Figure 3.94: Close up of force time history to show load arrival times in Composite Joint Test 4.	104
Figure 3.95: Averaged pressure-time histories for Composite Joint Test 4. . . .	105
Figure 3.96: Impulses for Composite Joint Test 4.	105
Figure 3.97: Strain-time histories for Composite Joint Test 4.	106
Figure 3.98: Composite Joint Test 5.	107
Figure 3.99: Sequence of events during Composite Joint Test 5.	108
Figure 3.100: Damage progression in Composite Joint Test 5 @ t= 85.25 ms. . . .	109
Figure 3.101: Damage progression in Composite Joint Test 5 @ t= 88.75 ms. . . .	110
Figure 3.102: Damage progression in Composite Joint Test 5 @ t= 101.0 ms. . . .	111
Figure 3.103: Damage progression in Composite Joint Test 5 @ t= 114.5 ms. . . .	112
Figure 3.104: Photo of post damage in Composite Joint Test 5.	113
Figure 3.105: Photo of post damage in Composite Joint Test 5.	113
Figure 3.106: Force-time histories for Composite Joint Test 5.	114
Figure 3.107: Averaged pressure-time histories for Composite Joint Test 5. . . .	114
Figure 3.108: Impulses for Composite Joint Test 5.	115
Figure 3.109: Strain-time histories for Composite Joint Test 5.	116
Figure 4.1: QS Bend Test setup.	119
Figure 4.2: QS Bend Test geometry.	120
Figure 4.3: Sequence of events during QS Bend Tests.	120
Figure 4.4: Force-displacement plots for QS Bend Tests.	121
Figure 4.5: Strain-displacement plots for QS Bend Tests.	121

Figure 4.6:	Post test damage for QS Bend Test 1 demonstrating both compressive buckling of the top facesheet as well as shearing of the core.	122
Figure 4.7:	Post test damage for QS Bend Test 2 demonstrating compressive buckling of the top facesheet and delamination.	123
Figure 4.8:	Post test damage for QS Bend Test 3 denoting compressive failure and hinge formation.	124
Figure 4.9:	Blast Simulator configuration for Dynamic Bend Tests.	125
Figure 4.10:	Dog-bone specimen for Dynamic Bend Tests	126
Figure 4.11:	Impact plate assembly for Dynamic Bend Tests.	126
Figure 4.12:	Side view sequence of events during Dynamic Bend Tests.	127
Figure 4.13:	Angled view of sequence of events during Dynamic Bend Tests.	127
Figure 4.14:	Post test photos for Dynamic Bend Tests (a) 1, (b) 2, and (c) 3.	128
Figure 4.15:	Front load cell force-time histories for Dynamic Bend Tests 1-3.	128
Figure 4.16:	Reaction load cell force-time histories for Dynamic Bend Tests 1-3.	129
Figure 4.17:	Strain time histories for Dynamic Bend Tests 1-3.	130
Figure 4.18:	Schematic of QS Shear Tests.	131
Figure 4.19:	QS Shear Test instrumentation locations.	132
Figure 4.20:	Typical sequence of events for QS Shear Tests 1-6.	132
Figure 4.21:	Force displacement results for QS Shear Tests 1-6.	133
Figure 4.22:	Bending and shear strain-time histories for QS Shear Test 2.	134
Figure 4.23:	Bending and shear strain vs displacement for QS Shear Tests 2.	134
Figure 4.24:	Typical sequence of events for IS Shear Tests 1-9.	135
Figure 4.25:	Force-displacement results for IS Shear Tests 1-9.	136
Figure 4.26:	Strain time histories for IS Shear Test 6 denoting as shear strain to failure of approximately 0.6%.	137
Figure 4.27:	Strain displacement results for IS Shear Tests 1-9.	137
Figure 4.28:	UCSD Gas Gun Facility.	138
Figure 4.29:	Example of Gas Gun projectile.	138
Figure 4.30:	Load cell used for load-velocity calibration.	139
Figure 4.31:	Example of pressure pulse from Gas Gun projectile.	139
Figure 4.32:	Instrumentation placement for Dynamic Bend Tests.	140
Figure 4.33:	Photo and schematic of Dynamic Bend Tests specimens.	140
Figure 4.34:	Typical sequence of events during Dynamic Bend Tests.	141
Figure 4.35:	Strain-time histories for Dynamic Bend Test 3.	141
Figure 4.36:	Failure strains as a function of strain rate for QS, IS and Dynamic Shear Tests.	143
Figure 4.37:	Delamination Test setup.	144
Figure 4.38:	Sequence of events during Delamination Test 2.	144
Figure 4.39:	Force-time plots for Delamination Tests 1-3.	145
Figure 4.40:	Strain-displacement plots for Delamination Tests 1 & 3.	145
Figure 5.1:	Computationally assigned material directions (a) CFRP facesheets (b) balsa core.	148

Figure 5.2:	Delamination Test(a) and Simulation (b).	150
Figure 5.3:	Displacement application and boundary conditions for Delamination Test Simulations.	151
Figure 5.4:	Tiebreak surfaces in Delamination Test Simulations.	151
Figure 5.5:	Surface contacts in Delamination Test Simulations.	152
Figure 5.6:	Load and strain outputs for Delamination Test Simulations.	152
Figure 5.7:	Comparison of Delamination Test 3 Simulation and experiment.	153
Figure 5.8:	Delamination Tests experimental and calculated force histories comparisons.	153
Figure 5.9:	QS Bend Test(a) and Simulation (b).	155
Figure 5.10:	Load application and boundary conditions for QS Bend Test Simulations.	156
Figure 5.11:	Strain and displacement output locations for QS Bend Test Simulations.	156
Figure 5.12:	Comparison of QS Bend Tests and Simulation.	157
Figure 5.13:	Strain-displacement of QS Bend Test Simulation and experiment.	158
Figure 5.14:	Dynamic Bend Test(a) and Simulation (b).	159
Figure 5.15:	Velocity-time histories applied to Dynamic Bend Test Simulations.	160
Figure 5.16:	Numerical representation of reaction load cells, strain gauges and boundary conditions in Dynamic Bend Test Simulations.	161
Figure 5.17:	Dynamic Bend Test 2 Simulation and experiment.	162
Figure 5.18:	Strain time histories of Dynamic Bend Test simulations compared to experiment.	163
Figure 5.19:	Simulated reaction force-time histories of Dynamic Bend Tests 1-3 compared to experimental results.	163
Figure 5.20:	IS Shear Test (a) and Simulation (b).	165
Figure 5.21:	Location of velocity application, surface contacts and boundary conditions for IS Shear Test Simulations.	166
Figure 5.22:	Locations of tiebreak surfaces and strain outputs for IS Shear Test Simulations.	166
Figure 5.23:	IS Shear Test 2 Simulation displacements and comparison to experiment.	167
Figure 5.24:	Shear strain-displacement correspondence between simulation and IS Shear Tests 2-5.	168
Figure 5.25:	Comparison of (a) IS Test 5 with finite element results using $G_{f_{\parallel}} =$ (b) $106G_{f_{\perp}}$, (c) $50G_{f_{\perp}}$, (d) $10G_{f_{\perp}}$ and $G_{f_{\perp}}$ values from 5.2	170
Figure 5.26:	Comparison of (a)experiment to (b) derived $G_{f_{\parallel,\perp}}$, (c) 2/3 of derived $G_{f_{\parallel,\perp}}$, and (d) one third of $G_{f_{\parallel,\perp}}$ keeping the ratio of $G_{f_{\parallel}} = 10G_{f_{\perp}}$ constant.	171
Figure 5.27:	Comparison of IS Test 8 failure mode with numerical results using 0.33x (a) $G_{f_{\parallel}}=106G_{f_{\perp}}$, (b) $G_{f_{\parallel}}=50G_{f_{\perp}}$, (c) $G_{f_{\parallel}}=10G_{f_{\perp}}$.	172
Figure 5.28:	Strain-displacement histories of parametric study varying fracture energies compared to experiment.	173

Figure 5.29: Strain-displacement histories comparing reduction of analytical fracture energies keeping $G_{f_{\parallel}}=10G_{f_{\perp}}$ constant.	174
Figure 5.30: Close-up of maximum strains observed in simulations, highlighting reduction ranges of (a) strongly perpendicular damage dominated, (b) perpendicular damage and (c) mixed perpendicular/parallel damage.	175
Figure 5.31: Dynamic Shear (a) Test and (b) Simulation.	176
Figure 5.32: Load application, strain outputs and boundary conditions for Dynamic Shear Test Simulations.	177
Figure 5.33: Tiebreak and surface contacts for Dynamic Shear Test Simulations.	177
Figure 5.34: Dynamic Shear Test 3 Simulation and experiment.	178
Figure 5.35: Shear and bending strain-time history comparison between simulation and Dynamic Shear Tests 3.	178
Figure 6.1: Composite Joint Test (a) and Simulation (b).	182
Figure 6.2: Material orientations for Composite Joint Test Simulations.	183
Figure 6.3: Gripping fixtures for Composite Joint Test simulations.	184
Figure 6.4: Contact surfaces assigned to gripping fixture assembly and boundary conditions for Composite Joint Test simulations.	185
Figure 6.5: Strain output locations for Composite Joint Test simulations.	185
Figure 6.6: Spatial pressure distributions for Composite Joint Test simulations.	186
Figure 6.7: Overlamine tiebreak surface contact assignments for Composite Joint Test simulations.	187
Figure 6.8: Experimental and approximated pressure-time histories for Composite Joint Test 1 simulation.	188
Figure 6.9: Illustration of excessive damage in simulation of Composite Joint Test 1 using full scale experimental pressures.	188
Figure 6.10: Experimental and approximated reduced pressure-time histories for Composite Joint Test 1 Simulation.	189
Figure 6.11: Shear strain development in simulation of Composite Joint Test 1 compared to experimental sequence of events.	190
Figure 6.12: Comparison of Composite Joint Test 1 experimental and numerically calculated strain time histories.	191
Figure 6.13: Experimental and approximated reduced pressure-time histories for simulation of Composite Joint Test 4.	192
Figure 6.14: Shear strain development in simulation of Composite Joint Test 4 compared to experimental sequence of events.	193
Figure 6.15: Comparison of Composite Joint Test 4 experimental and numerically calculated strain time histories in the base and panel facesheets.	194
Figure 6.16: Experimental and approximated reduced pressure-time histories for Composite Joint Test 3 simulation.	195

Figure 6.17: Simulated shear strains from Composite Joint Test 3 and frames of experiment taken from high speed video.	196
Figure 6.18: Comparison of (a) post test damage and (b) simulated damage propagation to balsa stiffeners.	197
Figure 6.19: Comparison of Composite Joint Test 3 experimental and numerically calculated strain time histories in the base and stem panel facesheets.	198
Figure 6.20: Composite Joint Test 2 experimental and approximated reduced pressure-time histories.	199
Figure 6.21: Simulated shear strain development in Composite Joint Test 2 compared to experimental sequence of events.	200
Figure 6.22: Overlamine delamination and balsa shear failures in (a) Composite Joint Test 2 compared to (b) finite element results @ $t=6$ ms.	201
Figure 6.23: (a) Experimental balsa shear propagation and stem panel detachment compared to (b) simulated results @ $t=14$ ms.	201
Figure 6.24: Experimental and simulated strain-time histories in Composite Joint Test 2.	202
Figure 6.25: Composite Joint Test 5 experimental and approximated reduced pressure-time histories.	203
Figure 6.26: Comparison of sequences in Composite Joint Test 5 and simulation, plotting shear strains.	204
Figure 6.27: (a) Experimentally observed joint failure in Composite Joint Test 5 compared to (b) simulated results @ $t=20$ ms.	205
Figure 6.28: Experimental and simulated strain-time histories in Composite Joint Test 5.	206

LIST OF TABLES

Table 2.1:	Conversion Factors for Explosives, reproduced from [33]	6
Table 2.2:	Composite sandwich material properties.	18
Table 3.1:	Test conditions of vinyl water bladder experiments.	36
Table 3.2:	Material properties for the two selected material systems.	39
Table 3.3:	Summary of key parameters and results from six impact tests.	44
Table 3.4:	Summary of 2D Impact Tests.	49
Table 3.5:	Comparison of embedded and reaction recorded impulses.	51
Table 3.6:	Summary of Load Cell Calibration Test 1.	54
Table 3.7:	Summary of Load Cell Calibration Test 2.	55
Table 3.8:	Summary of Load Cell Calibration Test 3.	57
Table 3.9:	Gripping Fixture Dimensions for Composite Joint Test 1 and 2.	77
Table 3.10:	Gripping Fixture Dimensions for Composite Joint Test 3.	92
Table 3.11:	Gripping Fixture Dimensions for Composite Joint Test 4 and 5.	102
Table 4.1:	Summary of composite sandwich Shear Test Results.	142
Table 5.1:	Initial CFRP facesheet property estimates	148
Table 5.2:	Initial balsa core property estimates [3]	149
Table 5.3:	Initial tiebreak contact parameters estimates	149
Table 5.4:	Updated CFRP facesheet property estimates	179
Table 5.5:	Updated balsa core property estimates	180
Table 5.6:	Updated tiebreak contact parameters estimates	180

ACKNOWLEDGEMENTS

I have learned much about life over my 10 years as a college student. I have seen my peers begin their lives in the workforce, some excelling right from the gate, others still trying to find their place. It has been both a blessing and a curse going through this process, as I have been able to delay the not-so-inevitable-anymore 9-5 day to day career, but also seen opportunities pass me by as I had not yet finished my schooling. What I have come out with is an understanding of the importance of the people you surround yourself with, and how those choices can affect both your ability to get jobs done as well as your day to day happiness.

I have been very fortunate to have the two advisors I have had through this. Professor Asaro taught me how to engage in both scientific and political presentations and debates, and the importance of the word "we" as it shows much more strength than one own's attempt at personal gain. He also has taught me never to panic, and when high stress circumstances arise to stay calm and collected. Professor Hegemier has taught me how engineers can have both academic and social intelligence, and that we will figure out a solution to the problem, so don't worry, just keep going. Both advisors allowed me to manage my work and progress on my own, which was the key as I don't think I could have handled a micromanager through all of this.

I would very much like to thank Professor Kim for his guidance and support in allowing us to use his testing facilities as well as his students, especially Daniel Whisler and Antony Chen, as their contributions in the material level testing as well as their unselfishness in assisting me outside of their own work was vital to the success of this project.

Additional gratitude is owed to the professors in both the UCSD MAE and SE departments who provided me with the fundamentals of mechanics and its application to all aspects of engineering, especially Dr. Vlado Lubarda, Dr. David Benson, Dr. Hidenori Murakami, Dr. Vitali Nesterenko, and Dr. Bimal Kad. I would like to thank Dr. Michael Prime of Los Alamos National Laboratories who was the first to teach me how to look at an engineering problem from a big picture standpoint and still pay the utmost attention to even the smallest detail. A special debt is owed to Dr. Keith Kedward of UCSB, who was the one who convinced me that graduate school was in my

best interest and the correct path for me.

One of the biggest thank yous I need to give is to the staff at Englekirk and the on-campus labs. Alex, Lonnie, Dan, Steve, Darren, Andy, Robert, Mike, Paul, Noah, Linda, Hector, Danny, both Bobs, RC, Chris, Larry and all of the student workers who came out to help - there is no way any of this would have been possible without the resilience and hard work all of you guys put in day in and day out. This was a team effort from day one and you guys helped just as much as anyone else on figuring out the solutions to problems and at the end of the day making things work and fit. I owe a large amount of gratitude to Don Johnson and the CRMS staff, who were able to get parts done in unheard of amounts of time, and were always friendly no matter what the case may be. I'd also like to give a thank you to Debra Bomar, Lindsay Walton, Michelle Vavra, Karen Arnett and the entire SE administration for their help, support and in general kindness through the trial and tribulations of graduate school. To Daryl Rysdyk - I don't know how you put up with me and the amount of computer issues and requests I had, but you helped create one hell of an arsenal of computer power that was and will continue to be the workhouse of this group. Thank you all very, very much, it's been a pleasure.

To my immediate family here at school - Dr. Mike Oeseterle for his guidance and recommendations as I started this project, Dr. Don Philipi who taught me how to think like a structural engineer, Aaron Freidenberg and Brad Durant for their continued help, support and in general being good company as we all tried to figure out how to get the job done, and Everett Chris who started UCSD with me and has kept trucking under even the most difficult of circumstances. It's difficult to put into words what Dr. Lauren Stewart has done for me as one of my best friends, mentor, colleague, business partner and life coach - Lauren, a lot of who I am today is because of you. You have made me a better person all around and showed me how to do things the right way, with integrity, and continued to put up with my weirdness and problems that would only happen to me. I really do feel we have the world at our fingertips and I am excited for what the future holds.

To my friends, all of you - you guys are the absolute best and worst influences in the entire world, and I wouldn't have it any other way. We still have so much ahead

of us.

Last and absolutely not least, my family. To all of my family in El Salvador - con Dios siempre, y a tío Federico - yo sé que nos está viendo del cielo, gracias por el ejemplo, fuiste el razón que empecé esto. To my sisters - I love you all so much, you guys are my rock. There is nothing like the bond the four of us have, and I'm so excited for the time we will be spending together and the huge family we will create. To Mom and Dad - this one is for you. You have believed in me since day one, supported me through everything and I can't tell you how much I love you. It's the combined gifts I have received from each of you that has given me the ability to finish this and I know will be what creates my path in the future.

VITA

- 2006 B. S. in Mechanical Engineering, Department of Mechanical Engineering, University of California, Santa Barbara
- 2008 M. S. in Applied Mechanics, Department of Mechanical and Aerospace Engineering, University of California, San Diego
- 2012 Ph. D. in Structural Engineering, Department of Structural Engineering, University of California, San Diego

PUBLICATIONS

P. Huson, L. Stewart, R.J. Asaro and G. Hegemier, “Laboratory Techniques for Blast Loading of Structures with Complex Geometries”, *8th International Conference on Shock and Impact Loads on Structures*, Adelaide, Australia, Dec. 2010.

P. Huson, R.J. Asaro, L. Stewart and G. Hegemier, “Non-Explosive Methods for Simulating Blast Loading of Structures with Complex Geometries”, *International Journal of Impact Engineering*, July 2011.

D. Whisler, A. Chen, H. Kim, P. Huson and R. Asaro, “Methodology for Exciting Dynamic Shear and Moment Failure in Composite Sandwich Beams”, *Journal of Sandwich Structures and Materials*, May 2012.

ABSTRACT OF THE DISSERTATION

Experimental and Numerical Simulations of Explosive Loading on Structural Components: Composite Sandwich Connections

by

Peter Huson

Doctor of Philosophy in Structural Engineering

University of California, San Diego, 2012

Professor Robert Asaro, Chair
Professor Gil Hegemier, Co-Chair

The extreme loading conditions produced from the detonation of an explosive are severely detrimental to structures and structural components. These effects are amplified when a blast occurs in an enclosed or confined geometry, where reduced ventilation and oblique angles result in extended pulse durations and added reflections of generated pressures. The objective of this dissertation is to develop experimental methodologies and numerical assessment tools to document and simulate failure sequences in composite sandwich connections under simulated internal blast loads.

The experimental research was conducted using the UCSD Blast Simulator, a one-of-a-kind system able to simulate explosive events without the use of explosive

materials and therefore without the associated fireballs. This is accomplished with an array of high velocity hydraulic actuators driven by a combined high pressure nitrogen/hydraulic energy source. In explosive field testing, video and data from instrumentation is often lost to the destructive nature of the blast environment. The simulator allows for the generation of high fidelity data that documents the response and failure progression in structural members, which in turn lends researchers the ability to develop and test damage mitigation strategies as well as design guidelines for critical infrastructure subject to impulsive loads.

First, the development of loading protocols were presented, in which pressures of prolonged durations distributed in multiple directions were achieved through the impact of high strength water filled bladders. These methods were then implemented in the testing of 90° composite sandwich joint specimens, which were reacted *via* adjustable steel gripping fixtures mounted in configurations suitable for impact with the high powered Blast Generators.

In an effort to create a numerical model capable of simulating the failure modes observed in the Blast Simulator experiments, a series of individual component tests were conducted to assist in the calibration of finite element material models. The characterization of the CFRP facesheet/balsa wood core sandwich material's failure properties in bending, shear and delamination were documented experimentally and validated numerically using LS-DYNA under both quasi-static and dynamic load rates.

Finally, the updated material models were implemented into the simulation of the Composite Joint Tests, which highlight the key mechanisms involved in connection failure and ultimately joint breach. The studies found that failure of the connection structure were functions of the bond strength between the panel facesheets and overlamine used to adhere the sandwich panels together, strongly coupled with the shear capacity of the individual panel cores. Recommendations for improved joint design were made and suggestions for extrapolation of the developed technologies to larger scale testing were offered.

Chapter 1

Introduction

Engineering efforts in the design, analysis and experimental testing of blast resistant structures are vital to human safety. Threats posed by accidental explosions and terrorist attacks have led to heavy research investments from both governmental and commercial industries worldwide to develop blast mitigation strategies and standards in protective design. Such mitigation strategies include the use of advanced materials such as composites, which have gained momentum in aerospace, marine, automotive and civil applications as fabrication techniques have become more efficient and their structural characteristics better understood.

Engineers have taken advantage of the increases in stiffness-to-weight and strength-to-weight ratios offered by composites to produce structures of greater size and progressively more complex in geometry. The performance and structural integrity of these large scale structures, even with advanced design concepts and the most resistant of materials, are highly contingent on assembly details and how individual components are connected.

The motivation behind the work presented in this dissertation was based on the need to develop experimental methods coupled to numerical models capable of accurately simulating and predicting composite connection failures under blast loading conditions. In an effort to address this necessity, an experimental procedure has been developed using the University of California, San Diego (UCSD) Blast Simulator. The Blast Simulator employs an array of ultra high speed actuators that can deliver controlled and repeatable simulated blast loads without the use of explosives. These features pro-

vide improved quantitative measurements as well as valuable visualization of structural behavior and failure progression, which are problematic to obtain in harsh field test environments where damage to instrumentation and loss of visual field are common.

The research described through the course of this dissertation focused on the following objectives:

- Develop experimental methods to deliver blast-like loads to structures of complex (non-flat) geometries, *i.e* those characterized by high curvatures;
- Develop and assess force measurement techniques to quantify imposed pressures in Blast Simulator experiments;
- Design reaction structures and tailorable composite joint specimen gripping fixtures suitable for testing with the UCSD Blast Simulator;
- Identify specific failures modes in a set of 90° composite sandwich joint specimens;
- Perform material experiments for the calibration and validation of finite element material models;
- Develop numerical models of the composite sandwich joint;
- Evaluate the presented experimental methods for extrapolation to larger structural assemblies;

This dissertation is divided into six chapters. Chapter 2 provides background for the several topics discussed throughout the presented research. The fundamentals of blast loading are first reviewed, describing the explosive process and the key parameters and equations used to define blast loads. A brief description of composite joint design follows, highlighting the current state of practice and the need for continued experimental research. Key features of the UCSD Blast Simulator are then described, including the advantages of the controlled test environment and examples of previous work completed at the facility. The final section review material models and numerical methods used in finite element simulations.

Chapter 3 describes the evolution of experimental loading procedures for loading structures with concave surfaces. To simulate the fluidic nature of the blast wave, water bladders of varying material and geometry were tested in a series of impact experiments. In parallel, a range of load measurement techniques were evaluated. The following section discusses the development of gripping fixtures and a reaction structure to test composite joint specimens using the Blast Simulator. The remainder of the chapter reports the findings from five Blast Simulator experiments conducted on composite sandwich joint specimens.

The results from Chapter 3 demonstrated the need for individual material system testing and Chapter 4 provides a synopsis of these investigations conducted at the various structural testing facilities of UCSD. This included both static and high rate testing of the shear, bending and adhesive properties critical to the characterization of the composite sandwich structure's failure modes.

In Chapter 5, the data from the previous chapter was used to calibrate finite element material models. The simulations are described in detail, highlighting important parameters affecting failure progression such as shear damage propagation in the core material, bending strain capacities of the FRP facesheets and delamination strength of the adhesive used to bond the materials together.

The experimental and numerical results from Chapters 3, 4 and 5 were then incorporated into a finite element model of the Composite Joint Tests outlined in Chapter 6. Force-time histories taken from embedded load cells were applied to a numerical joint model and the simulations were validated quantitatively through comparison of experimentally measured outputs and qualitatively *via* affirmation of experimental failure progression sequences.

The seventh and final chapter concludes the dissertation, summarizing the presented research and highlighting key findings. The testing methods are evaluated and recommendations for extending the experimental procedures to larger scale configurations and future research are made.

Chapter 2

Background

The focus of this chapter is to provide background information on the characteristics of the blast environment and present the need for evaluation of structural connections in composite sandwich joint structures under blast loads. The chapter is divided into four sections. First, the fundamentals of blast loading are reviewed, followed by a presentation of previous work done in the study of composite joints. The UCSD Blast Simulator is then described in detail, highlighting the systems functionality as well as previous research conducted at the facility. The final section summarizes aspects of numerical methods, specifically finite element simulation techniques and background on material models relevant to this dissertation.

2.1 Fundamentals of Blast Loading

Explosions

An explosion is typically categorized as a physical, nuclear or chemical event. Physical explosions are results of occurrences such as the eruption of a volcano, catastrophic failure of pressure vessels or the violent mixing of liquids at different temperatures. A nuclear explosion manifests from the energy released during the redistribution of protons and neutrons within different interacting atomic nuclei. The third type of explosion, and the one that is the focus of this section, are chemical explosions.

Chemical explosions occur when the fuel elements of an explosive compound

rapidly oxidize, a reaction known as combustion. Most practical explosives are solid or liquid in form, also known as *condensed* explosives, and the oxygen required to initiate combustion is typically contained within the compound. During the reaction process, the carbon and hydrogen atoms composing the fuel element of the explosive decompose violently, releasing heat and high pressure gas. When the velocity of the high pressure gas is significantly higher than the speed of sound of the material, the explosive reaction is referred to as a *detonation*, and results in a high intensity shock wave known as a *blast wave* [33]. Figure 2.1 distinguishes the fireball (heat) from the faster moving shock wave (gas).

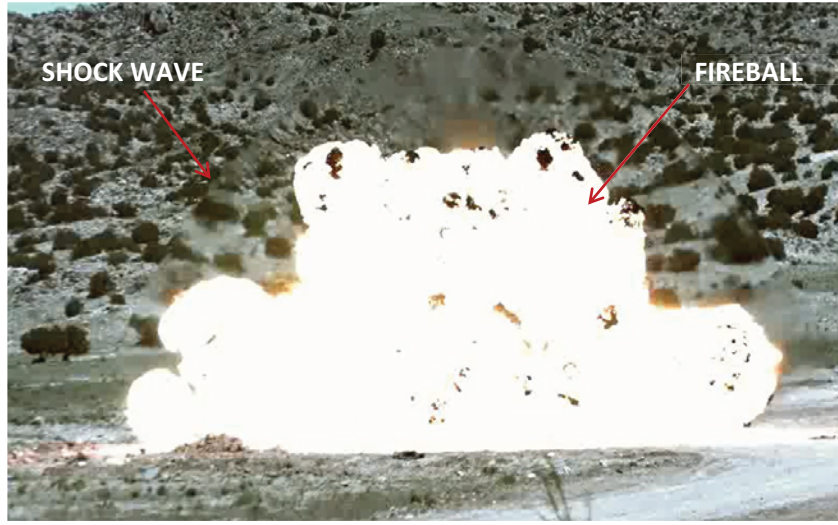


Figure 2.1: Photo of the shock wave and fireball created during an explosion.

A list of conventional explosives used in military and commercial applications can be seen in Table 2.2, along with values for mass specific energy and what is known as the *TNT equivalent*. Using TNT equivalence, written as W_{TNTeq} , is the universally accepted first step in the quantification of blast waves and is defined as the ratio of the explosive's specific energy, Q_e , to that of TNT [22].

$$W_{TNTeq} = \frac{Q_e}{Q_{TNT}} W_e \quad (2.1)$$

Table 2.1: Conversion Factors for Explosives, reproduced from [33]

Explosive	Mass Specific Energy Q_e (kJ/kg)	TNT Equivalent (Q_e/Q_{TNT})
TNT	4520	1.00
C4	-	1.19-1.37
Nitroglycerin dynamite	2710	0.60
Comp-B	5190	1.15
Semtex	5660	1.25
RDX	5360	1.19
ANFO	3930	0.87

Blast Waves

When an explosive is detonated, gases at high pressure and temperature are released violently, rapidly expanding and compressing the surrounding air. This results in a pressure drop near the reaction source, forcing the air outward in the form of a blast wave, which contains most of the energy released by the explosion. As the wave of compressed air travels away from the detonation point, the pressure and temperature of the gases decay. The moving gas molecules continue to possess momentum as the pressures fall below atmospheric pressure, generating a negative pressure phase, in which the wave reverses direction and continues to travel back towards the source until equilibrium is reached [33].

Blast waves are typically classified by their location relative to surrounding surfaces. When an explosive is detonated in free air, isolated from any sources of reflection, it is referred to as a *free airburst* and the recorded peak pressure is referred to as the *incident pressure*. Figure 2.2 illustrates this scenario.

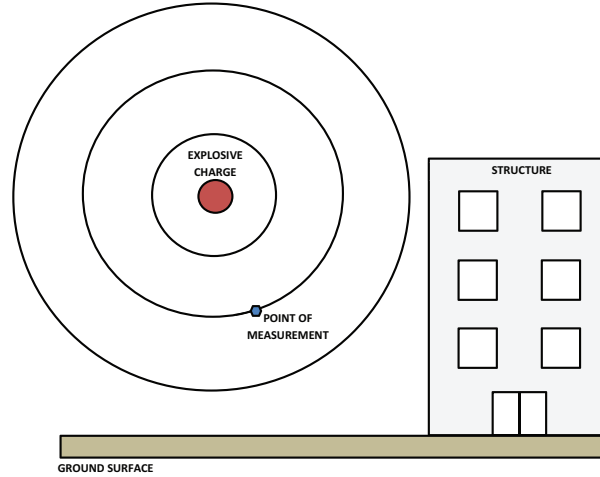


Figure 2.2: Schematic of a free airburst.

Although this scenario does not describe the loading directly applied to a surface of a structure, it is important in quantifying incident pressures generated from various charges at different distances from the detonation point, also known as *standoff*. An idealized pressure-time history resulting from the free airburst scenario is illustrated in Figure 2.3.

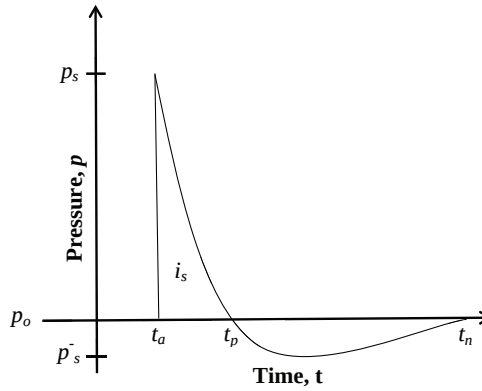


Figure 2.3: Characteristic pressure-time history of a free airburst.

At the time of arrival, t_a , the rise from ambient pressure, p_o , to the incident side-on overpressure, p_s , is assumed to be instantaneous. The pressure decays exponentially over the positive phase duration time, t_p , then falls below ambient pressure, *i.e.* p_s^- , during the negative phase duration, t_n .

Numerically, the approach suggested by Brode [6] estimates the peak incident overpressure as,

$$p_s = \frac{6.7}{Z^3} + 1 \text{ bar} \quad (p_s > 10 \text{ bar}) \quad (2.2)$$

and

$$p_s = \frac{.975}{Z} + \frac{1.455}{Z^2} + \frac{5.85}{Z^3} - .019 \text{ bar} \quad (.1 < p_s < 10 \text{ bar}) \quad (2.3)$$

The scaled distance, Z , is given by,

$$Z = \frac{R}{\sqrt[3]{W}} \quad (2.4)$$

where R is the standoff, *i.e.* the distance from the charge, and W is the TNT equivalent charge weight defined by Equation 2.1.

The exponential pressure decay may be described using the Friedlander equation,

$$p(t) = p_s \left[1 - \frac{t}{t_p} \right] e^{-\frac{bt}{t_p}} \quad (2.5)$$

where b is the waveform parameter [22].

Another parameter important to the analysis of blast waves is *specific impulse* i_s , which is the area under the positive phase of the pressure-time curve and is given by,

$$i_s = \int_{t_a}^{t_p} p_s(t) dt \quad (2.6)$$

For simplified analysis, the decay may be approximated as linear from t_a to t_p , and the impulse may be written as,

$$i_s = \frac{1}{2} t_p p_s \quad (2.7)$$

In contrast to a free airburst scenario, a *reflected overpressure* is caused by a detonation close to a reflecting surface, such as a structure and/or the ground. As the blast wave impinges onto the surface, the reflection causes further compression of the

molecules closest to the surface, resulting in recorded pressures of higher magnitude than that of the incident overpressure. The scenario is illustrated in Figure 2.4.

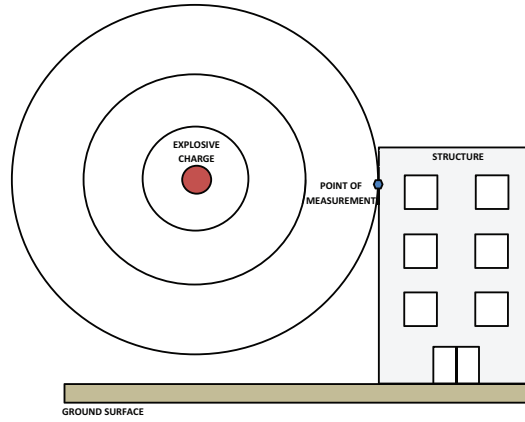


Figure 2.4: Schematic of a reflected airburst.

An idealized pressure-time history on a structure is shown in Figure 2.5, denoting the incident overpressure, p_s , and the reflected blast wave overpressure, p_r .

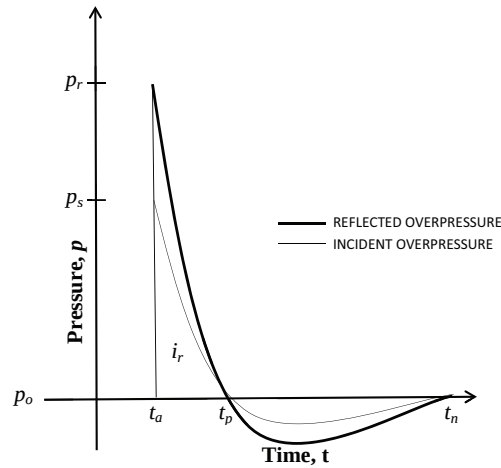


Figure 2.5: Characteristic pressure-time history of a reflected airburst.

To approximate peak reflected pressures, Rankine and Hugoniot [31] derived an equation for p_r as a function of ambient and static overpressure, p_{so}

$$p_r = 2p_{so} \left[\frac{7p_o + 4p_{so}}{7p_o + p_{so}} \right] \quad (2.8)$$

The increases in amplification from reflected overpressures are even more detrimental to structural integrity when the blast wave arrives at a corner or joint composed of multiple reflecting surfaces. The blast loading environment described in this dissertation is focused on the third classification of blast waves, called *internal* or *confined* explosions, which occur when a high energy explosive is detonated within a structure. Under these conditions, pressures are amplified and durations lengthened by means of additional reflections and gas confinement. An illustration of the scenario is depicted in Figure 2.6.

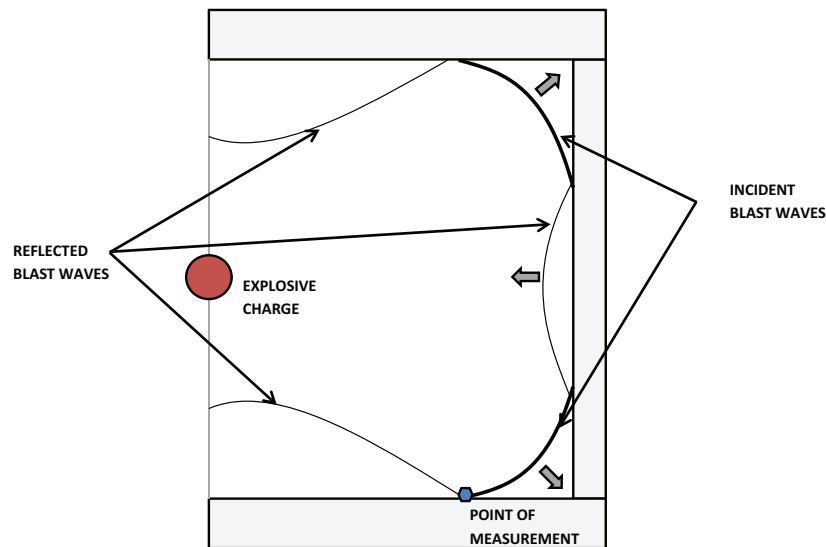


Figure 2.6: Schematic on an internal explosion, reproduced from [33].

The three phases following a detonation at a point on a surface inside a structure can be described in terms of the pressure time history shown in Figure 2.7. The initial shock loading phase, (a), denotes the arrival of the initial peak reflected shock overpressure, and is followed by successive reflected pulses from the surrounding surfaces, known as the reverberation phase, shown during (b). As the pressures decay and the reflective oscillations dissipate, the heated gases contained within the structure create what is referred to as a *quasi-static* or *gas overpressure* stage, phase (c). The gas overpressure continues to load the structure until vented via already existing openings or breach into an adjacent room or compartment due to structural failure [30].

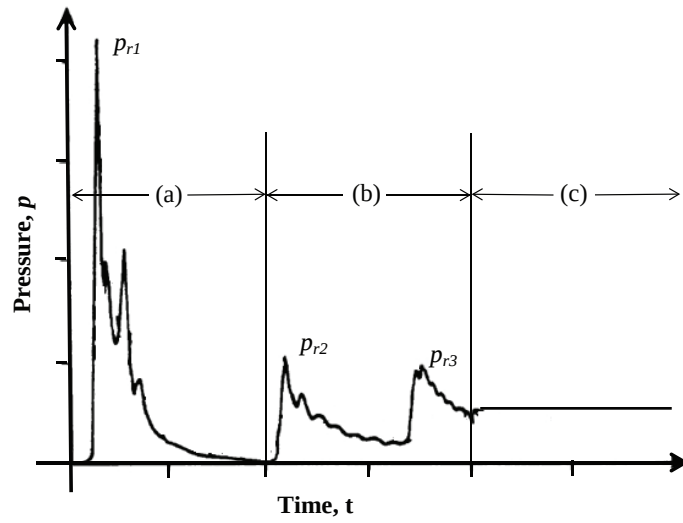


Figure 2.7: Characteristic pressure-time history of an internal explosion, reproduced from [13].

To quantify the additional pressures caused by the reflections to occur during the reverberation phase, Baker [1] suggested an approach in which the peak pressures of each sequential reflection and re-reflection are halved, while keeping the time delay between each reverberation constant, $2t_a$. Figure 2.8 illustrates the load approximation, which also assumes a maximum of three reflected pulses.

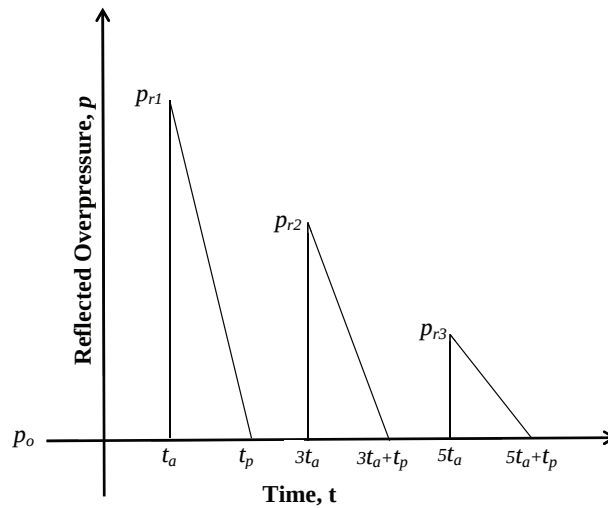


Figure 2.8: Characteristic pressure-time history of an internal explosion.

Mathematically the pressures are described as,

$$p_{r2} = \frac{1}{2}p_{r1} \quad p_{r3} = \frac{1}{2}p_{r2} = \frac{1}{4}p_{r1} \quad p_{r4} = 0 \quad (2.9)$$

and therefore the impulses as,

$$i_{r2} = \frac{1}{2}i_{r1} \quad i_{r3} = \frac{1}{2}i_{r2} = \frac{1}{4}i_{r1} \quad i_{r4} = 0 \quad (2.10)$$

The remaining quasi-static component of the blast wave pressure is a function of the type of explosive, volume of the structure of interest and the size of any venting, among other variables more specific to the geometry and materials of the structure [1]. The important features of this phase are used in the approximation used by [1], where the initial rise of the gas pressure loading is assumed linear up to the end of the reverberation stage, at which time the decaying pressure time history is assumed as,

$$p(t) = (p_{QS} + p_o)e^{(-2.13\tau)} \quad (2.11)$$

where p_{QS} is the peak quasi-static pressure, and p_o is the ambient pressure. Defining the total structural volume as V , α_e as the ratio of vent area to wall and roof area, A_s as the total inside wall and roof area of the structure, τ can be expressed as

$$\tau = \frac{\alpha_e A_s t a_0}{V} \quad (2.12)$$

where a_0 is the speed of sound at ambient conditions.

Ignoring the initial linear rise, the total gas pressure specific impulse can be written as

$$i_g = \int_0^{t_{max}} (p(t) - p_o)dt = \frac{p_{QS} + p_o}{C} \left[1 - e^{-Ct_{max}} \right] - p_o t_{max} \quad (2.13)$$

where

$$C = \frac{2.13\alpha_e A_s a_0}{V} \quad (2.14)$$

One of the objectives of the research described in this dissertation was to develop a methodology that could simulate the reflections and additional loadings caused by a

confined explosive event. More specifically, the aim was to simulate these loadings at the connection points of composite structures, *i.e.* corners and joints.

2.2 Composite Joint Connections

Early investigations on the strength and robustness of connections under blast loading have primarily focused on the behavior on concrete and steel joints. Krauthammer's [18] experimental and numerical work demonstrated the importance of connection reinforcing details, highlighting safety concerns within standard blast design procedures which disregard localized failure modes caused by the intense nature of the blast environment. The United Facility Criteria (UFC) Technical Manual TM 3-340-02 [37] provides various guidelines for the design of steel and concrete structures, which relies heavily on the plastic design concept demanding connections that fulfill functionality up to the ultimate load capacity of the structure. More specifically, the UFC criteria emphasizes that connections must be capable of transferring axial and shear loads as well as moments with sufficient strength, stiffness and rotation to allow structural members to reach fully plastic moments.

In recent years, the introduction of more commercially and economically available composite materials has created the demand for engineering investigations in the realm of connection behavior of high performance aerospace, marine and automotive applications. Many large scale composite structures utilize the concept of the composite sandwich, a multi-material configuration that provides a low weight structural member with high stiffness, strength and mechanical energy absorption characteristics [10].

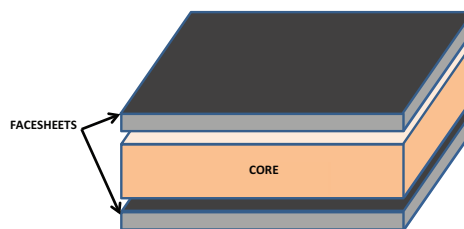


Figure 2.9: Composite sandwich structure.

Composite sandwich structures are generally composed of the three main parts

shown in Figure 2.9: two stiff, high strength and usually thin facesheets separated by a thicker, lightweight compressible core. The resultant assembly takes advantage of the properties of the individual materials to create structures with very high stiffness-to-weight and bending strength-to-weight ratios. Common facesheet materials include aluminum plates, fiber reinforced polymers (FRP) and high pressure laminates, while the softer, lighter core materials are generally realized in the form of structural foams, metal honeycombs and balsa wood [10].

One of the most cost effective and high quality manufacturing processes used for mass production of composite sandwich members is Vacuum Assisted Resin Transfer Molding (VARTM) [5]. In the VARTM process, the materials are adhered in a vacuum bag connected to injection/ejection vacuum lines. A high power vacuum slowly draws a low viscosity resin over the laminate until the bag is sealed to the mold, at which point the pressure reduction to below ambient creates an equal and even force over the entire surface of the envelope [12]. A schematic of the process is shown in Figure 2.10.

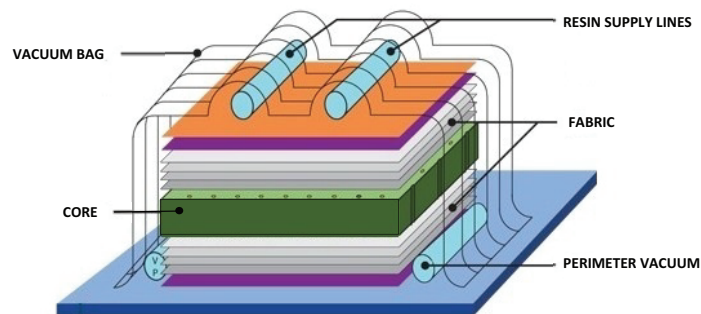


Figure 2.10: Schematic of resin infusion process, taken from [26].

After curing, the results are components with high fiber-to-resin ratios on the order of parts produced using autoclave methods in aerospace applications. The even clamping forces provided by the use of the atmosphere for confinement pressure allow assemblies to be molded into to a wide variety of custom shapes and sizes [9]. In turn, the VARTM process lends itself well to the joining of composite sandwich members.

Typically, large composite structures are assembled from multiple flat panels *via* VARTM [11]. Similar to steel and concrete connections of columns to beams, joint designs are intended to transfer tensile/compressive, flexural and shear forces from one

panel to the other [35]. Traditional mechanical fasteners have been used extensively in various composite to steel connections, however, mechanical fasteners often require the introduction of holes in the composite material, which can lead to stress concentrations triggering undesirable failures [28].

A typical configuration for a 90° sandwich joint is shown in Figure 2.11.

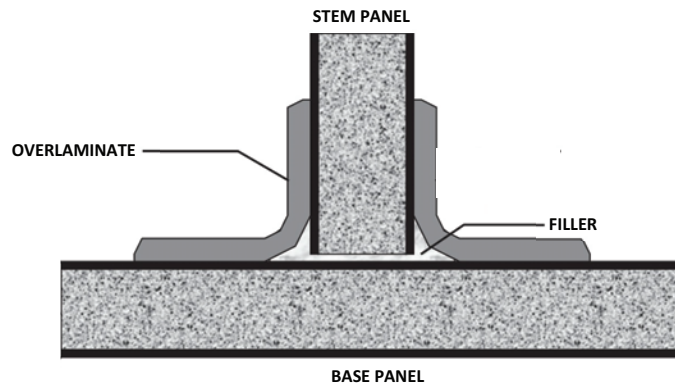


Figure 2.11: Typical composite sandwich joint construction [28].

A curved attachment lap or *overlaminates* is adhered to both panels *via* VARTM, forcing any gaps between the interfaces to be filled with resin. Failure strength of the overlaminates to facesheet interface bond have been studied by [15], [4] and most notably [19], in which a numerical crack close technique was used to investigate strain energy release rates at the points of initial debonding to predict failure loads and crack growth mechanisms. The most common observed failures were delamination of the overlaminates due to voids and cracks in the resin beneath the overlaminates as well as the debonding at the connection point of the two panels [19]. These types of defects are illustrated in Figure 2.12.

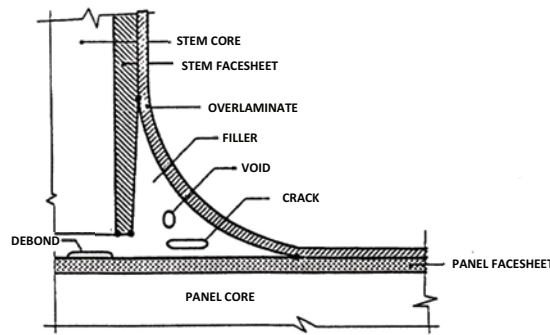


Figure 2.12: Types of composite sandwich joint manufacturing defects [35].

The European Cooperation for the Long-term In Defence (EUCLID) have done extensive studies on the failures of composite sandwich T-joints, specifically in the realm of PVC foam cored structures with GFRP facesheets. The experimental work from the ongoing EUCLID project has shown consistent results: failure of the overlaminate from the base panel leading to joint fracture at modest transverse loads [14]. In a set of studies conducted by [23]], the main variables that affected overlaminate to base panel detachment were surface treatments, radius of the attached panel, and lay up of the overlaminate. A typical connection failure is shown in Figure 2.13, demonstrating complete detachment of the panels.

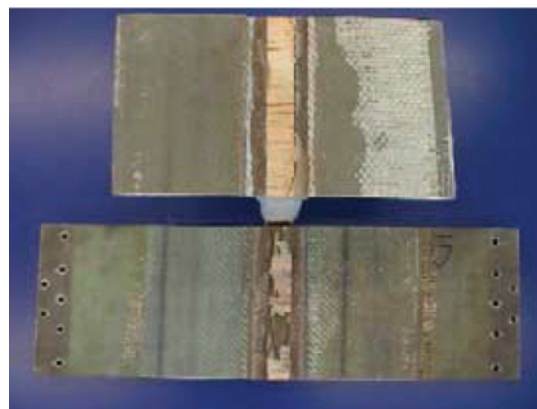


Figure 2.13: Example of complete joint failure due to overlaminate delamination [14].

More recent designs have incorporated the use of triangular stiffeners (*i.e.* fillets) made of the core material placed on either side of the cross or *stem* panel, as seen in Figure 2.14.

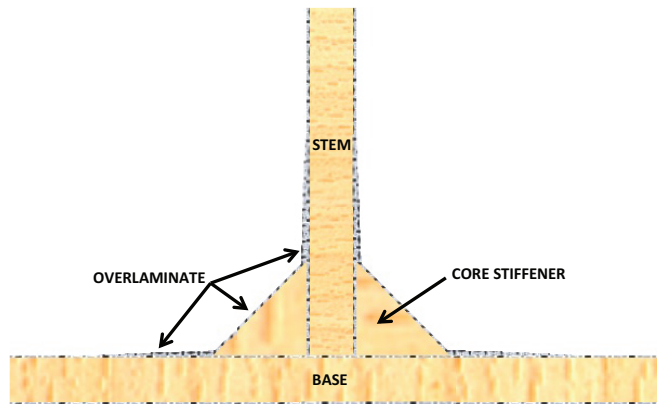


Figure 2.14: Composite connection utilizing triangular core material stiffeners/fillets.

The design was aimed at a more rotationally flexible joint that would mitigate the edge bending moments at the source of overlamine peel in the previous design while allowing more load absorption and therefore deformation of the stem panel [23]. In experimental and numerical work completed by [36], the use of triangular stiffeners demonstrated 20-25% increases in joint load capacity. [17] tested the triangular stiffened design both statically and dynamically, using balsa as the core material along with facesheets made of 2D and 3D woven CFRP fabrics. The improved design exhibited close to double the load capacity of the baseline joints without stiffeners, inducing various failures before reaching ultimate capacity including core shear failure through the stiffener, debonding near the connection point and delamination of the composite facesheets, all of which are noted in Figure 2.15.

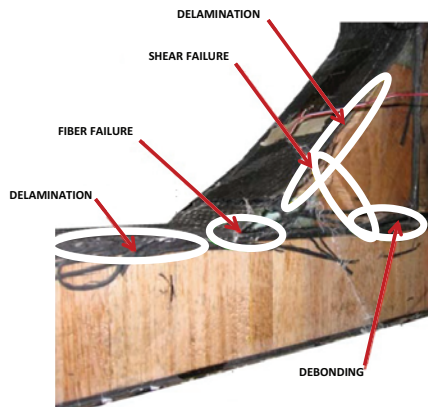


Figure 2.15: Example of failure in stiffened joint design [17].

The composite connections of interest in this research were provided in the form of 90° sandwich structures, composed of 0.125 in FRP facesheets and a 2 in balsa core. The two outside CFRP outer skins were made of a carbon-vinylester composite system with typical effective in-plane elastic properties shown in Table 2.2. Typical 9.5 lb/ft^3 Baltek SB Structural End-Grain Balsa materials [3] were assumed for the core, also reported in Table 2.2. A snapshot showing the sandwich material dimensions and orientation of the grain in the balsa core is shown in Figure 2.16.

Table 2.2: Composite sandwich material properties.

Material	E_x (ksi)	E_y (ksi)	G_{xy} (ksi)
CFRP	6100	6100	2200
Balsa	518	22.0	23.2

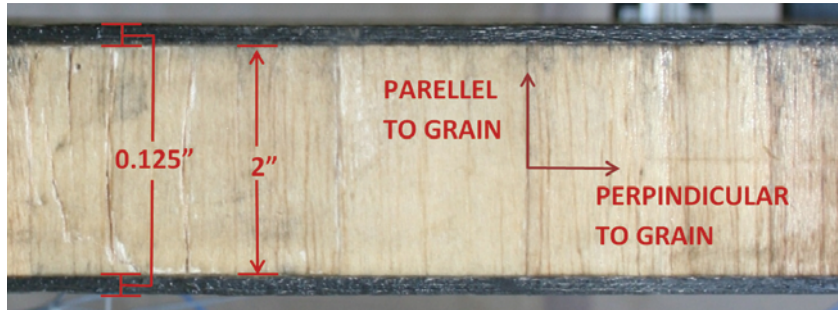


Figure 2.16: Photo of composite sandwich material denoting dimensions and grain direction in the balsa core.

The connections were composed of a 24 in *stem* panel joined to a 48 in *base* panel to form a 90° T-joint. To each side of the stem, two 6 in x 6 in triangular balsa support members were adhered under an FRP overlamine *via* VARTM. A photo of the joint section can be seen in Figure 2.17.

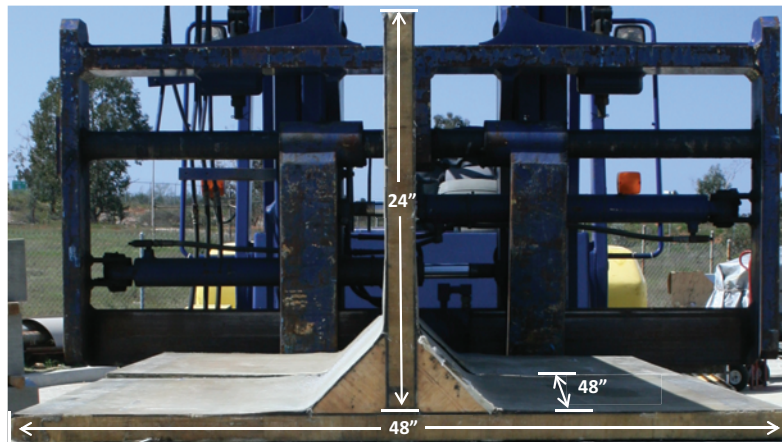


Figure 2.17: Photo and dimensions of 90° composite sandwich joint.

The focus of this dissertation was to investigate the performance of these joint specimens under blast-like loading conditions. Typical *box tests*, a term commonly used to describe the blast testing of a prototype structure or substructure with a single explosive experiment, often limit the amount of quantitative and qualitative data available to assist in the full calibration of a predictive numerical model. The following section describes the UCSD Blast Simulator Facility, a one-of-a-kind system able to simulate blast

events without the use of explosive materials and therefore without the associated fire-balls. These features allow for the conduction of controlled experiments, which produce repeatable data sets and high quality visuals from the use of ultra high speed video, all essentials for reliable analytic tools required in the development of efficient structural blast-mitigation strategies.

2.3 The UCSD Blast Simulator Facility

The UCSD Blast Simulator Facility, rendered in Figure 2.18, is configured along a west facing, base isolated concrete reaction floor and another south facing fixed reaction floor. Both floor slabs run perpendicular to a fixed reaction wall, to which the actuators are attached. Specimens placed in the west configuration are reacted off a 18 ft tall moveable reaction wall, whereas in the south configuration reaction masses must be fabricated, typically out of concrete blocks. At the intersection of the two slabs, a 12 ft fixed reaction wall can be mounted with up to four BGs vertically on the west face as is typically done for single story structures such as concrete walls or steel columns. The sets of joint experiments presented in this dissertation were the first Blast Simulator tests to be conducted along the south side of the facility.

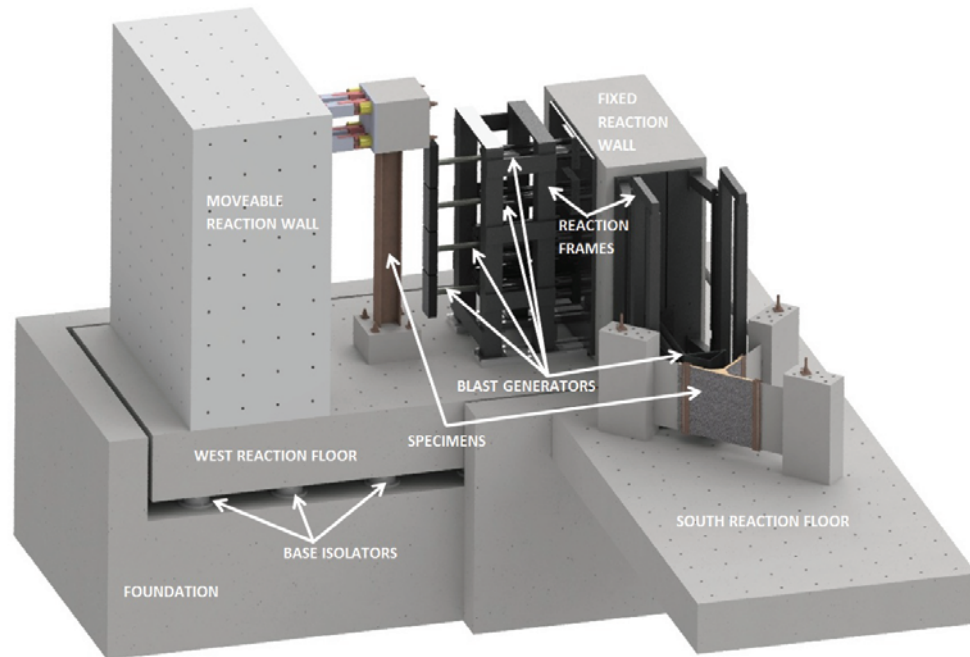


Figure 2.18: UCSD Blast Simulator Facility Layout.

The most unique feature of the Blast Simulator is an array of high velocity hydraulic actuators driven by a combined high pressure nitrogen/hydraulic energy source. Each actuator, referred to as a Blast Generator (BG), is depicted in Figure 2.19, illustrating locations of the impacting mass, piston, control valves, and accumulators.

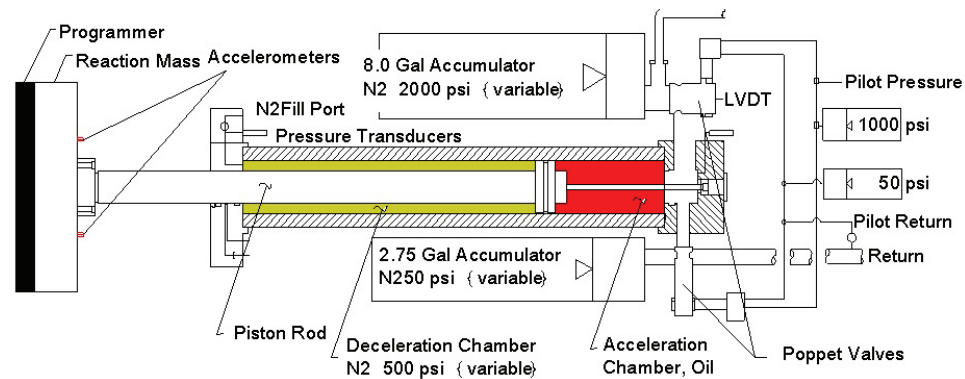


Figure 2.19: Schematic of Blast Generator.

To achieve the necessary pressures, nitrogen is first pumped into an accumulator followed by a volume of oil that is compressed to pressures up to 5,000 psi. The

oil flow into the acceleration port of the actuator is regulated through ultra high speed servo-controlled poppet valves. The poppet valves are opened and the pressurized oil drives the piston/impacting mass assembly towards the specimen. At impact, a smaller servo-controlled, return poppet valves opens, and a deceleration chamber filled with pressurized nitrogen forces the oil out, retracting the impacting mass. Pressure transducers and magnetostrictive position sensors give precise feedback on the accumulator pressures and impactor positions. User supplied inputs such as impacting mass, target velocity, chamber pressures and valve timings all play critical roles in the control of the instrument. The UCSD Blast Simulator is described in detail, including calibration of the device by Hegemier [16]. A photo of the one of the Blast Generators is shown in Figure 2.20.



Figure 2.20: Photo of a Blast Generator.

Previous to the present study, impulsive loads were delivered onto flat structures such as walls or columns through the use of a *programmer* shown in Figure 2.21, which is made of a viscoelastic urethane material developed by Material Testing Systems (MTS). The approximately 2 in thick pad is typically affixed to the end of the impacting mass, and the highly deformable material assists in the tailoring of magnitude and duration of the applied pulse. One goal of this dissertation was to develop a methodology to load non-flat or *complex* geometries using the Blast Simulator, and details of

these trials are discussed in full in Chapter 3.

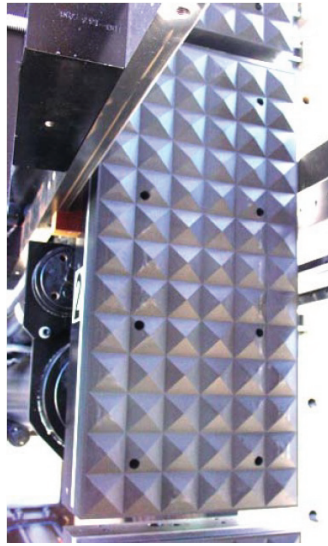


Figure 2.21: Urethane impacting pad.

Another attractive feature of the UCSD Blast Simulator is the improved ability to monitor failure modes during the small time scales involved in the high speed investigations. In explosive field testing, video and data from instrumentation is often lost due to the destructive nature of the blast environment. With no fireball, a structure can be tested repeatedly in a controlled environment, resulting in both high quality quantitative and qualitative data sets. Specimen behavior is captured throughout the course of the event through the use of Phantom cameras capable of recording at maximum rates of 10,000 frames per second.

Examples of UCSD Blast Simulator experiments are documented in previous research investigated at the facility. Figure 2.22 shows the sequence of events for one of many tests conducted during the research completed by Rodriguez [32], in which concrete columns were tested to develop structural hardening strategies such as CFRP retrofits.

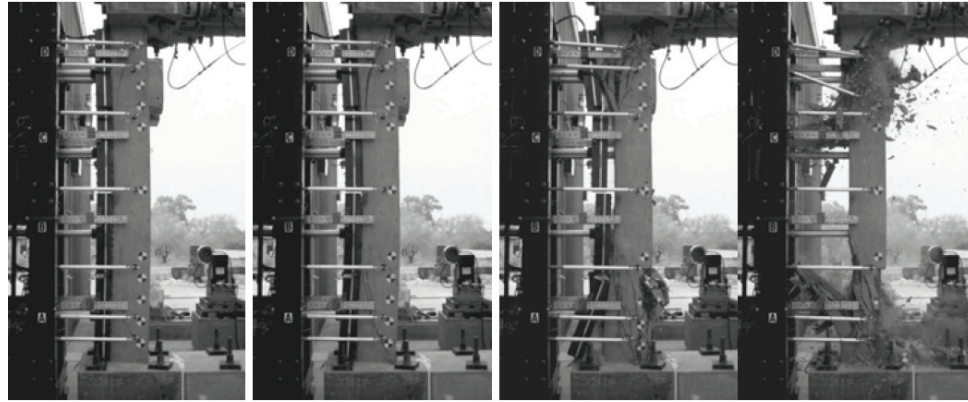


Figure 2.22: Damage evolution of a reinforced concrete column [32].

In 2003, Oesterle [27] conducted a set of studies on retrofit strategies for concrete and CMU walls, an example of which is shown in Figure 2.23.



Figure 2.23: Response of CMU wall retrofitted with polyurea catcher system [27].

The deformation of steel structures was also investigated by Stewart [34], who studied the effects of blast simulated loading on steel columns in the strong and weak axes, and example of which is seen in Figure 2.24.

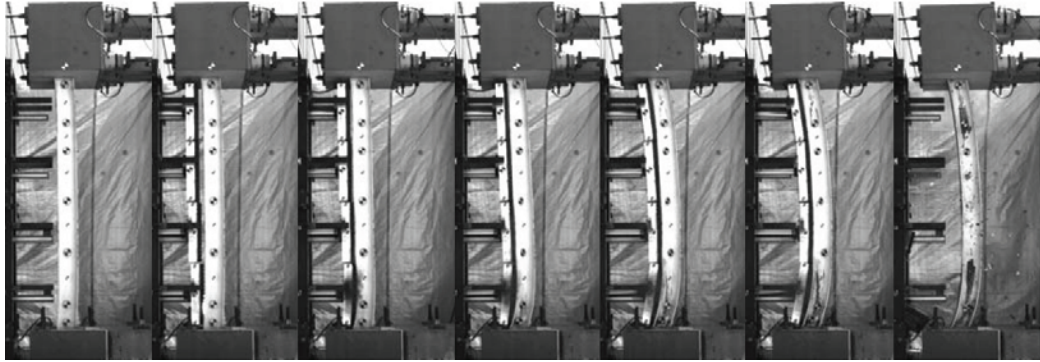


Figure 2.24: Severe deformation incurred by a W10x132 steel section under simulated truck bomb loads [34].

The high quality data produced from Blast Simulator experiments is extremely useful in the development and validation of predictive numerical models. In many cases, the accuracy of a finite element model is highly dependant on material input parameters, especially in the high strain rate scenarios that occur from a blast or blast simulated event. The following section provides background on the material models and simulation techniques used throughout the course of this dissertation.

2.4 Numerical Simulation

The finite element code, LS-DYNA, was used throughout the the course of this research program. LS-DYNA is an explicit code offering a wide range of element formulations and material models [21]. This dissertation focused on the study of composite sandwich materials, specifically carbon-fiber-reinforced polymers (CFRP) facesheets bounding a balsa wood core. The material models utilized in the the finite element simulations presented in Chapters 4 and 5 are first reviewed, followed by a synopsis of modeling techniques used to simulate delamination.

CFRP Material Model

The CFRP facesheets were modeled using LS-DYNA's material model 22, a Chang-Chang composite damage model. The model assigns orthotropic material stiffness and failure properties to shell or solid elements through the selection of a local

material coordinate system in which composite directionality can be prescribed. Failure in *MAT_COMPOSITE_DAMAGE is based on the Chang-Chang criteria, a widely used composite failure model that uses five material strength parameters obtained from material testing [20]:

$$S_1, \text{longitudinal tensile strength} \quad (2.15)$$

$$S_2, \text{transverse tensile strength} \quad (2.16)$$

$$S_{12}, \text{shear strength} \quad (2.17)$$

$$C_2, \text{transverse compressive strength} \quad (2.18)$$

$$\alpha_1, \text{nonlinear shear stress parameter} \quad (2.19)$$

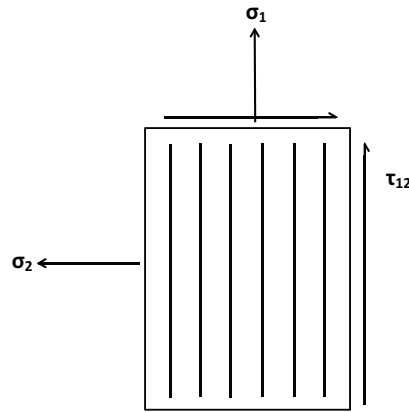


Figure 2.25: Stresses in fiber direction, σ_1 , matrix direction, σ_2 , and shear stress, τ_{12} .

Fiber orientations are shown in Figure 2.25. During the calculation, the code evaluates the current stress state against the following parameters defining three failure criteria: fiber breakage, F_{fiber} , compressive failure F_{comp} , and matrix cracking, F_{matrix} , defined as:

$$F_{fiber} = \left(\frac{\sigma_1}{S_1} \right)^2 + \bar{\tau} \quad (2.20)$$

$$F_{comp} = \left(\frac{\sigma_2}{2S_{12}} \right)^2 + \left[\left(\frac{C_2}{2S_{12}} \right)^2 - 1 \right] \frac{\sigma_2}{C_2} + \bar{\tau} \quad (2.21)$$

$$F_{matrix} = \left(\frac{\sigma_2}{S_2} \right)^2 + \bar{\tau} \quad (2.22)$$

where $\bar{\tau}$ is the ratio of the shear stress to the shear strength defined as

$$\bar{\tau} = \frac{\frac{\tau_{12}^2}{2G_{12}} + \frac{3}{4}\alpha\tau_{12}^4}{\frac{S_{12}^2}{2G_{12}} + \frac{3}{4}\alpha S_{12}^4} \quad (2.23)$$

Failure is assumed whenever F_{fiber} , F_{comp} , or $F_{matrix} > 1$ and subsequently the material constants E_2 , G_{12} , ν_1 and ν_2 are set to zero [20].

Balsa Material Model

LS-DYNA offers a comprehensive material model available for wood, material model 143, *MAT_WOOD, capable of incorporating transversely isotropic constitutive equations, yield surface with plastic flow, hardening, damage-based softening with erosion and rate effects [24].

Figure 2.26 shows wood's typical structure, with the longitudinal direction (z) defining the grain direction and the two planes perpendicular to the grain, (r) and (θ), considered as planes of elastic symmetry.

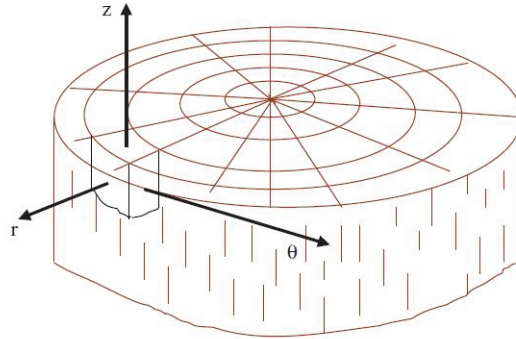


Figure 2.26: Balsa wood directionality taken from [38].

In general, wood is a complex anisotropic material and exhibits material property differences as a function of various conditions including moisture content, temperature, and load rate [38]. Several studies using LS-DYNA's wood model, most notably

the Federal Highway Administrations's *Evaluation of LS-DYNA Wood Material Model* [25], in which a series of numerical studies were compared to experimental results to assess the accuracy of the model and various of it's 29 input parameters. The evaluation focuses primarily on southern yellow pine and Douglas fir, as the model was developed specifically for prediction of wood components used in roadside safety structures and therefore provides default parameters for those types of wood. Limited amount of data is available when using the model for for the simulation of balsa. [38] modeled balsa sandwich structures under the high velocity impacts of projectiles and found good correlation to test data with respect to energy absorption characteristics.

Balsa panels used in sandwich construction are typically constructed in a tiled mosaic, where balsa wood of varying density and stiffness is adhered together in small blocks, as shown in Figure 2.27. The degree in to which material properties vary in a single panel depends on application and manufacturer, and this posed additional challenges in the effort to calibrate the material models numerically, which is discussed in detail in Chapter 5.



Figure 2.27: Typical balsa panel construction.

The reduced form of the Modified Hashin criteria allows wood to fail in the perpendicular modes (along the grain) prior to failure in the parallel mode (across the grain) which otherwise would lead to catastrophic failure [24]. The following six material ultimate strength parameters are used for the wood model failure criterion,

$$X_T, \text{Tensile strength parallel to the grain} \quad (2.24)$$

$$X_C, \text{Compressive strength parallel to the grain} \quad (2.25)$$

$$Y_T, \text{Tensile strength perpendicular to the grain} \quad (2.26)$$

$$Y_C, \text{Compressive strength perpendicular to the grain} \quad (2.27)$$

$$S_{\parallel}, \text{Shear strength parallel to the grain} \quad (2.28)$$

$$S_{\perp}, \text{Shear strength perpendicular to the grain} \quad (2.29)$$

These values are compared to two of the five invariants of a transversely isotropic material in both the parallel and perpendicular to the grain directions.

The invariants $I_1 = \sigma_{11}$ and $I_4 = \sigma_{12}^2 + \sigma_{13}^2$ are used for the parallel mode and the Modified Hashin criteria predicts that the normal and shear stresses are mutually weakening in the form,

$$f_{\parallel} = \frac{\sigma_{11}}{X^2} + \frac{(\sigma_{12}^2 + \sigma_{13}^2)}{S_{\parallel}^2} - 1 \quad (2.30)$$

where $X = X_T$ when σ_{11} is positive (tensile) and $X = X_C$ when σ_{11} is negative (compressive).

For the perpendicular modes, invariants $I_2 = \sigma_{22} + \sigma_{33}$ and $I_3 = \sigma_{23}^2 - \sigma_{22}\sigma_{33}$ are used to define the failure criteria in the form,

$$f_{\perp} = \frac{(\sigma_{22} + \sigma_{33})^2}{Y^2} + \frac{(\sigma_{23}^2 - \sigma_{22}\sigma_{33})}{S_{\perp}^2} - 1 \quad (2.31)$$

where $Y = Y_T$ for $\sigma_{22} + \sigma_{33} > 0$ and $Y = Y_C$ for $\sigma_{22} + \sigma_{33} < 0$.

MAT_143 models strength degradation with a damage formulation utilizing a scalar damage parameter that transforms the stress tensor in the undamaged state into a stress tensor in the damaged state. When element damage approaches 99 percent, the strength and stiffness approach 1 percent of their original values, and therefore the element erodes [24].

The damage model for wood is based on fracture energy, which is defined as the critical strain energy dissipated per unit of newly created fracture surface area [24]. For three dimensional problems, Mode I and II fracture intensities are related to fracture energies through the following analytical expression.

$$G_{fI} = C_I K_I^2 \quad (2.32)$$

$$G_{fII} = C_{II} K_{II}^2 \quad (2.33)$$

where C_I and C_{II} are constants related to the moduli of an orthotropic material through

$$C_I = \left(\frac{S_{11}S_{22}}{2} \right)^{1/2} \left[\left(\frac{S_{22}}{S_{11}} \right) + \left(\frac{2S_{12} + S_{66}}{2S_{11}} \right) \right]^{1/2} \quad (2.34)$$

$$C_{II} = \frac{S_{11}}{\sqrt{2}} \left[\left(\frac{S_{22}}{S_{11}} \right) + \left(\frac{2S_{12} + S_{66}}{2S_{11}} \right) \right]^{1/2} \quad (2.35)$$

in which S_{ij} are reciprocals of the elastic moduli [24].

Additional details of the damage model are discussed in detail in Chapter 5, as fracture energies played an important role in the calibration of the material models used to simulate the balsa behaviors observed in experiment.

Delamination Model

As previously discussed, the evaluation of the bond strength at the facesheet-core interface played an important role in the ability to predict failure progression in the sandwich panel joint structures.

In order to numerically simulate the strength of the bond, LS-DYNA's tiebreak contact option was utilized. Traditional contacts transmit only compressive forces, hence provide zero resistance when pulled apart. The tiebreak formulation offers the ability to transmit both tensile and compressive forces as well as a computationally less expensive option than cohesive elements. Another benefit of the tiebreak was that after separation, the contact still retains its ability to transmit compressive forces and act as a classical contact preventing unrealistic penetrations [2].

The tiebreak's resistance to compressive and tensile forces is simulated using a linear contact spring for each master-segment/slave-node pair. The numerical representation of a tiebreak is illustrated in Figure 2.28.

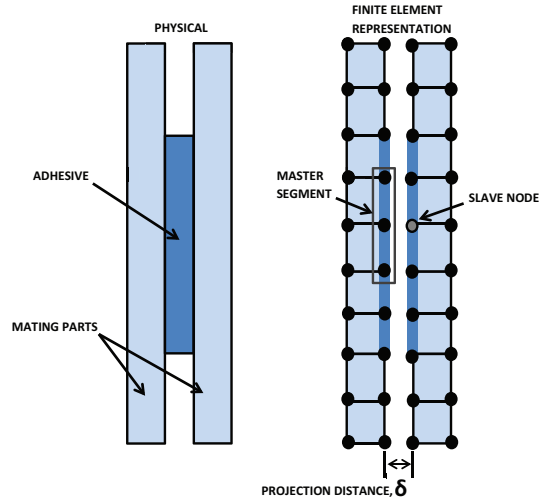


Figure 2.28: Numerical representation of LS-DYNA tiebreak.

When the distance between the two, δ , is negative, this *penetration depth* is used to calculate the slave nodal force, f_s , which in turn calculates the contact stiffness, K_c , using

$$f_s = K_c \delta \quad (2.36)$$

Based on the spring force and the area of the segment, contact stresses are computed and decomposed into normal and shear components. The absolute value of these components are normalized by user input parameters NFLS, the Normal Failure Stress, and SFLS, the Shear Failure Stress and then squared, denoted as R_N and R_S in Figure 2.29.

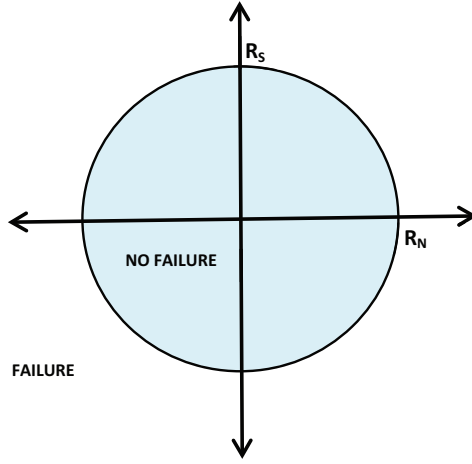


Figure 2.29: Graphical representation of tiebreak failure surface.

where

$$R_N = \left(\frac{|f_n|}{NFLS} \right)^2 \quad (2.37)$$

and

$$R_S = \left(\frac{|f_s|}{SFLS} \right)^2 \quad (2.38)$$

If the sum of the ratios is equal or greater than 1, the tensile resistance of the linear contact spring is deactivated and the slave node is allowed to pull away from the master segment [2].

$$R_N + R_S \geq 1 \quad (2.39)$$

Each node-segment pair is evaluated independently, enabling the ability to model peeling or unzipping along the interface. Moreover, utilizing LS-DYNA contact option *CONTACT_AUTOMATIC_ONE_WAY_SURFACE_TO_SURFACE_TIEBREAK allows the user to take advantage of the built in damage model for solid elements referred in the literature as Option 6. This valuable feature scales the stress components after the failure criteria are met linearly until a critical crack opening depth is reached, designated at *PARAM* [2]. The damage formulation is illustrated graphically in Figure 2.30.

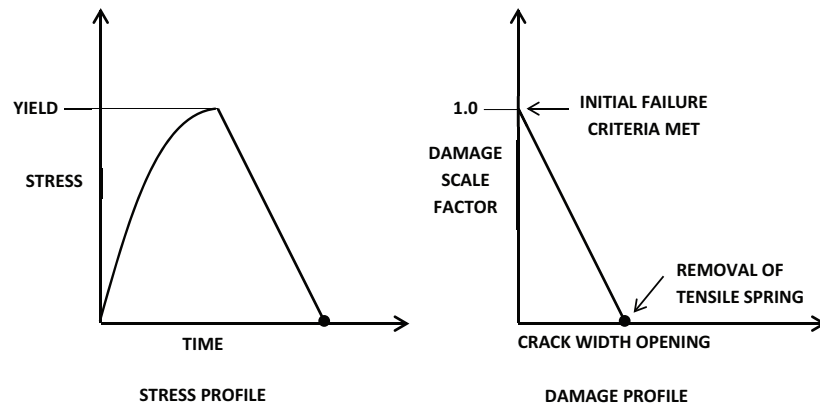


Figure 2.30: Graphical representation of tiebreak damage formulation applied after initial tiebreak failure.

Chapter 3

Structural Tests

This chapter describes the development of loading protocols, data acquisition techniques and reaction structure designs used in a series of simulated blast tests on composite sandwich joint structures.

First, a series of impact tests is presented, in which water filled bladders mounted on steel masses were impacted at different velocities and with varied bladder configurations to investigate resultant pressures pulse characteristics. A series of one and two dimensional tests were conducted and pressures and associated impulses were measured in the both normal and lateral directions. In the following section, the results from the impact tests were used as a basis for investigating load cell configurations suitable for embedment in the composite sandwich material to measure induced loads.

The second half of the chapter focuses on the design and results from Blast Simulator tests conducted on the composite sandwich joints. The first section describes the investigation of representative bladder/impacting mass configurations appropriate for use with the concave geometries of the joints. The ensuing section discusses the constraints imposed by the facility geometry in reference to possible reaction structure configurations and requirements for specimen gripping fixtures. The remainder of the chapter is devoted to the documentation of five composite sandwich joint experiments and the presentation of observed structural deformations and failure patterns.

3.1 Loading Complex Geometries

The effort in the following experiments was aimed at lengthening the pulse durations and increasing reflections seen in previous Blast Simulator research, discussed in Chapter 2, to more accurately simulate blast wave profiles in internal blast scenarios. This required a compliant medium capable of transferring momentum in multiple directions, which gave early rise to the concept of using water. To this end, the first tests focused on finding a suitable and controllable fluid confinement method.

3.1.1 Preliminary 1D Impact Tests

The first series of one dimensional (1D) impact tests was conducted on three bladders obtained from a waterbed manufacturer, who was asked to fabricate the typical vinyl bags in 16 in wide by 16 in tall geometries to be tested in the setup seen in Figure 3.1. The bladders used for each test are shown in Figure 3.2.

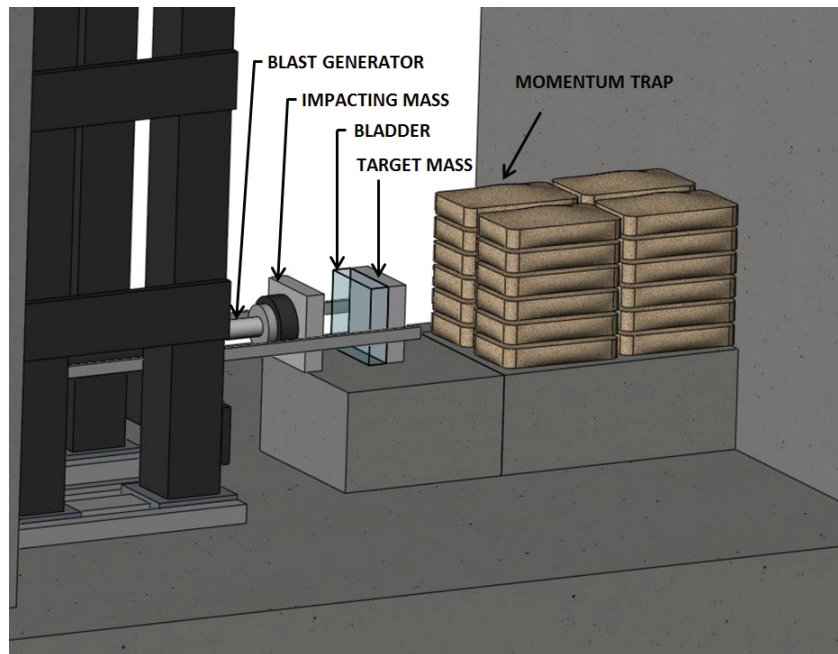


Figure 3.1: Schematic of 1-D Impact Test setup.

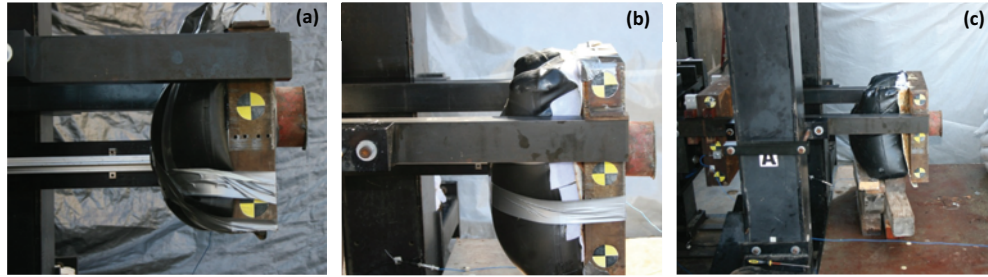


Figure 3.2: Photos of water bladders used for 1D Impact Test 1 (a), Test 2 (b), & Test 3 (c).

The bladders were placed on a 16 in x 16 in x 3 in steel target mass that rested on support rails in front of a 16 in x 16 in x 3 in steel impacting mass. The first two tests were conducted at 394 in/s (10 m/s) and 591 in/s (15 m/s) on 4 in thick bladders (unfilled) and the third on a 6 in thick bladder at 591 in/s (15 m/s). The conditions for each test are summarized in Table 3.1 and the sequence of events for 1D Impact Test 1 are shown in Figure 3.3.

Table 3.1: Test conditions of vinyl water bladder experiments.

Test	Velocity (in/s) [m/s]	Thickness (in)	Mounting Method
1	394 [10]	4	Duct tape
2	591 [15]	4	Duct tape
3	591 [15]	6	Velcro

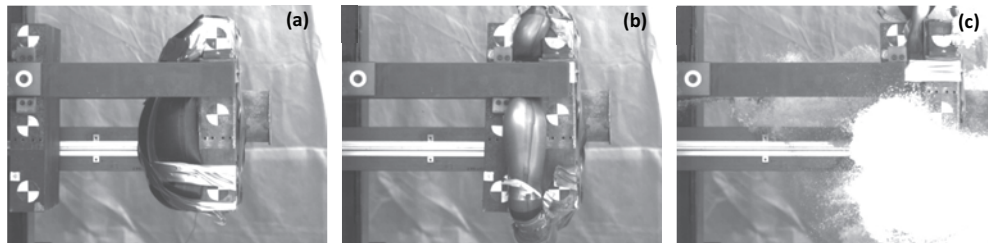


Figure 3.3: Sequence of events for 1D Impact Test 1.

Accelerations during the experiment were measured using 10k g piezoelectric

shock accelerometers centered on the back side of the target mass and the time histories are plotted in Figure 3.4.

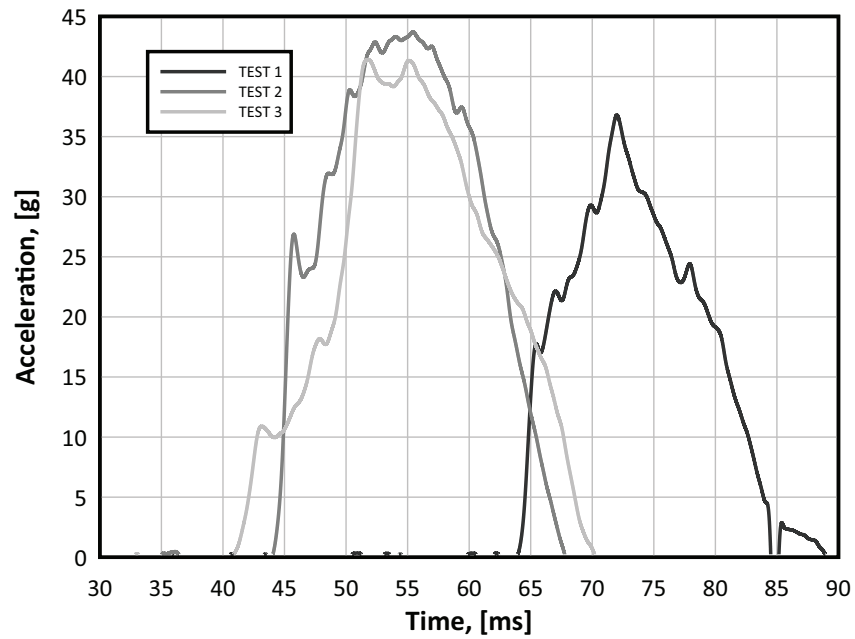


Figure 3.4: Target mass acceleration histories for 1D Impact Tests 1, 2 & 3.

Multiplying by the mass of the target plate (230 lbf) and dividing by impact area 256 in^2 the converted pressure time histories for the three tests are shown in Figure 3.5 and associated impulses in Figure 3.6.

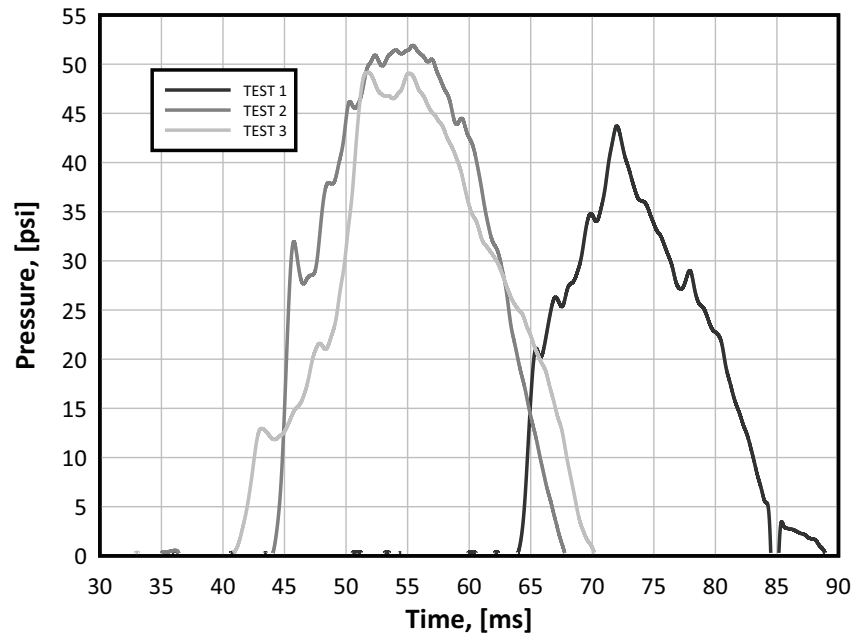


Figure 3.5: Converted pressure time histories for 1D Impact Tests 1, 2 & 3.

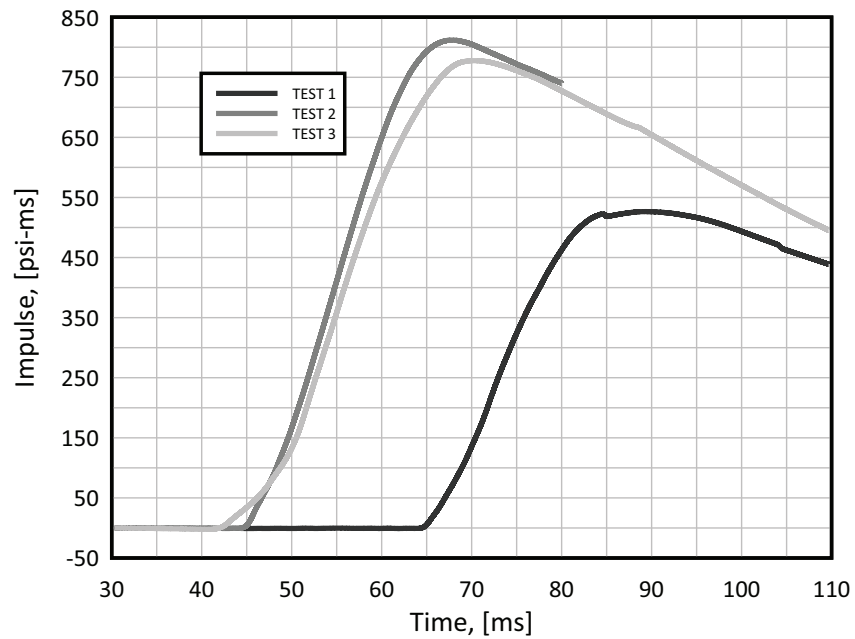


Figure 3.6: Impulses for 1D Impact Tests 1, 2 & 3.

The increase in velocity from 394 in/s in Test 1 to 591 in/s in Test 2 caused an increase in pressure of 7.5 psi. The increase in bladder thickness had very little

effect on peak pressure as both pulses reached close to 50 psi, however the 6 in bladder was impacted 2.5 ms prior to the 4 in bladder and had a 5.5 ms longer duration. Tests 2 & 3 demonstrated a significant increase in impulses of 818 psi-ms and 780 psi-ms respectively, compared to 530 psi-ms for Test 1. The pulses demonstrated durations on the order of 30-40 ms, far longer than the durations of loads imparted by the flat impacting mass assemblies used in prior experiments which generally generated pulses less than 5 ms in duration. However, the profiles denoted symmetric rises to and drops from peak pressures, uncharacteristic of the near instantaneous and exponential decay of the typical blast wave profiles discussed in Chapter 2. Moreover, when filled, the bladders displayed significant deformations or bulges due to the weight of the water. An improved water confinement method was examined next in order to control the filled bladder shape as well as provide a less invasive method of affixing the loading medium to the target mass.

The second set of bladders were obtained from Interstate Products, a company that produces storage tanks for large scale water containment as well as hazardous material control. The most compliant water containment materials used by the manufacturer were woven polyester and nylon fabric *geomembrane* material systems produced by Seamen Inc. Material properties for the bladder materials tested are presented in Table 3.2.

Table 3.2: Material properties for the two selected material systems.

Material type	Fabric type	Thickness (in)	Weight (oz/yd ²)	Burst strength (lbf)	Tear strength (lbf)
XR5	Polyester	0.03	6.5	650	35
U1940	Nylon	0.045	13	1200	40

To further improve bladder shape, the new design incorporated *baffles*, a term used to describe internal structures that redirect fluid flow or reinforce gas filled containers. The purposes of the baffles were, *inter alia*, to control the flow of water within the bladders, and to provide additional structural reinforcement. In order to maintain flow direction, the baffles were designed to run from front to back, creating the chambers or compartments shown in Figure 3.7.



Figure 3.7: Photo of typical vertical internal baffles used to control water flow within the bladders and provide additional structural reinforcement.

Strapping eyelets were added along the back side of the bladder to attach it to the target mass without interfering with the impact. The mounted bladder is shown in Figure 3.8.

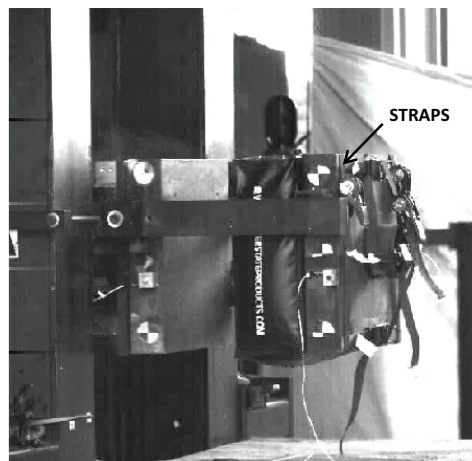


Figure 3.8: Photo of improved bladder design mounted to target mass with ratchet straps.

To measure force directly, the new series of tests also employed the use of series 500 lbf 1050V4 dynamic piezoelectric load cells manufactured by Dytran. In order to

measure the loads on the surface of the target, the mass was drilled and tapped, and the load cells were embedded in the locations shown in Figure 3.9

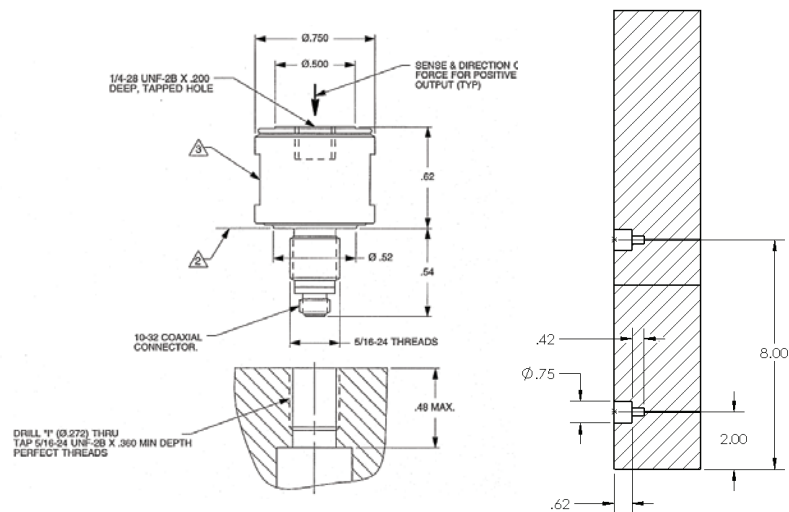


Figure 3.9: Dynamic load cell and target plate schematic.

The following two sections summarize the results from impact tests conducted on the adjusted bladder design.

3.1.2 1D Impact Tests

A total of six bladders were tested using the same experimental setup. Each test exhibited a similar sequence of events: As the impacting mass comes in contact with the bladder, the resulting shock propagates the fluid towards the target. As the bladder compresses, the impinging fluid reflects off of the target mass, and the water is redirected towards the outer boundaries of the bladder until breach. This progression is illustrated for Test 7 in Figure 3.10 (a)-(c), which was conducted at a target velocity of 787 in/s (20 m/s).

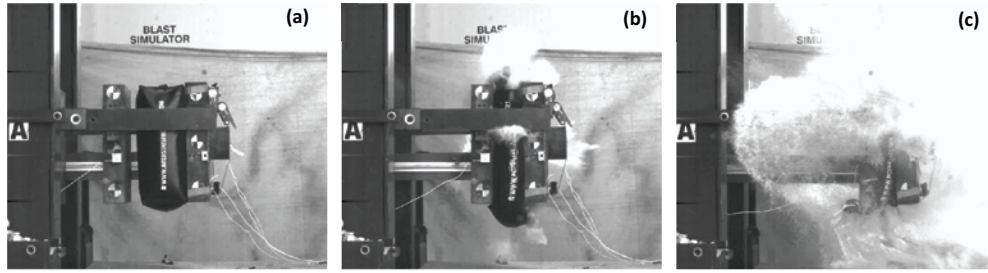


Figure 3.10: Sequence of events during 1D Impact Test 7. (a) Before impact, (b) at impact, (c) after impact.

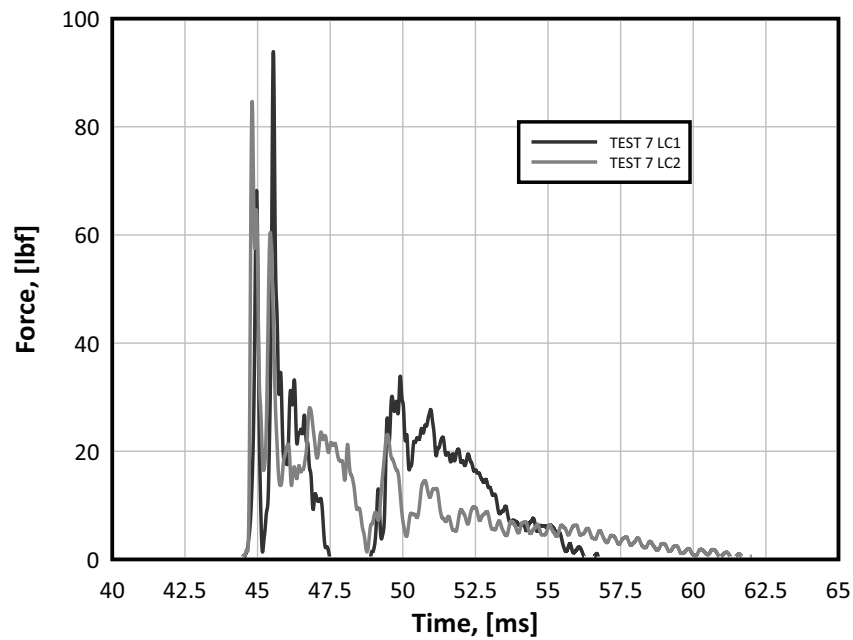


Figure 3.11: 1D Impact Test 7 force-time history from embedded load cells.

The force-time history recorded from the embedded load cells are shown in Figure 3.11. The forces were then converted to pressure by dividing over the load cell cap area and are shown in Figure 3.12 followed by the impulse histories denoted in Figure 3.13.

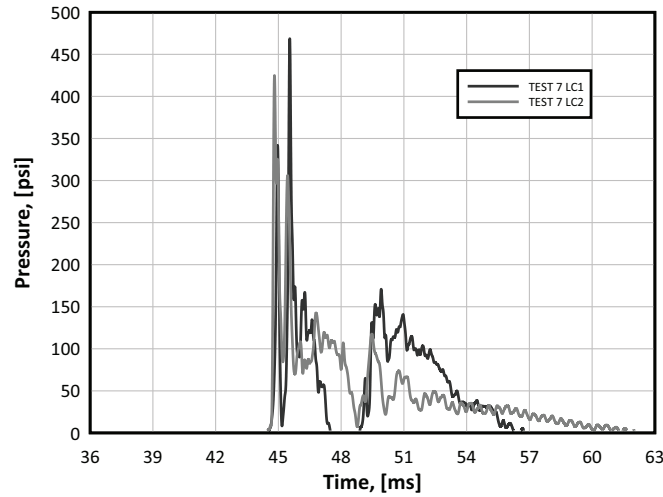


Figure 3.12: Pressure-time history for 1D Impact Test 7.

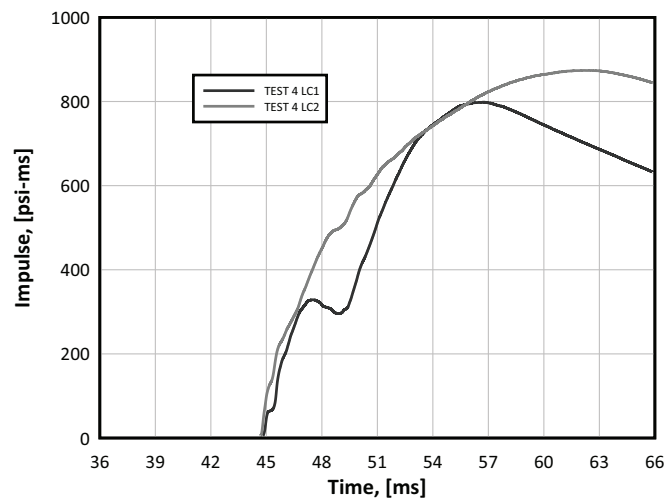


Figure 3.13: Test 7 impulses recorded from embedded embedded load cells.

The sharp rise to peak pressure followed by reflections and a gradual decay to zero was characteristic to the pressures profiles induced by confined explosions discussed earlier. The readings from both load cells demonstrated these similarities, with the longer duration of LC2 most likely caused by the redirection of force at bladder breach.

Table 3.3 summarizes the input parameters and results for the second set of 1D impact tests, followed by a discussion of the observations.

Table 3.3: Summary of key parameters and results from six impact tests.

Test	Bladder Type	Depth (in)	Velocity (in/s) [m/s]	Peak Pressure psi	Avg. Duration (ms)	Avg. Impulse (psi-ms)
4	XR5	6	591 [15]	117.4	4.5	234.9
5	U1940	6	591 [15]	301.3	6.5	476.2
6	XR5	8	787 [20]	198.0	26	1801.0
7	XR5	6	787 [20]	430.1	7	500.4
8	XR5	6	394 [10]	103.1	5	112.5
9	XR5	6	984 [25]	34.5	16	75.5

The effect of material selection can be seen between Tests 4 and 5. The thicker nylon U1940 bladder delivered an average peak pressure of 301.3 psi and duration of 6.5 ms compared to the 117.4 psi peak and 4.5 ms duration of the polyester XR5 bladder. The large difference in the impulse, 234.9 psi-ms compared to 476 psi-ms, can be attributed to the increased strength of the U1940 material which caused multiple near peak pressure reflections. The pressure-time histories are compared in Figure 3.14.

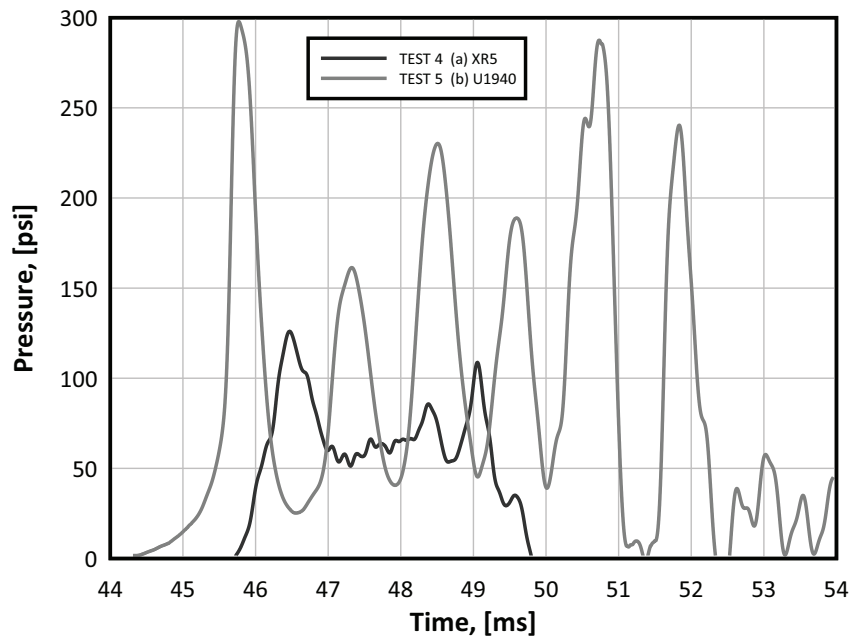


Figure 3.14: Comparison of pressures from bladder material selection (a) XR5 and (b) U1940.

Examining Tests 6 and 7, the effects of bladder thickness are noted. The thicker material produced close to 2 times the peak pressure at the same velocity, however, as seen in Figure 3.15, the 8 in thicker bladder resulted in a duration of nearly 19 ms, leading to the increase in impulse of close to 3.5 times than that of the 6 in bladder of the same material.

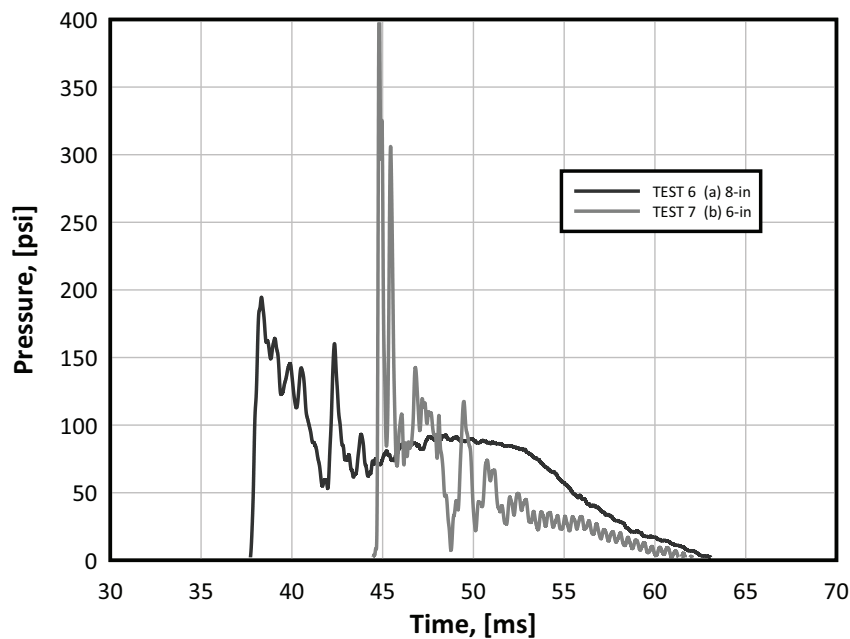


Figure 3.15: Pressure-time histories for XR5 (a) 6 in and (b) 8 in bladder.

Changes in impact velocity also had significant effects. Decreasing the velocity from 591 in/s (15 m/s) in Test 4 to 384 in/s in Test 8 reduced impulse by 48%. The same increase in velocity in Test 7 demonstrated a similar 47% increase in impulse from Test 4. However, increasing the velocity to 984 in/s (25 m/s) in Test 9 created an interesting result. The faster impact and lack of confinement in the lateral directions caused the bladder to breach almost instantaneously, recording a peak of only 35 psi and resulting in an impulse of only 75 psi-ms. This last result will be scrutinized closely in the following section where the impact is confined in two additional directions.

To demonstrate the similarities the generated pulses had to the characteristic profiles of confined explosive events discussed previously, the pressure-time profile from Test 9 is compared to the Chapter 2 example in Figure 3.16. Both illustrate a sharp rise to peak pressure (a), followed by a series of similar duration yet lower in magnitude

reflections (b) and a steady decay (c).

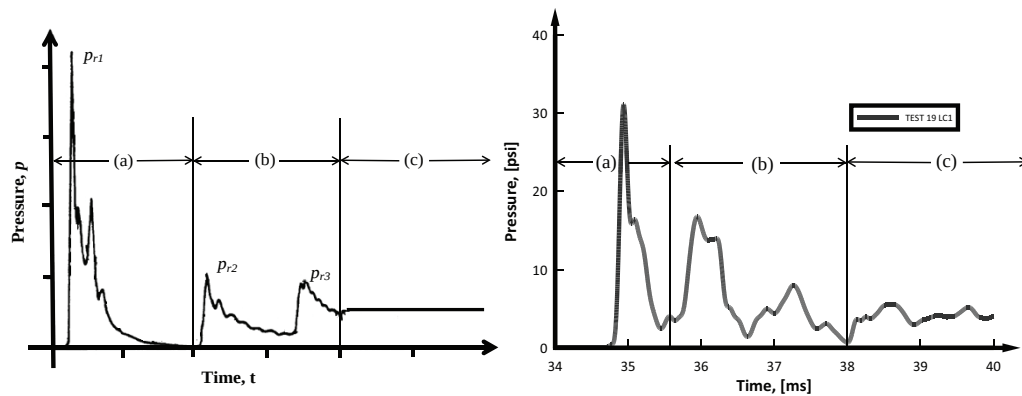


Figure 3.16: Comparison of field test example (left) and Test 9 (right).

The next section describes a series of tests which investigated pressure-time histories in multiple directions.

3.1.3 2D Impact Tests

The two dimensional (2D) Impact Tests were conducted in an effort to document pressures and impulses recorded in multiple directions *via* added confinement. A 2 in thick steel channel was placed on three 1220 series 200 kip Interface load cells which were affixed on a concrete reaction block in the Blast Simulator configuration seen in Figure 3.17.

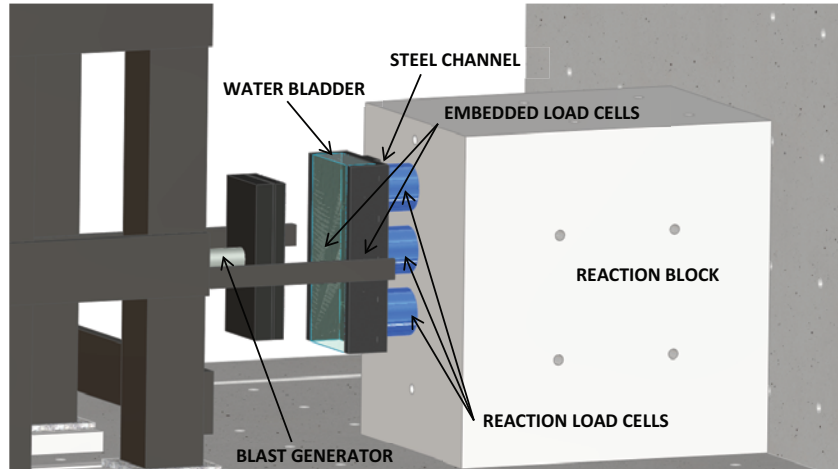


Figure 3.17: (a) Schematic of 2D Impact Test setup.

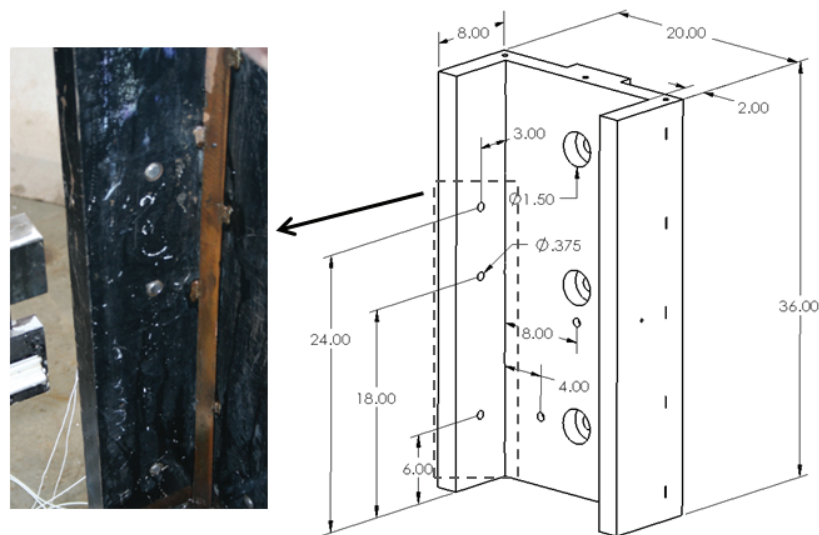


Figure 3.18: Channel dimensions and locations of load cells.

Holes for the small dynamic load cells were drilled along the three faces of the channel as seen in Figure 3.18. A series of 32 in tall by 16 in wide baffled water bladders were placed along the inside of the channel and impacted by a 32 in x 16 in wide x 3.75 in thick aluminum mass attached to the Blast Simulator actuators. Input parameters of interest included actuator velocity, depth of bladder, and bladder material. Mirrors were mounted to produce overhead camera views of the experiment. The typical sequence

of events *via* the overhead mounted mirror is shown in Figure 3.19. As an example of typical output, recorded pressures and impulses recorded from the smaller embedded load cells for 2D Impact Test 2 are shown in Figures 3.20 and 3.21.

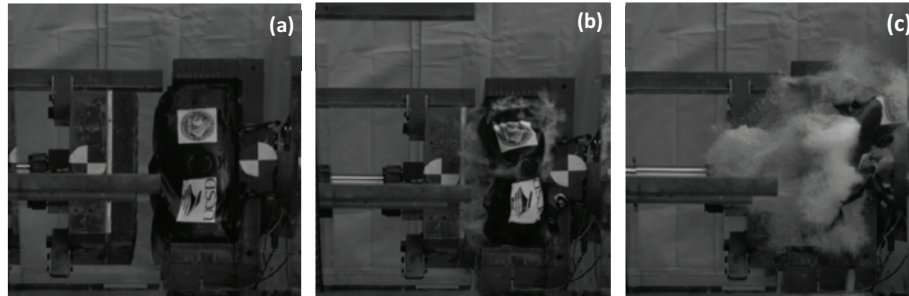


Figure 3.19: Sequence of events of 2D Impact Tests. (a) Before impact, (b) at impact, (c) after impact.

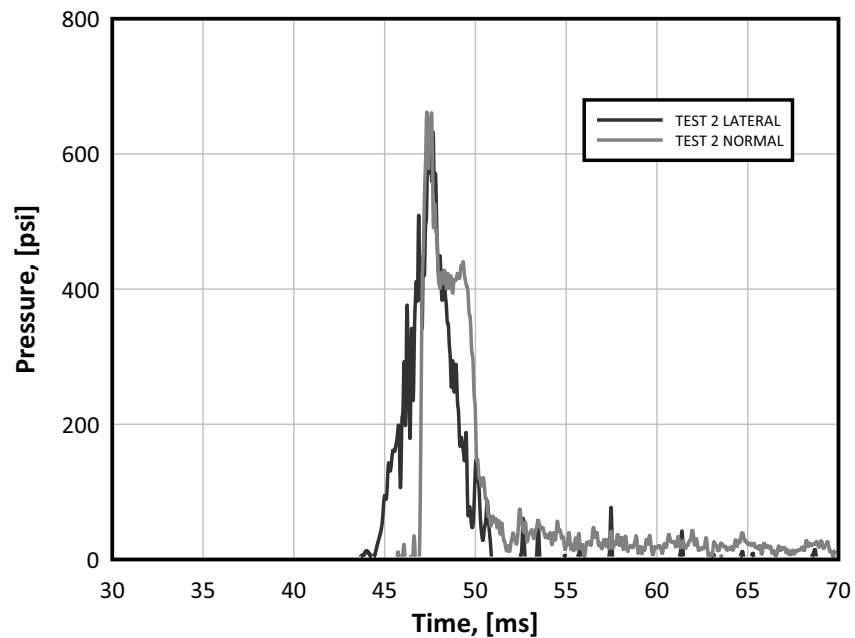


Figure 3.20: Lateral and normal pressure time histories for 2D Impact Test 2.

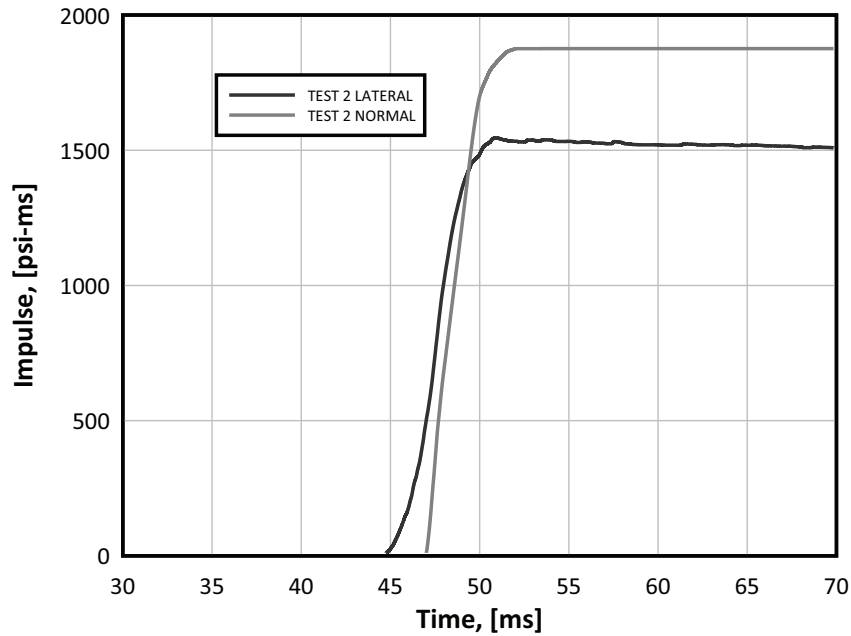


Figure 3.21: Impulses on normal and lateral faces of channel for 2D Impact Test 2.

Table 3.4 summarizes the input parameters and results of the 2D Channel Tests. Force measurements were taken from both the normal and lateral faces of the channel. It should be noted that values presented are averages over multiple pressure transducers positioned along each side.

Table 3.4: Summary of 2D Impact Tests.

Test #	Bladder Type	Depth (in)	Velocity (in/s) [m/s]	Peak Normal pressure (psi)	Peak Lateral pressure (psi)	Normal impulse (psi-ms)	Lateral impulse (psi-ms)
1	XR5	6	276 [7]	600	630	1460	1780
2	XR5	6	394 [10]	610	620	1720	1840
3	XR5	4	394 [10]	1050	1120	1640	1660
4	XR5	4	512 [13]	1328	1054	1750	1750
5	XR5	6	512 [13]	880	790	2675	2135
6	XR5	4	787 [20]	2000	2150	1750	1775
7	U1940	4	787 [20]	2840	3000	2270	2525
8	XR5	4	1181 [30]	2840	3000	2285	2520
9	XR5	6	1181 [30]	3475	3800	3875	4240
10	U1940	6	1181 [30]	4000	6200	3690	3690
11	XR5	4	1181 [33]	4312	3692	6696	4651

The effects of velocity can be clearly seen *via* the comparisons of tests 1, 2, 5 and 9. As the velocity was increased, both normal and lateral pressures were increased. An increase from 276 (7 m/s) to 394 in/s (10 m/s) produced a 17% in normal impulse with a 3% increase in lateral impulse. An increase from 394 in/s (10 m/s) to 512 in/s (13 m/s) , produced a 50% increase in normal impulse, with only a 16% increase in lateral pressure. Increasing the velocity from 512 in/s (13 m/s) to 1181 in/s (30 m/s) produced impulses on the order of 40% for normal pressures, but created almost double the lateral impulse. The same comparison can be made between Tests 6 and 8 for the 4 in deep bladder. An increase of 394 in/s (10 m/s) increased both normal and lateral impulses by 40%.

The result of varying bladder depth for the 2D cases can be seen between Tests 2 & 3, 4 & 5 and Tests 8 & 9. The smaller bladder produced greater pressures and impulses at a velocity of 394 in/s (10 m/s) and 512 in/s (13 m/s), where as the larger bladder produced the larger pressures and impulses at a velocity of 1181 in/s (30 m/s). This suggests that bladder geometry has a greater effect at lower velocities, whereas at higher velocities bladder geometry becomes less significant.

Material property comparisons can be made through analysis of Tests 6 & 7 and Tests 9 & 10. At an impact velocity of 787 in/s (20 m/s), the U1940 nylon bladder exhibits a 40% increase in both normal and lateral pressures over the XR5 material. However, at 1181 in/s (30 m/s) the XR5 shows slightly larger impulses in both the normal and lateral directions. This is consistent with the conclusion that at higher velocities, small variations in bladder type and geometry have less of an effect than at lower velocities. It is worth noting that impacts of the XR5 material at a velocity of 1181 in/s (30 m/s) produced almost identical results to the impact of a U1940 bladder at 787 in/s (20 m/s).

An important observation was made when comparing the impulses recorded from the smaller *embedded* load cells and those recorded from the larger *reaction* load cells to which the channel was mounted. Table 3.5 shows the two sets of impulses for each test as well as a column demonstrating the ratio of embedded impulse to reaction impulse. It should be noted that the back reaction load cells were removed for the faster velocity impacts due to capacity limits.

Table 3.5: Comparison of embedded and reaction recorded impulses.

Test #	Embedded Impulse (psi-ms)	Reaction Impulse (psi-ms)	Percentage Difference (%)
2	1720	496	28.8
3	1640	465	28.3
4	1750	497	28.4
6	1750	472	27.0

The data suggests a very consistent margin of difference between the two sets of load cells. Force measurements taken from the reaction load cells were converted to pressure by taking the surface area of the normal channel surface ($512in^2$) and then integrated over to time to obtain impulse. To convert the embedded load cell readings, the measurement was divided by the load cell cap area ($0.196in^2$) and again integrated for impulse. For additional clarity into the observations, the overall average of the load cell ratios from Table 3.5, 28.1%, is applied to the pressure-time history for 2D Channel Test 6 in Figure 3.22.

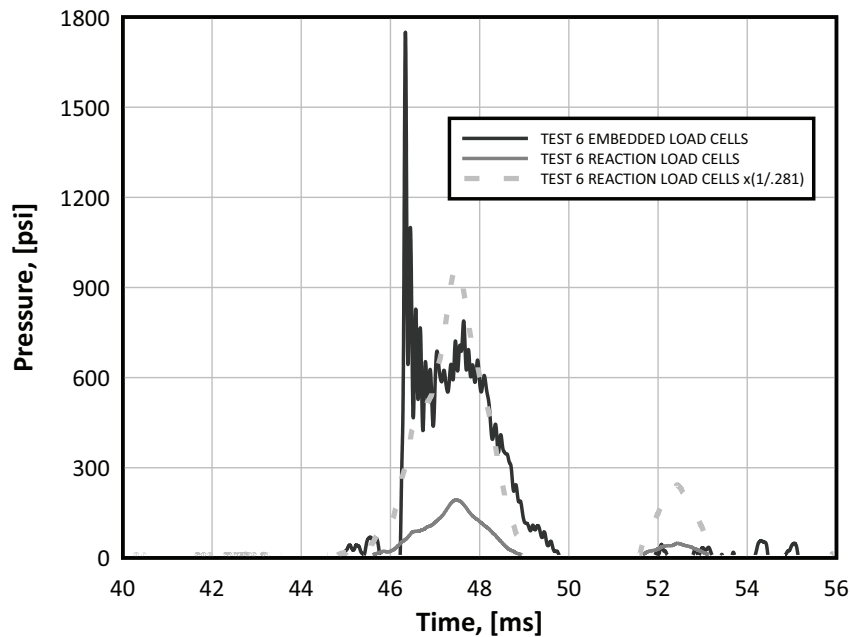


Figure 3.22: Normal pressure-time histories of 2D Impact Test 6: (a) embedded load cells (b) reaction load cells (c) reaction load cells x (1/.281).

The following section delves further into this load cell phenomena. In both the 1D and 2D Impact Tests, the smaller stainless steel load cells were embedded in A36 cold rolled steel plates. To be used in the testing of the composite connections of interest, the load cells would need to be embedded within the sandwich material. The next section presents a series of load measurement experiments to investigate the most effective means of measuring force from load cells embedded within the CFRP/Balsa/CFRP sandwich material.

3.1.4 Load Cell Calibration Tests

This section describes a series of load cell calibration tests performed using the Blast Simulator with the same reaction block used for the 2D Impact tests. A 32 in x 10 in x 6 in water bladder was mounted on a 36 in x 20 in x 2.25 in composite sandwich panel, which in turn was again affixed to the reaction load cells connected to the concrete block. The complete setup for the load cell calibration tests can be seen in Figure 3.23 .



Figure 3.23: Photos of Load Cell Calibration Test configuration.

The required depth to mount the load cell flush with the surface of the panel was approximately 1.2 in (see Figure 3.9). This required the balsa core to serve as the reacting surface as the CFRP facesheets measured only 0.125 in. To remain consistent with the previous tests that used steel as the reaction surface material, a 1 in diameter

steel bolt was drilled and threaded as detailed in Figure 3.24 to provide the steel support along the back face of the load cell. A smaller 0.31 in holed was drilled all the way through the specimen to allow for cable connection to the data acquisition system.

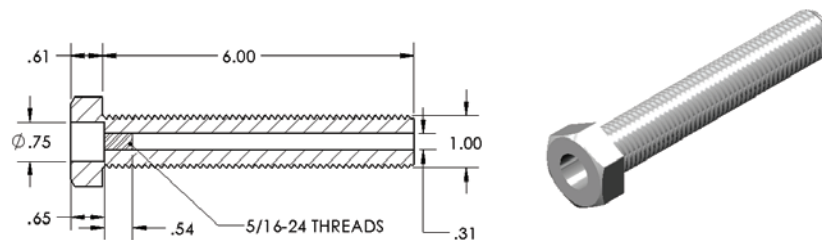


Figure 3.24: Schematic of steel load cell housing.

Variables of interest were load cell type, impact area, load cell size, load cell cap shape, quantity of load cells and mounting method. The location, configuration and details of the various configurations used for Load Cell Calibration Test 1 & 2 are illustrated in Figure 3.25.

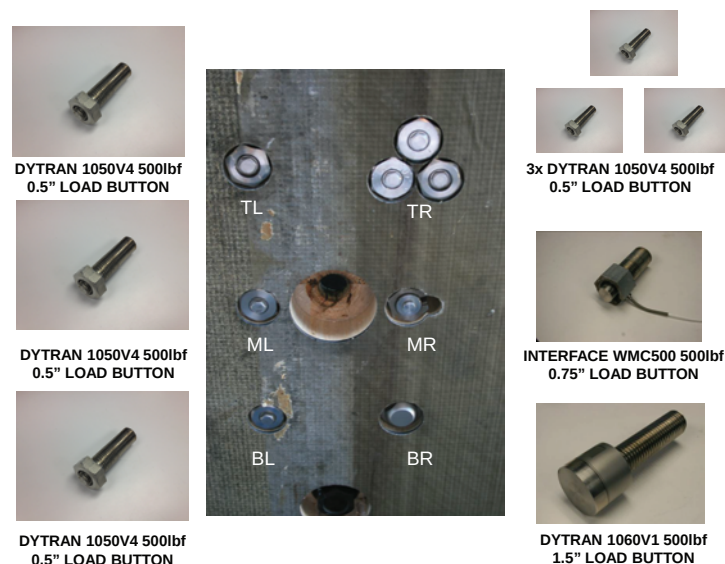


Figure 3.25: Configuration, location and assembly details for Load Cell Calibration Test 1 & 2.

For comparisons, a 500 lbf capacity Dytran 1050V4 cell with a stock 0.5 in hex load cell cap and steel bolt assembly was used as the control (TL), (ML), (BL). Quantity

of load cells were compared by mounting three of the control load cell assemblies next to each other and averaging force over the three load cells (TR). To see the effect of load cell manufacturer, a 500 lbf Interface WMC500 load cell was mounted in a similar fashion, however due to the orientation of the cable, the load cell was mounted to a 1 in thread rod with a custom machine nut of the same dimensions as the steel bolt head (MR). A 500 lbf Dytran 1060V1 load cell with a 1.5 in stock cap was used as the third variable and served to compare load cell size and impact area (BR).

A total of three tests were performed and a 30 in x 10 in x 3.75 in aluminum mass weighing 110 lbf was launched at 591 in/s (15 m/s) for each test. Force measurements were divided by load cell cap area to obtain pressures and then integrated with respect to time for impulse. Forces recorded from the three reaction load cells (RLC) were summed and divided by the water bladder tributary area to obtain pressure. Table 3.6 summarizes the results from 2D Impact Test 1.

Table 3.6: Summary of Load Cell Calibration Test 1.

Position	Peak Force (lbf)	Area (in ²)	Peak Pressure (psi)	Impulse (psi-ms)
RLC	18280.1	300.0	60.9	306.4
TL	208.6	0.2	1064.3	660.2
TR	254.9	0.2	1330.7	1643.4
ML	263.3	0.2	1343.2	1166.7
MR	246.9	0.2	1259.7	1016.0
BL	226.8	0.2	1157.1	1383.4
BR	335.6	0.8	427.3	596.0

In comparing TL and TR, peak pressures of 1064.3 and 1330.7 psi and impulses of 660.2 and 1643.4 psi-ms were recorded. A similar discrepancy was seen comparing BL and TL, with the larger 1060 series Dytran load cell recording 40 percent less of impulse at 596.0 psi-ms compared to 1382.4 psi-ms measured with the control. Comparing configuration ML and MR, a better correlation between impulse is seen, with 1666.7 psi-ms recorded from the control configuration and 1016.0 psi-ms from the WMC interface manufactured load cell. The total recorded impulse from the three reaction load cells, was 306.4 psi-ms. Averaging the impulses from the load cells mounted in the specimen,

a 28.4% reduction in impulse was noted, similar to the 28.1% differences seen in the 2D Impact Tests.

Load Cell Calibration Test 2 was conducted under the same conditions as Test 1. Table 3.7 summarizes the results.

Table 3.7: Summary of Load Cell Calibration Test 2.

Position	Peak Force (lbf)	Area (in ²)	Peak Pressure (psi)	Impulse (psi-ms)
RLC	20234.0	300.0	67.4	373.0
TL	B/C	0.2	B/C	B/C
TR	206.1	0.2	1051.5	928.5
ML	497.3	0.2	2537.2	1901.0
MR	475.8	0.2	2427.6	2321.8
BL	B/C	0.2	B/C	B/C
BR	236.5	0.8	301.1	1055.0

Two cables in positions TL and BL broke during the test, noted at "B/C" in the summary table. An average peak pressure of 1579.4 psi was measured between the four remaining embedded load cells, with an average impulse of 1551.6 psi-ms. When compared to the reaction load cells which recorded an impulse of 373.0 psi-ms, a 24.0 % difference.

In Load Cell Calibration Test 3, load cell manufacturer, size, cap size, cap shape and the effect of mounting with a bolt versus mounting directly into the panel were tested. The load cell positions and configurations can be see in Figure 3.26.

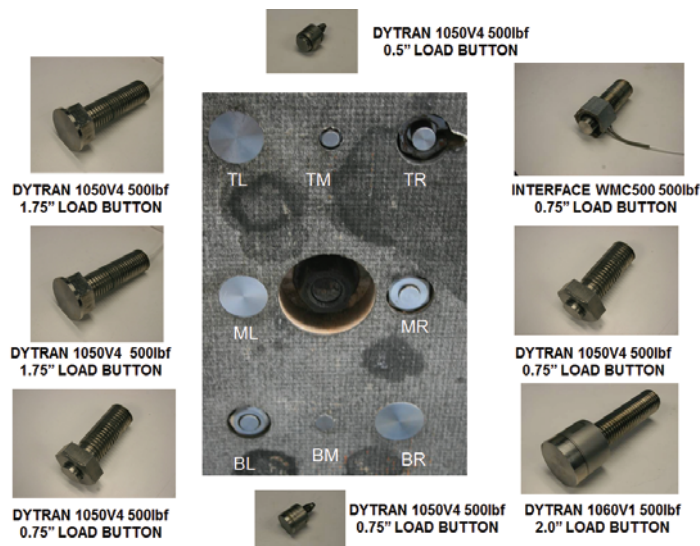


Figure 3.26: Configuration, location and assembly details for Load Cell Calibration Test 3.

To measure the effect of impact area, the 1050V4 cell was mounted in the exact same fashion as the control except for the cap size which was increased to 1.75 in and covered the entire diameter of the steel bolt head (TL) & (ML). The Dytran 1060V1 series load cell (BR) was used to test load cell type, and the rounded cap from the previous test was replaced with a flat 2 in load cell cap. To demonstrate the effect of the steel bolt mounting configuration, a Dytran 1050V4 was mounted without the steel bolt housing directly into the panel. The boltless configuration was also used for impact cap shape comparison, in which the 0.5 in standard hexagonal load cell cap (TM) was replaced with a 0.75 round load cell cap (BM). Manufacturer differences were compared using (TR), while (MR) and (BL) utilized the control assembly with the 0.75 in round load cell cap. As an additional data point, the water bladder was fitted with an AST 41-B500 500 psi pressure gauge to measure the water pressure within the bladder during impact. The pressure sensor, referred to as (BDR) in the data, can be seen in Figure 3.27.



Figure 3.27: Bladder mounted pressure gauge.

The results from Load Cell Calibration Test 3 are shown in Table 3.8.

Table 3.8: Summary of Load Cell Calibration Test 3.

Position	Peak Force (lbf)	Area (in ²)	Peak Pressure (psi)	Impulse (psi-ms)
RLC	47037.0	300.0	156.8	216.9
TL	491.4	2.4	1112.2	864.2
TR	358.6	0.4	811.7	678.3
ML	494.7	2.4	1119.8	980.4
MR	423.8	0.4	959.3	938.3
BL	307.9	0.4	696.9	595.6
BR	B/C	3.2	B/C	B/C
TM	182.1	0.2	927.4	562.2
BM	B/C	0.4	B/C	B/C
BLDR	N/A	N/A	246.8	339.7

Peak pressures of 204.3 and 205.7 psi were measured at TL and ML, which utilized the 1.75 in load cell cap on the Dytran 1050 series load cell, resulting in impulses of 864.2 and 980.4 psi-ms. The 980.4 psi-ms recorded at TL showed good correspondence 938.3 psi-ms impulse measured MR. The load cell without the steel housing assembly demonstrated 53 % and 20 % drops in recorded impulse when compared to TL and TR, respectively. The pressure sensor attached at the valve of the bladder, BLDR, recorded a peak pressure of 246.8 psi, corresponding to an impulse of 339.7 psi-ms. The average impulse for the seven embedded load cells that recorded data was 769.8 psi-ms and when compared to the 216.9 psi-ms impulse measured by the reaction load cells and

to the 339.7 psi-ms by the pressure sensor, 28.2% and 31.1% reductions in recorded impulses were noted.

The steel bolt housing assembly used for the load cell assemblies produced similar results as the load cells embedded directly into steel in the 1D Impact Tests and 2D Channel Tests when compared with the reaction load cells. The control assembly utilizing the Dytran 1050 series dynamic load cell was used for the remainder of the Blast Simulator experiments, however for consistency in calculating surface areas and therefore pressures, the 0.5 in hex shaped load cell caps were replaced with the 0.75 in round load cell caps with a flush surface.

3.1.5 Loading Methods Summary

The preceding detailed the development of a method to load structures with fluid media using the UCSD Blast Simulator. The experiments conducted in the 1D Impact Tests demonstrated the ability to produce pressure and impulse profiles similar to confined blast events through the use of custom water bladders. The 2D Impact Tests established the capability to produce simulated blast loads in multiple directions. The final experiments of the section culminated in a load cell assembly suitable for measuring surface forces in the CFRP facesheet and balsa core composite sandwich material. The remaining portion of the chapter incorporates the loading methods into the testing of 90 composite joint structures, as well as describing the approach used for reacting the specimens of interest and documenting structural behavior.

3.2 Joint Tests

The following describes the development of experimental procedures for testing 90° composite sandwich joints with the UCSD Blast Simulator. The first section details the process of finalizing a bladder/impacting mass design to be used in the experiments, followed by a description of the reaction structure design and the methods for gripping the test specimens. The rest of the chapter chronicles the five Composite Joint Tests, highlighting structural deformation patterns and failure progressions.

3.2.1 Surrogate Joint Tests

Two Blast Simulator experiments were conducted prior to the testing of the composite joints to examine the spacial and temporal pressure distribution of bladders formed to the trapezoidal shape of the specimens. To conserve available material, surrogate sandwich joints were constructed from wood and structural foam to serve as dummy or "anvil" specimens. The surrogate specimens were constructed from typical 48 in x 96 in x 0.5 in plywood sheets, which served as the facesheets to a General Plastics FR 3707 structural foam core [29]. A 6 in x 6 in Douglas fir post was cut along the diagonal and used to simulate the triangular balsa stiffeners. Additional 4 in x 4 in stiffeners were placed along the back side corners for additional support. A photo of the surrogate joint assembly can be seen in Figure 3.28.



Figure 3.28: Plywood and structural foam surrogate sandwich specimen.

To react the specimen, two 72 in x 72 in x 36 in concrete blocks were placed side by side and tied to the reaction floor approximately 150 in from the back of the reaction wall plate. The specimen was mounted in between two 8 in x 8 in HSS sections connected by 2 in DSI tensioning bars which sat on a 6 in concrete riser. Sand bags were used to fill the volume in between the specimen and blocks. A schematic of the setup can be seen in Figure 3.29.

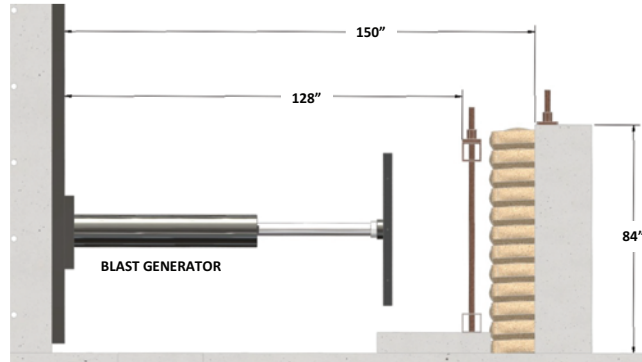


Figure 3.29: Surrogate Joint Test geometry.

An existing 48 in x 30 in x 2.75 in steel impacting mass was used as the basis for the first bladder iteration. A trapezoidal shaped bladder, seen in Figure 3.30, was designed in order to load the 3 faces of the joint and maintain a flat surface of impact.

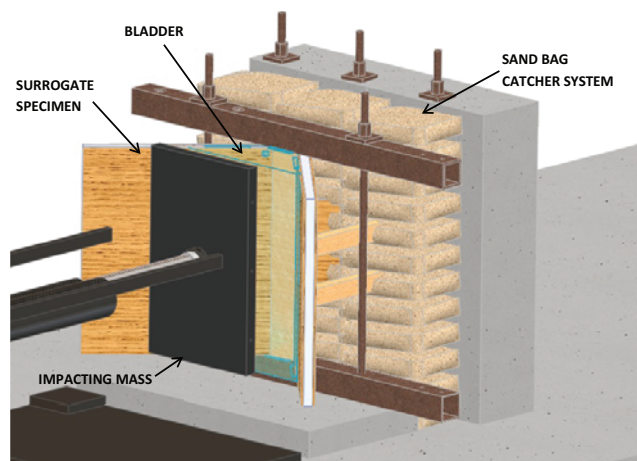


Figure 3.30: Schematic of Surrogate Joint Test setup.

To mount the bladder on the surrogate, 2 in wide strapping loops were welded along the top and back of the bladders and ratchet straps were passed through to tighten the medium against the specimen. Geometry and dimensions of the bladder used in Surrogate Joint Test 1 can be seen in Figure 3.31.

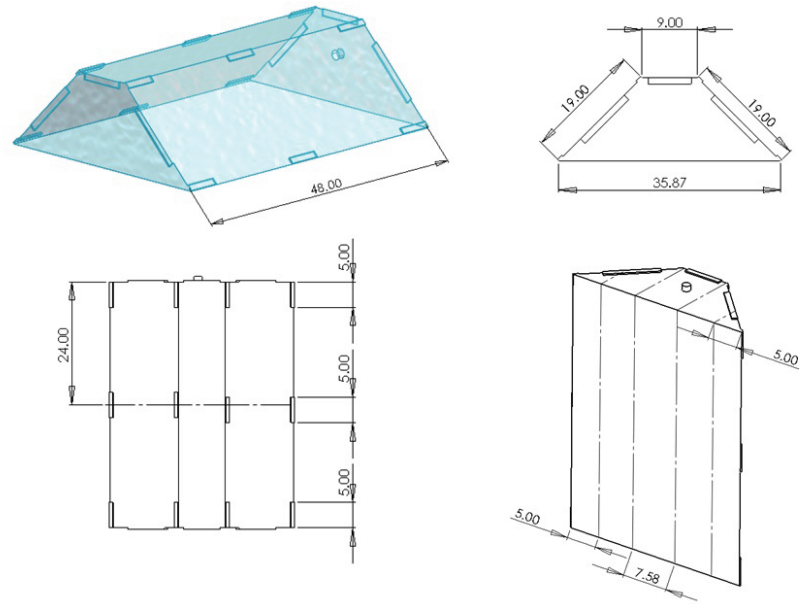


Figure 3.31: Dimensions of bladder for Joint Surrogate Test 1.

Six Dytran 1050V4 and 1050V5 load cell assemblies discussed in the previous section were used to measure force, shown installed in the plywood/foam sandwich structure in Figure 3.32(a) along with their locations shown in Figure 3.32(b). A photo of the full setup can be seen in Figure 3.33.

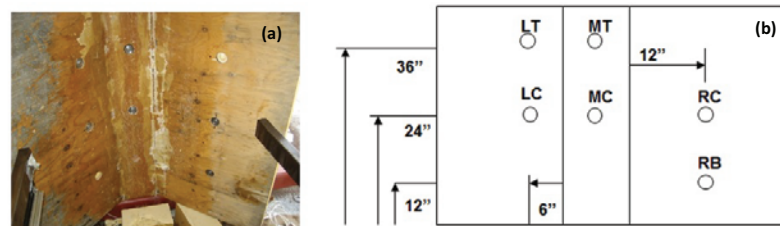


Figure 3.32: (a) Embedded load cells and (b) surrogate joint load cell placement.



Figure 3.33: Joint Surrogate Test 1.

In order to obtain the top down camera angle necessary to capture the entire event, a 48 in x 96 in mirror was placed in a custom wooden overhead mounting assembly shown in Figure 3.34.



Figure 3.34: Photo of overhead mirror used for live video.

Surrogate Joint Test 1 was conducted at a target velocity of 590 in/s (15 m/s). The sequence of events from a single Phantom camera placed on top of the Blast Generator and pointed toward the angled mirror is seen in Figure 3.35. The resultant force-time histories are presented in Figure 3.36.

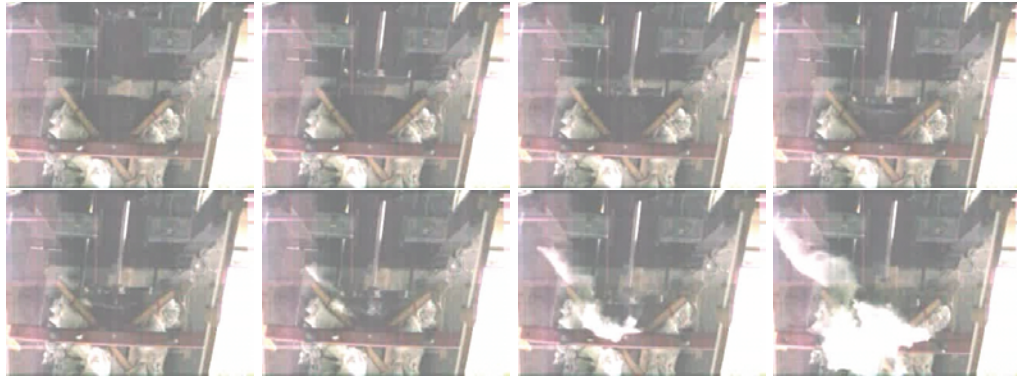


Figure 3.35: Sequence of events during Surrogate Joint Test 1.

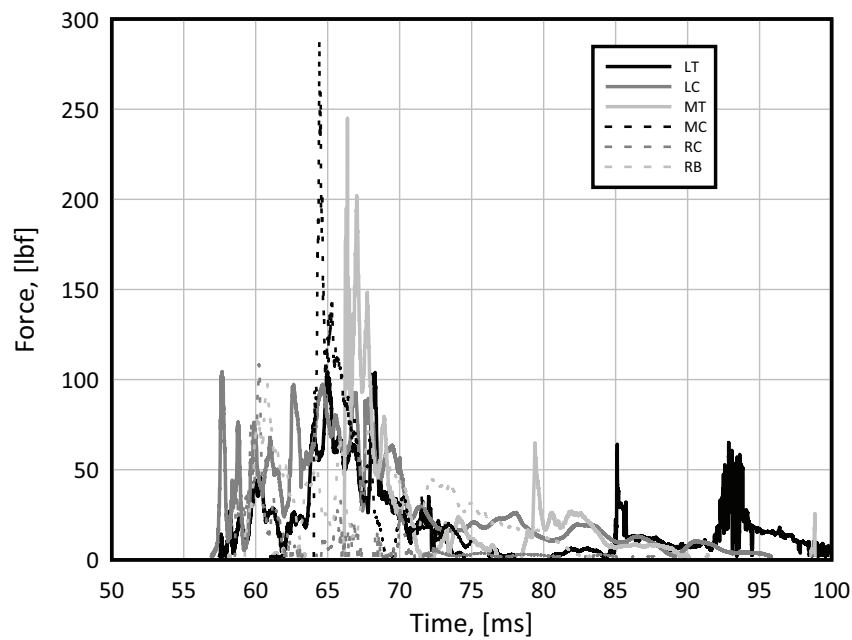


Figure 3.36: Force-time histories for Surrogate Joint Test 1.

The temporal differences between side mounted load cells (LT/LC, RC/RB) and the center load cells (MT/MC) were noted first. As expected from the geometry of

the bladder/mass configuration, the left and right arms of the joint demonstrated load between 56 and 57 ms, with average peaks of 100 lbf and durations on the order of 25 ms for the right and almost 45 ms for the left. The center face of the joint did not see force until 63 ms for the top cell and 66 ms for the center load cell, with peak forces of 276 and 244 lbf respectively, and durations of 6 ms and 5 ms. Converted pressure and impulse time histories are shown in Figures 3.37 and 3.38.

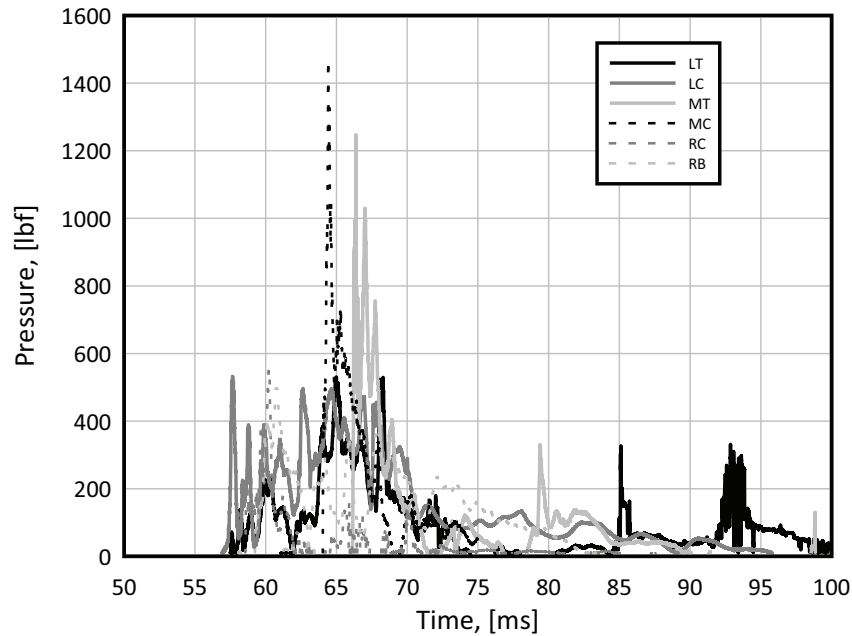


Figure 3.37: Pressure-time histories for Surrogate Joint Test 1.

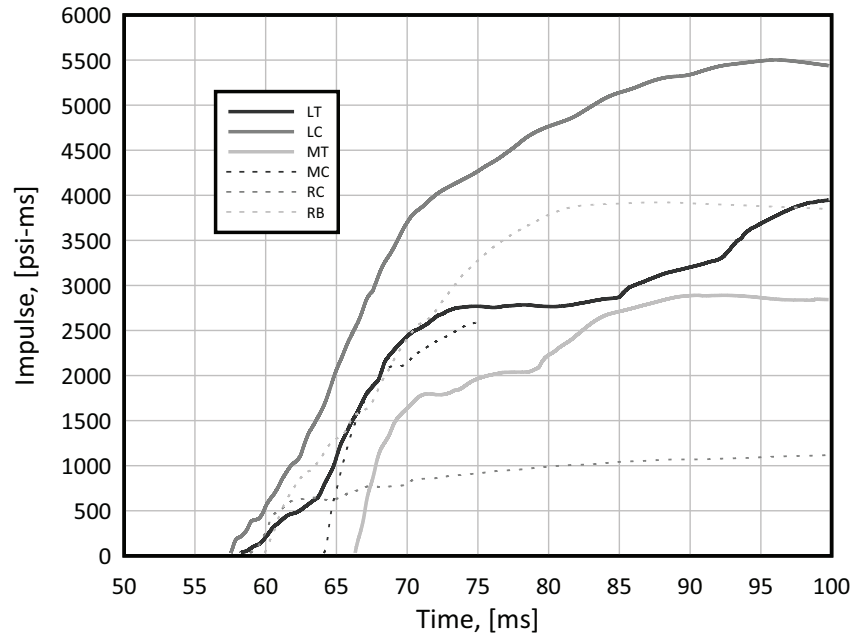


Figure 3.38: Impulse histories for Surrogate Joint Test 1.

The average recorded peaks for the left was 451 psi and for the right 460 psi, and the increased duration of the pulse on the left face created a 48% increase in impulse. The higher peak but shorter duration measured on the center face of the joint resulted in an impulse of 2681 psi-ms.

A closer examination of the video and photo shown in Figure 3.39 as well as the comparison of the impulse magnitude imply that the bladder ruptured towards the left side, sending the flow in that direction and in effect loading the left face for a continued duration.



Figure 3.39: Post test photo of bladder from Surrogate Joint Test 1.

The design for the bladder used in Joint Surrogate Test 2 maintained the same shape along the faces of the joint, however to better control bladder shape and limit post-breakage loadings seen in Test 1, a constant 6 in thickness was used, similar to the thickness used in the concept bladder tests discussed previously. Dimensions and a schematic of the new bladder can be seen in Figure 3.40.

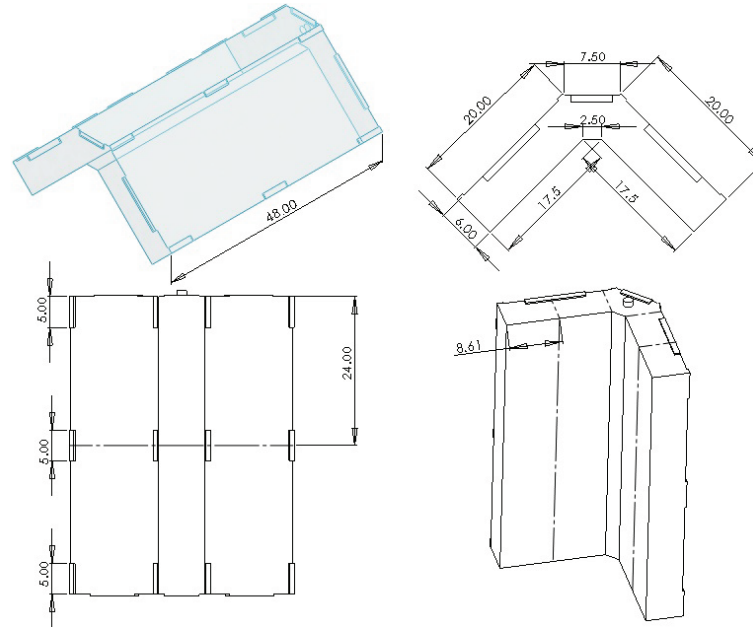


Figure 3.40: Dimensions of bladder for Joint Surrogate Test 2.

To load the concave shaped bladder, a trapezoidal shaped mass of the same dimensions was designed from 0.5 in steel plates welded to another 30 in x 48 in x 1.25 in steel plate. The geometry and dimensions of the custom mass can be seen in Figure 3.41 and a photo of the setup can be seen in Figure 3.42.

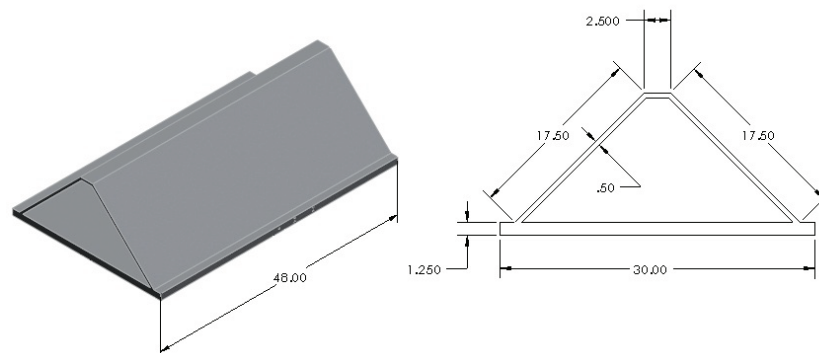


Figure 3.41: Dimensions of impacting mass for Joint Surrogate Test 2.

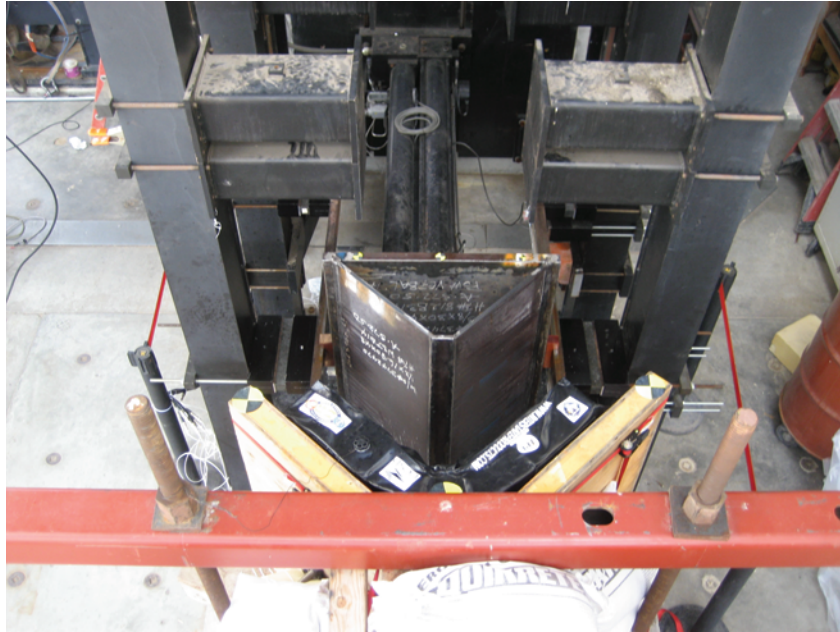


Figure 3.42: Joint Surrogate Test 2.

The target velocity for Surrogate Joint Test 2 was 590 in/s (15 m/s) and the sequence of events from the Phantom camera can be seen in Figure 3.43. The resultant force-time histories can be seen in Figure 3.44.

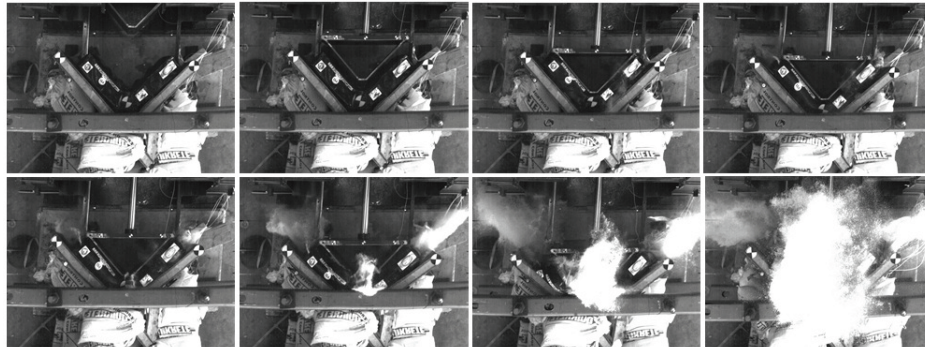


Figure 3.43: Sequence of events during Joint Surrogate Test 2.

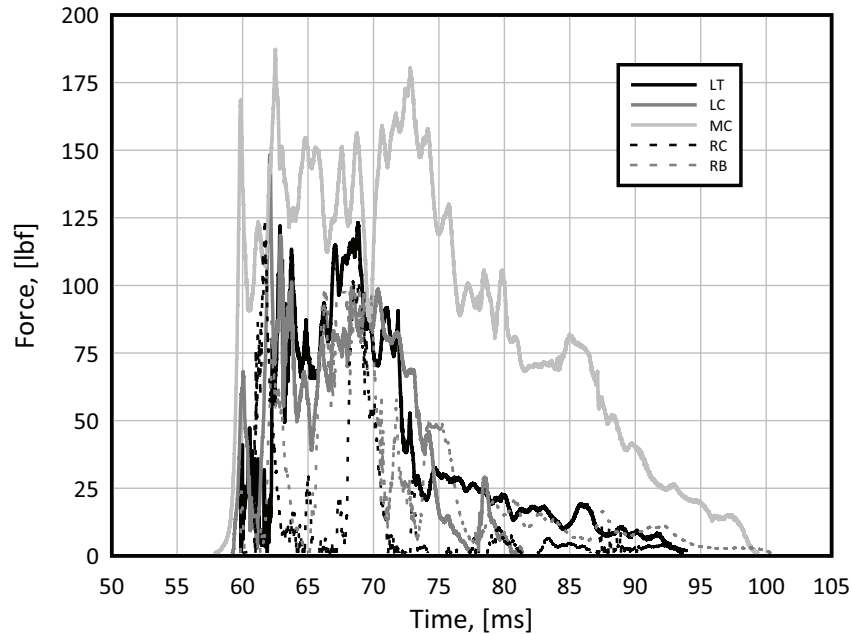


Figure 3.44: Force-time histories for Surrogate Joint Test 2.

The effect of the new bladder/mass assembly was immediately noticed, as all of the load cells began recording force between 58.3 and 60.5 ms. The left and right load cells recorded relatively similar peak forces between 120 and 139 lbf. The loads on the right face show a sharp drop to zero at 64 ms and reflection back up to near 100 lbf at 67 ms. The left face showed a drop to 50% of peak load and both faces gradually lost force over the 20 ms following. Only one load cell recorded force on the middle face of the joint, with peaks between 165 and 187 lbf over a duration of 42 ms. Converted pressures and impulses can be seen in Figures 3.45 and 3.46.

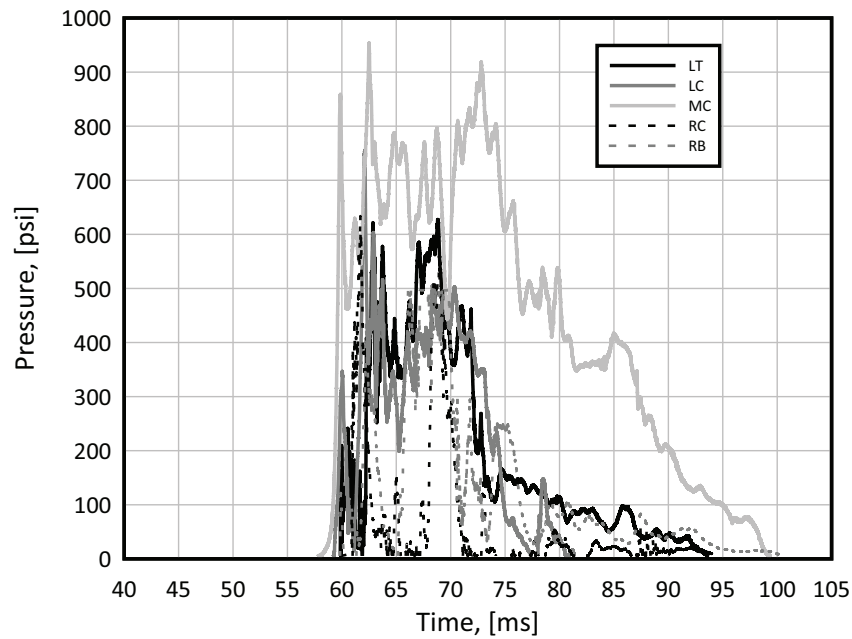


Figure 3.45: Pressure-time histories for Surrogate Joint Test 2.

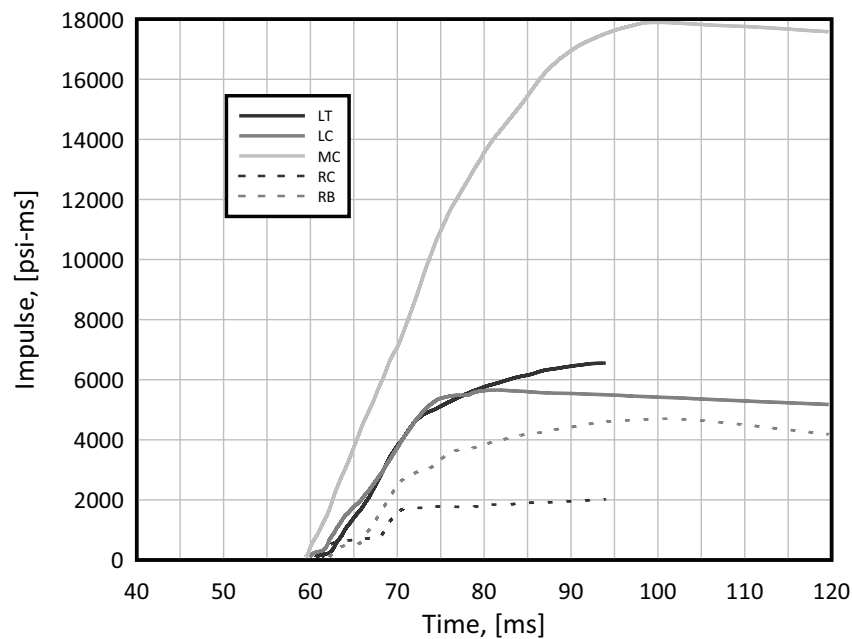


Figure 3.46: Impulse histories for Surrogate Joint Test 2.

Although the differences in pulse durations show significant impact on impulse between the left and right side, the major improvement in the bladder having a constant

thickness and shaped flyer is demonstrated through the much more consistent pressure time histories. Moreover, the water was more confined, leading to a larger loads directed towards the joint center. Another comparison can be made by examination of the bladder after the test, shown in Figure 3.47, demonstrating breaches throughout the bladder material.



Figure 3.47: Post test photo of bladder from Surrogate Joint Test 2.

The empirical investigations of the previous sections were completed in an effort to determine methods for loading joints of complex geometries, measure induced forces, and ultimately to be used as the loading method in the testing of sandwich joint specimens using the UCSD Blast Simulator. The next section describes the Composite Joint Test reaction structure design and the results from five experiments conducted on three specimens.

3.2.2 Composite Joint Tests

In order to react the specimens of interest, a gripping fixture/concrete block reaction structure was designed to orient one of the joint faces in line with the BG impacting mass. A schematic of the top down view of the south side of the UCSD Blast Simulator facility can be seen in Figure 3.48 and a side view in Figure 3.49.

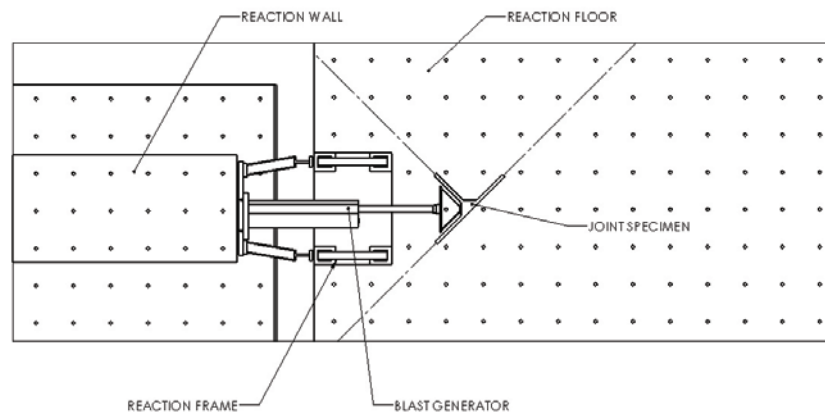


Figure 3.48: Plan view of south Blast Simulator facility configuration.

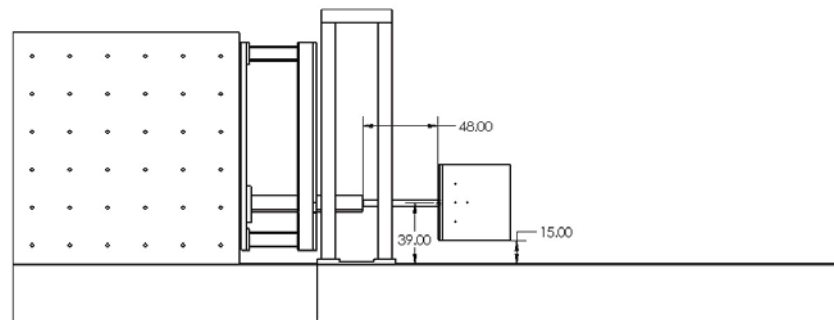


Figure 3.49: Side view of south Blast Simulator facility configuration.

The main requirement in the design of the gripping fixtures was to develop a method to hold the specimen in place with enough compliance to avoid failure at the connection points as well as to utilize materials that were suitable for numerical simulation. The fixtures needed to be adjustable in such way that axial and shear forces through the specimen as well as bending moment could be modified to simulate various structural conditions. The limitations on length were governed by reaction block placement and therefore the dimensions from the end of the joint arm to the face of the blocks were used as constraints. A schematic showing the reaction block placement and distances from the faces of the specimen can be seen in Figure 3.50.

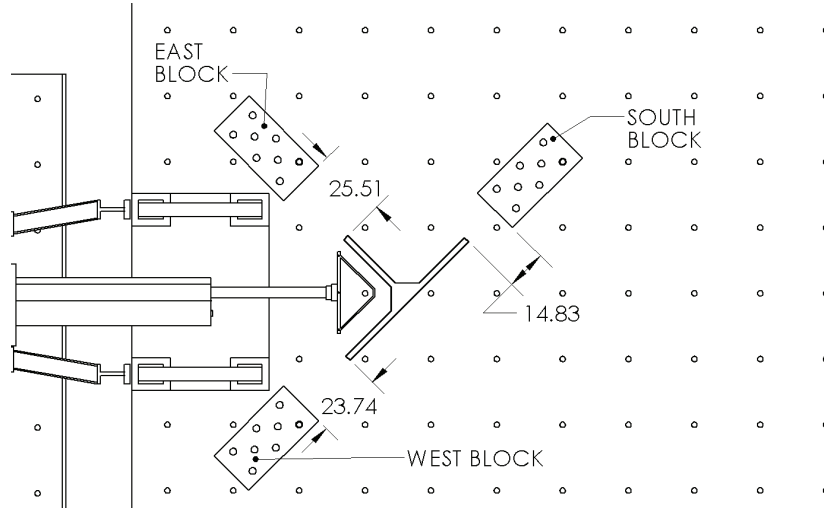


Figure 3.50: Reaction block configuration.

Using the proceeding to guide design, a set of thin, high strength steel plates or *webs* were used as a baseline. The webs were intended to act as extensions of the joint panels to assist in inducing greater bending moments. Thin steel plates offered not only the attractive feature of compliance and ease of simulation, but also a great degree of force and moment tailorability by varying thickness, length and yield strength of the plates. To attach the plates to the CFRP-balsa sandwich structure, a steel plate and angle assembly was designed with a staggered throughbolt pattern. The web attachment assembly can be seen in Figure 3.51.

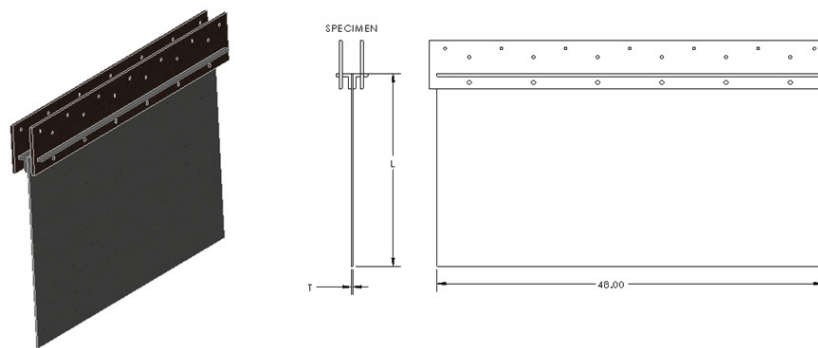


Figure 3.51: Gripping fixture web and connection assembly.

For attachment to the concrete reaction blocks, steel "Z" assemblies composed of a 0.375 in steel angle welded to a 0.375 in steel plate were drilled with a hole pattern

for mounting to the reaction blocks. In an effort to add tailorability to axial forces, a General Plastics FR-3707 structural foam was placed within the cavity created by the steel Z assemblies and reaction block. A small 3 in plate was then welded to the base of the steel webs, which would pass through an opening between the steel Z assemblies and foam. The configuration is illustrated in Figure 3.52.

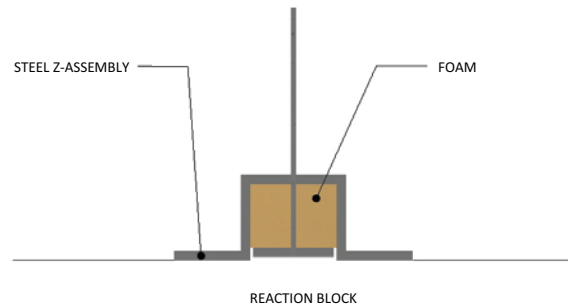


Figure 3.52: Gripping fixture Z assembly and structural foam placement.

Six 0.625 in high strength steel bolts were used for attachment of the steel webs to the angle-plate assembly surrounding the specimen. Fourteen 0.375 in bolts were staggered along the length of the specimen to connect the angle-plate assembly to the specimen. A photo of the resulting gripping fixture can be seen from two views in Figure 3.53.

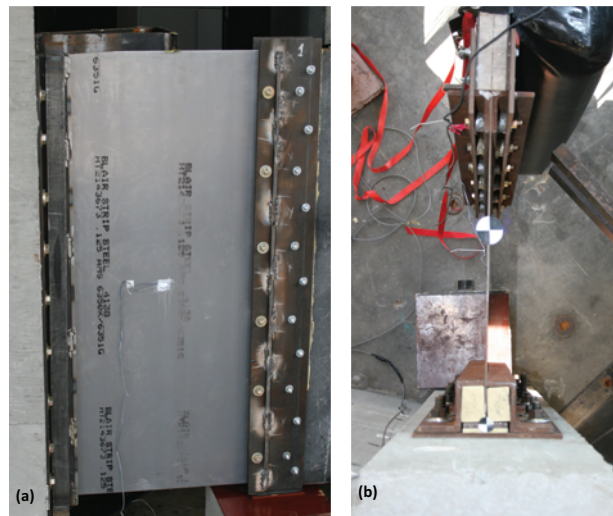


Figure 3.53: Gripping fixture assembly (a) side view (b) top view.

Load cells were placed in similar locations as the Surrogate Joint Tests, shown in Figure 3.54.

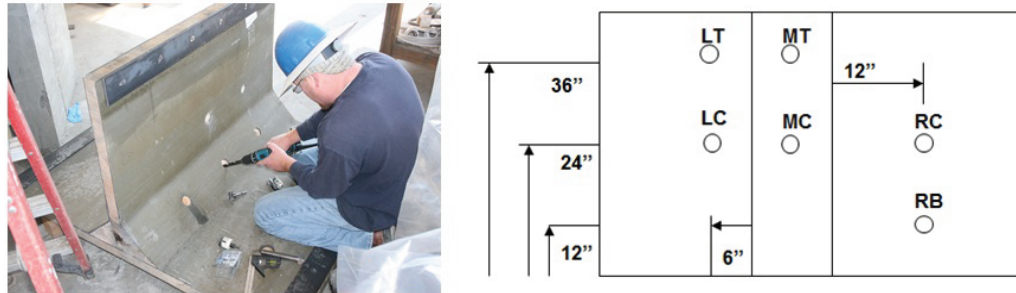


Figure 3.54: Load cell locations for Composite Joint Tests.

A total of four strain gauges were placed along the length of the back (tensile) side of the base and stem panels to which the bladder was attached, at one third and two thirds along the height of the joint. To distinguish between the two loaded panels in the remainder of this dissertation, the continuous panel will be referred to as the *base* panel, and the adjoining panel sandwiched by the two balsa core stiffeners and overlaminates will be referred to as the *stem* panel. These references and locations of the strain gauges are illustrated in Figure 3.55.

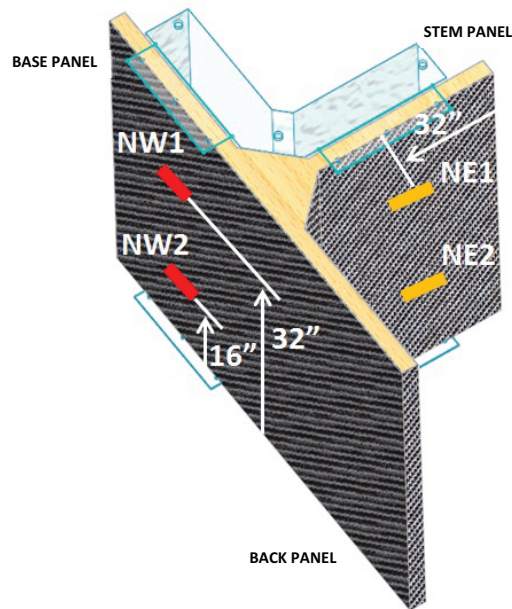


Figure 3.55: Strain gauge locations for Composite Joint Tests.

The same reflected camera view off of the ceiling mounted mirror as the Surrogate Joint Tests was used to film the experiments. A photo of the specimen mounted with the filled water bladder can be seen in Figure 3.56 and the dimensions of the gripping fixtures for each panel of the specimen can be seen in Table 3.9.



Figure 3.56: Composite Joint Test 1.

Table 3.9: Gripping Fixture Dimensions for Composite Joint Test 1 and 2.

CJ Joint Test 1, 2	L_{web} (in)	t_{web} (in)	σ_y (ksi)	w_{foam} (in)	t_{foam} (in)	E_{foam} (psi)
Base Panel	24	0.25	70.0	2.5	1.625	6730
Stem Panel	24	0.25	70.0	2.5	1.625	6730
Back Panel	15	0.25	70.0	2.5	1.625	6730

Composite Joint Test 1 was conducted at a target velocity of 590 in/s (15 m/s). The sequence of events filmed with the phantom cameras can be seen in Figure 3.57.

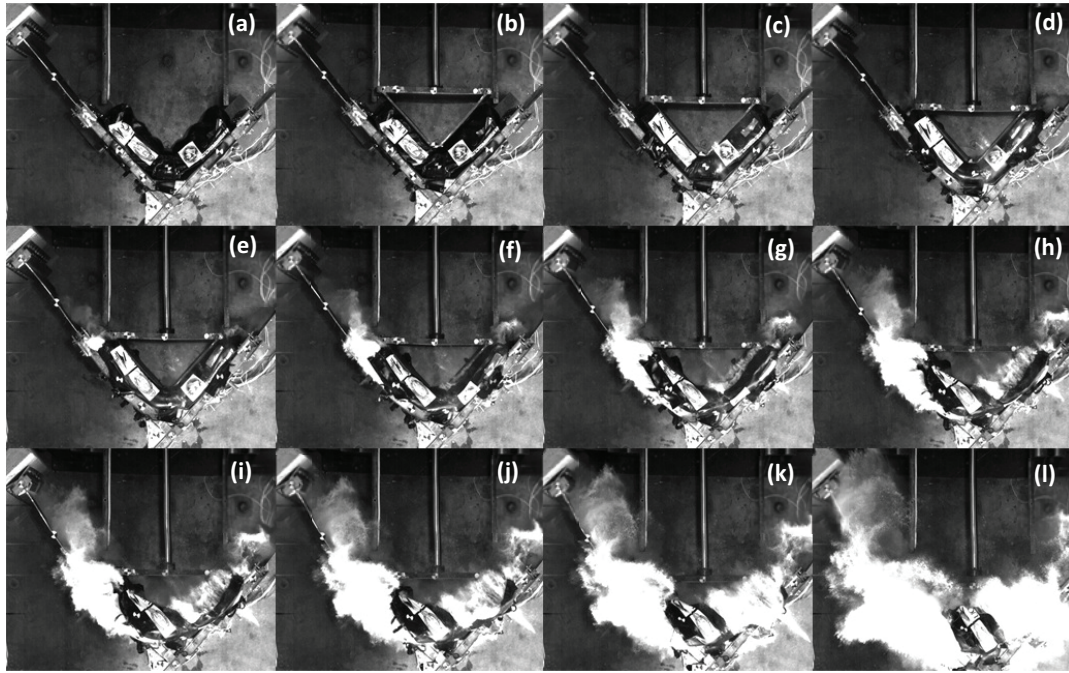


Figure 3.57: Sequence of events for Composite Joint Test 1.

As the bladder is impacted, (b), the bladder begins to bulge out and the specimen begins to displace (c). This continues as the rod begins to pull back and the break away bolts fail, (d), until the bladder breaches, (e). The bladder tears first at the center of the bladder followed by breach along the right and left sides, (h), until the diverted water blocks any additional deformation view. Forces recorded for the dynamic load cells can be seen in Figure 3.58.

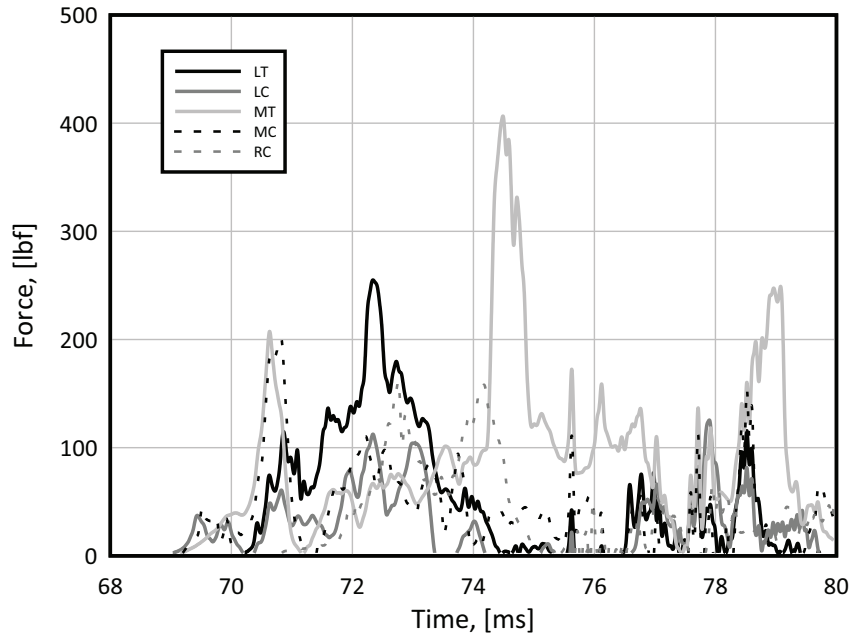


Figure 3.58: Recorded force-time histories for Composite Joint Test 1.

Rises to 200 lbf are seen at 70 ms in both middle load cells with durations of approximately 1 ms. Peaks ranging between 103 to 250 lbf are seen in the side load cells with an average duration of 3 ms. The right bottom load cell did not record data. Reflective pulses are seen throughout the remainder of the loading, with the most prominent forces seen on the middle face of the joint of nearly 400 lbf at 75 ms, 86 ms and 91.5 ms for the middle top load cell and at 81 ms and 82.5 ms for the middle center cell. The forces are averaged over each face, converted to pressures and integrated to produce the impulses seen in Figures 3.59 and 3.60.

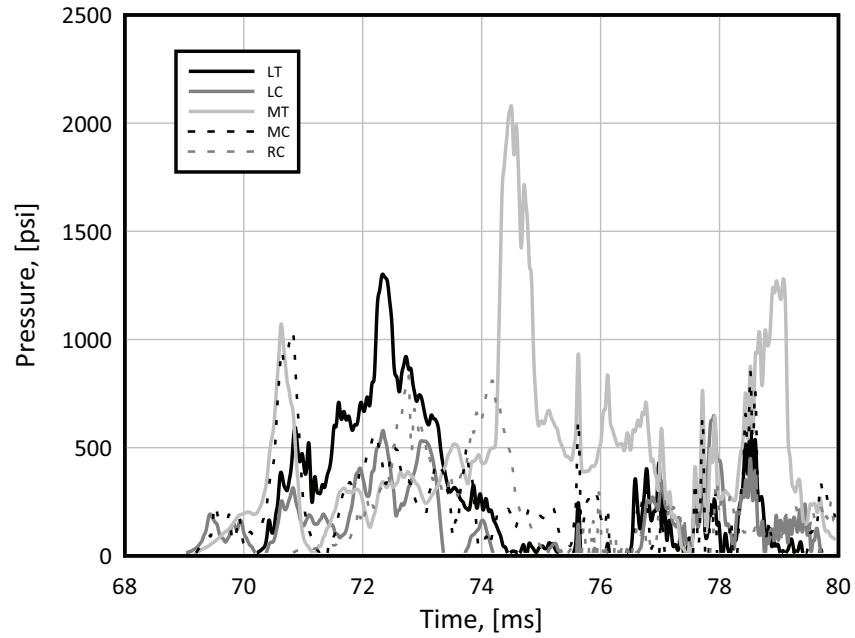


Figure 3.59: Averaged pressure-time histories for Composite Joint Test 1.

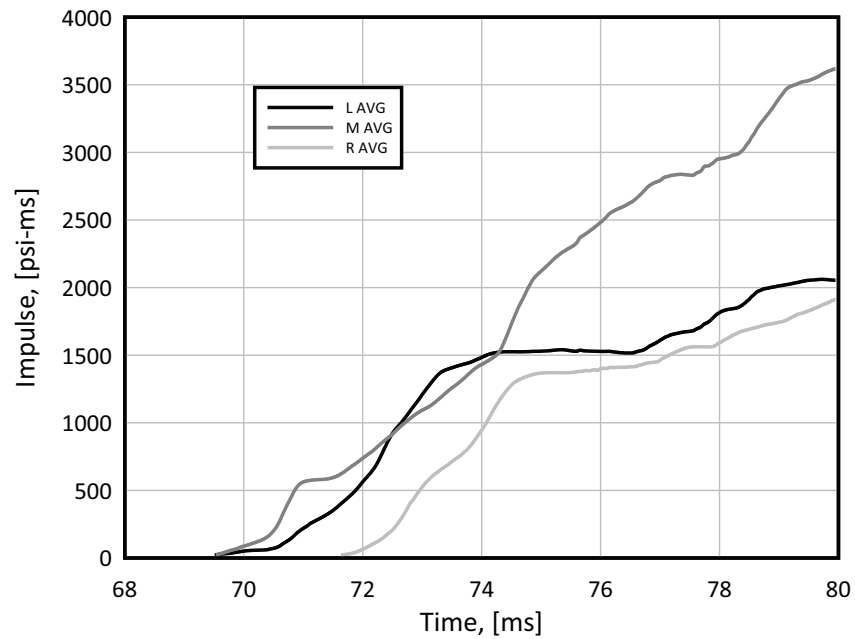


Figure 3.60: Measured impulses for Composite Joint Test 1.

Average pressure-time histories are consistent with the force-time histories, with an initial peak of 980 psi occurring 2 ms on the middle face before the peaks of near 900

psi on side faces and continued reflections during the near 20 ms event. The resultant impulses, averaged close to 2000 psi-ms for the right and left sides of the joint, with a 3,800 psi-ms impulse recorded on the middle face. Strain time-histories from the experiment can be seen in Figure 3.61.

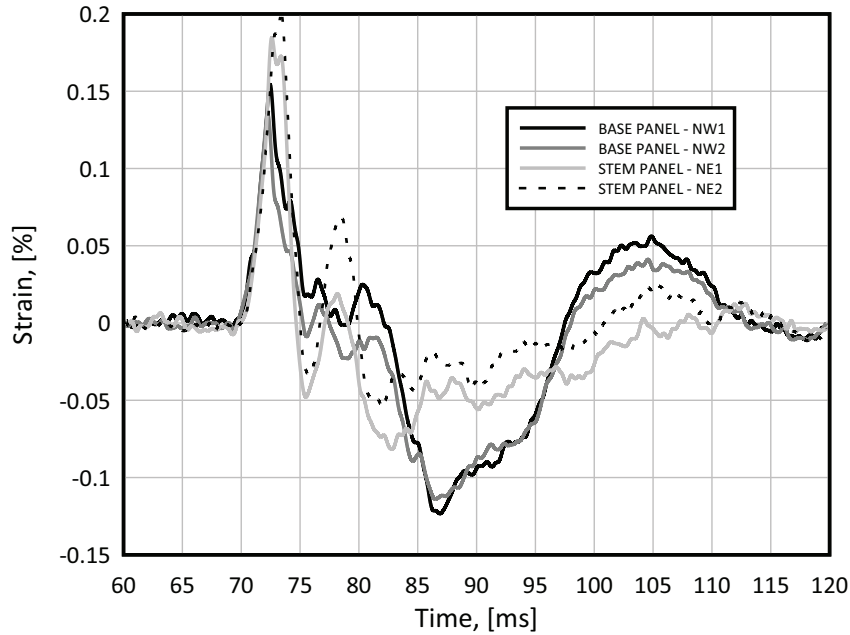


Figure 3.61: Strain-time histories for Composite Joint Test 1.

Peak bending strains of 0.2% were seen on the base panel of the T-joint and peaks of 0.15% strain were measured on the stem panel, with both panels recording tensile and compressive fluctuations until elastically returning to near zero at 120 ms. The joint remained fully in tact.

Composite Joint Test 2 was conducted in the same configuration with an increased target velocity of 787 in/s (20 m/s). A photo of the specimen before the test can be seen in Figure 3.62. The sequence of events captured by the top mounted Phantom cameras can be seen in Figure 3.63.



Figure 3.62: Composite Joint Test 2.

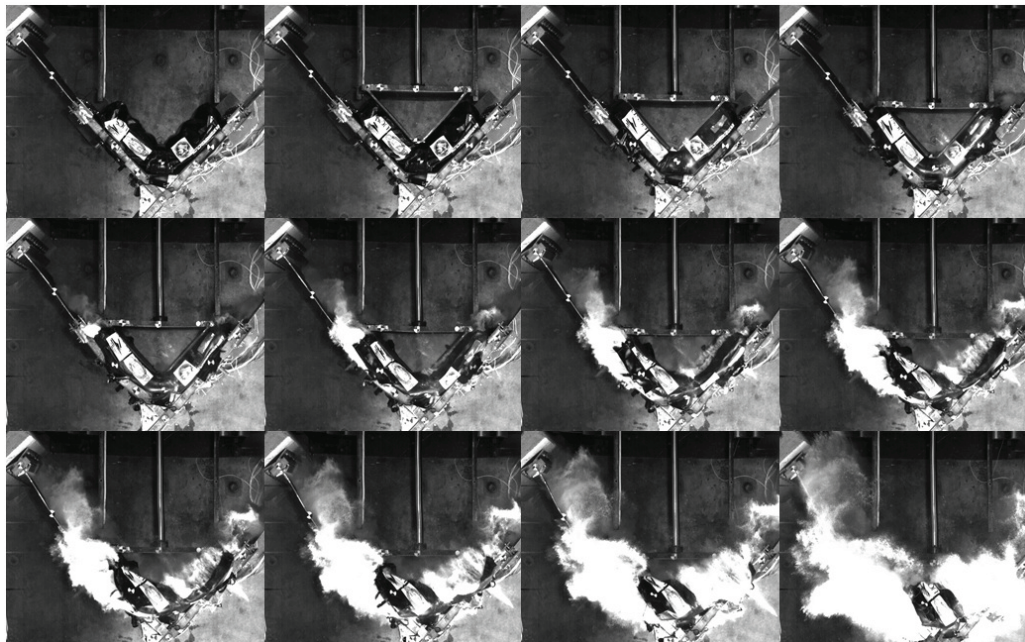


Figure 3.63: Sequence of events during Composite Joint Test 2.

The force-time histories from the embedded load cells can be seen in Figure 3.64. It was found that power had been cut from both load cells on the right side of the specimen, so only left and center face histories are shown.

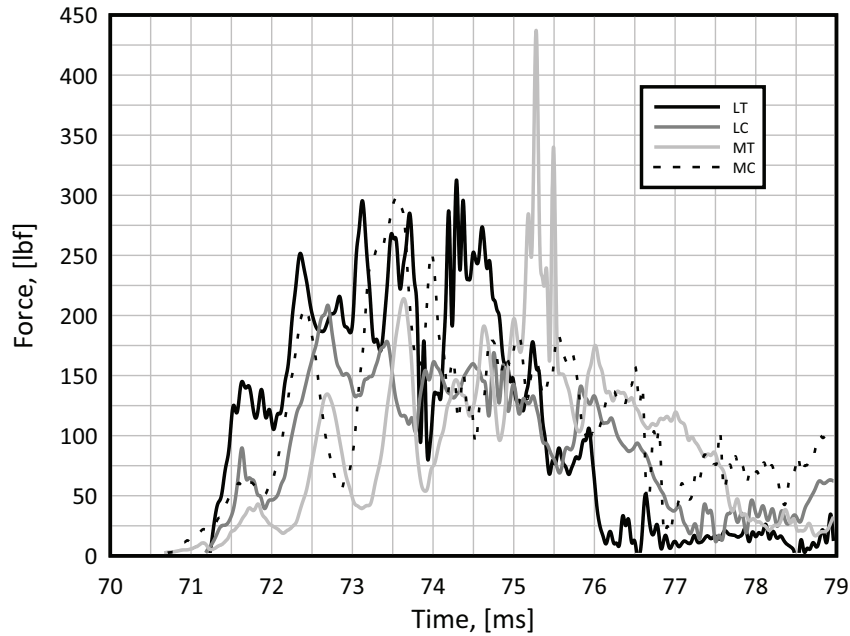


Figure 3.64: Force-time histories for Composite Joint Test 2.

Force-time histories were fairly consistent for both left and middle faces. Loading began at 71 ms, with an oscillatory rise to peaks near 300 lbf followed by a drop to near zeros force over a total duration of 5 to 6 ms. Exceptions to this general trend were a sharp peak of force up to 456 lbf in the middle top load cell at 75.3 ms, and a continued load of near 75 lbf up to a time of 82 ms for the middle center load cell. Average converted pressures and impulse time histories are shown in Figures 3.65 and 3.66.

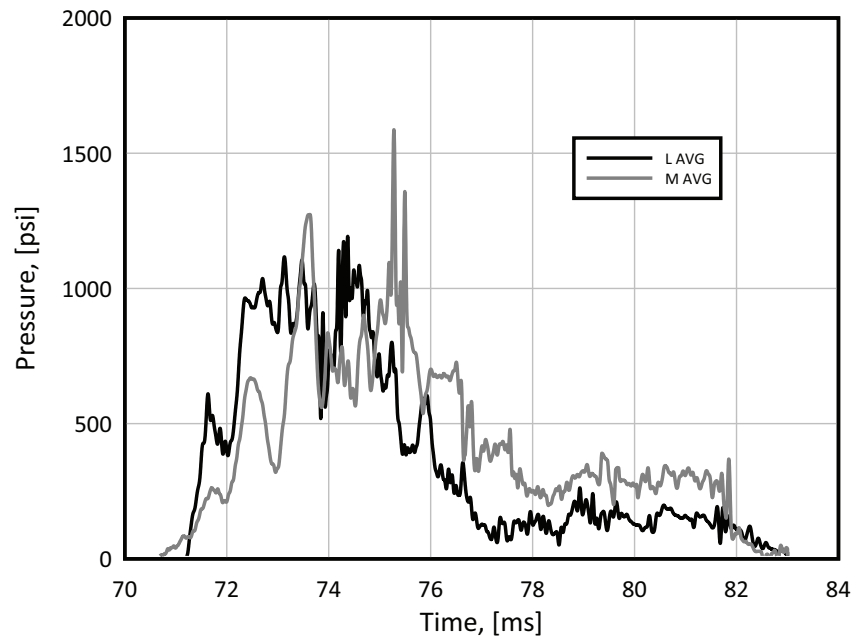


Figure 3.65: Pressure-time histories for Composite Joint Test 2.

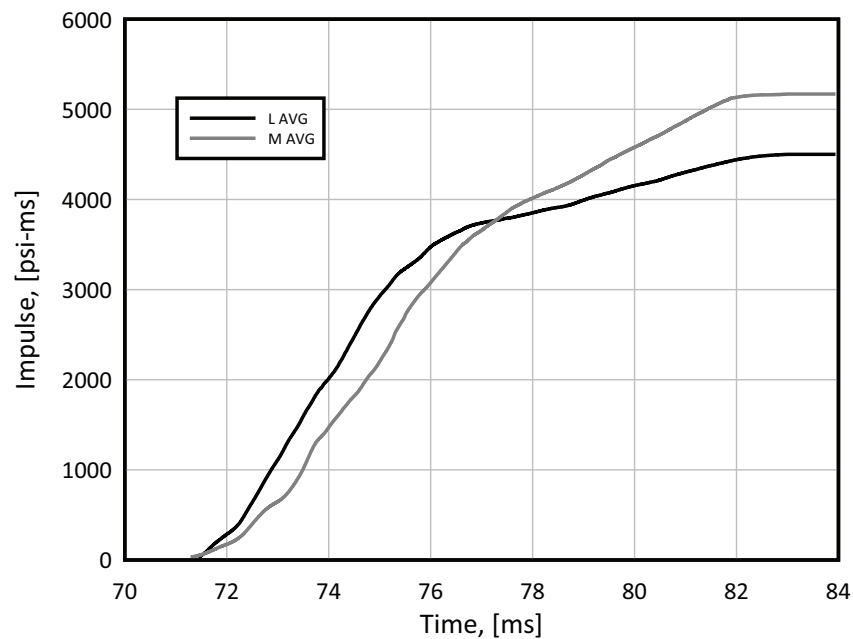


Figure 3.66: Impulses for Composite Joint Test 2.

The averaged pressure-time histories denote peaks of 1034 psi for the left face and 1508 psi for the middle both over durations of near 11 ms. The recorded impulses

for both face were 4500 psi-ms and 5132 psi-ms for the left and middle joint faces, respectively, with the longer middle face pulse duration contributing to the higher measurement. Strain-time histories are shown in Figure 3.67.

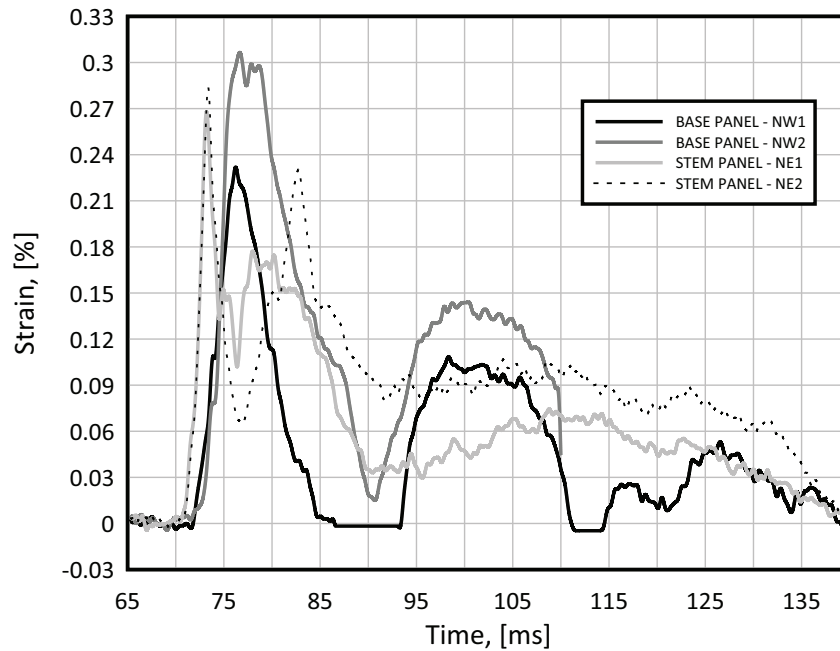


Figure 3.67: Strain-time histories for Composite Joint Test 2.

A maximum bending strain of 0.3% is seen in both arms, with the stem panel recording a peak 2.5 ms before the base and both panels show sharp decays near 80 ms, which was when the failure occurred. The zoomed in photos of the sequence events shown in Figures 3.68, 3.69, and 3.70 reveal the failures at various locations of the joint structure, ultimately leading to detachment of the stem from the base panel, or in otherwords, joint breach.

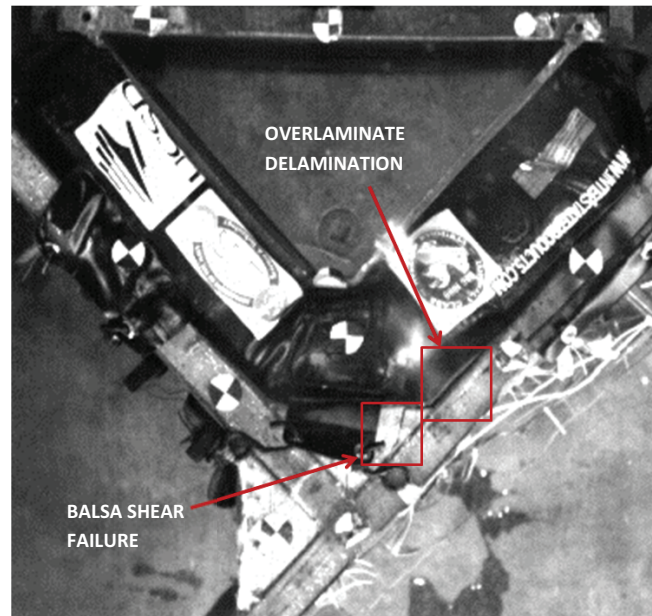


Figure 3.68: Damage progression in Composite Joint Test 2 @ $t = 74.75$ ms.

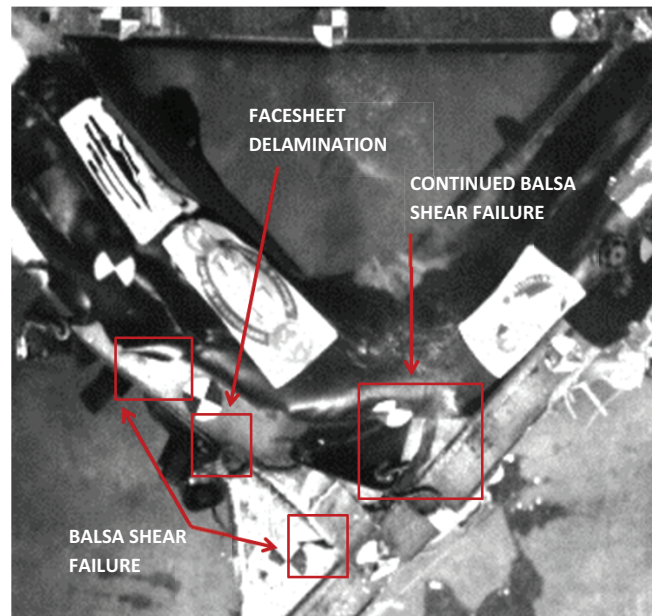


Figure 3.69: Damage progression in Composite Joint Test 2 @ $t = 78.25$ ms.

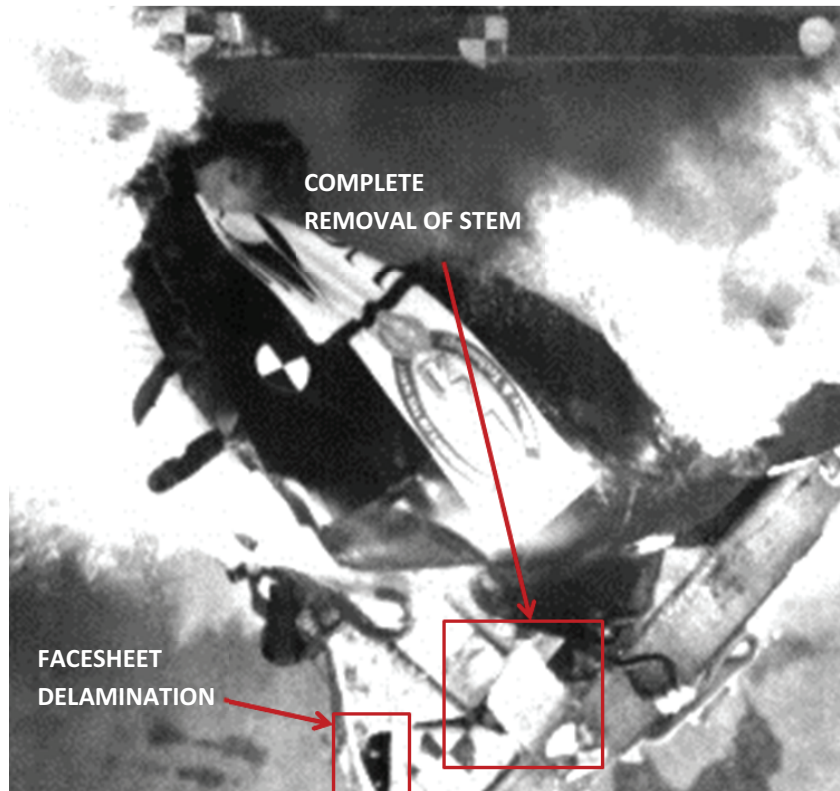


Figure 3.70: Damage progression in Composite Joint Test 2 @ $t = 86.5$ ms.

Failure first initiates at the corner where the triangular balsa and base panel are joined under the overlamine shown in Figure 3.68. The overlamine delaminates, resulting in shear failure propagation through the triangular balsa core. Figure 3.69 shows the continued shear damage through the triangular balsa as well as shear failure through the stem panel and the opposing core material stiffener. The shear failure in the stem also initiated delamination along the core-facesheet interface. Full breach is captured in Figure 3.70, where the backside overlamine delaminates from the balsa fillet and the stem is completely removed from the base. Post test photos in Figure 3.71 illustrate the resultant breach of Composite Joint Test 2.



Figure 3.71: Post test photo of breached joint.

From close examination of the videos from Composite Joint Tests 1 and 2, Figure 3.72 showed noticeable pull off of the Z assemblies from the blocks implying that the concrete wedge anchors used for mounting were not sufficient to hold the assembly in place.

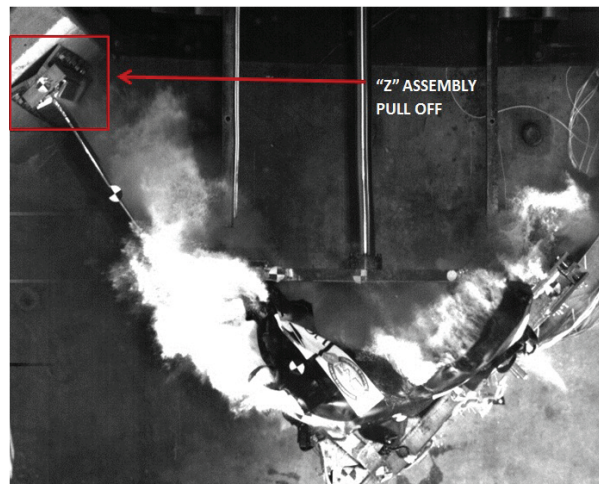


Figure 3.72: Pull off of Z assembly from concrete reaction block.

To improve this and to create blocks that could also be used for testing of joints other than 90° , a 2nd set of reaction blocks were designed for the remaining joint tests. Because of space constraints on the east side of the facility due to equipment, the specimen was flipped so that the base panel of the joint was facing west. A schematic of the south side of the facility with the newly-oriented joint can be seen in Figure 3.73.

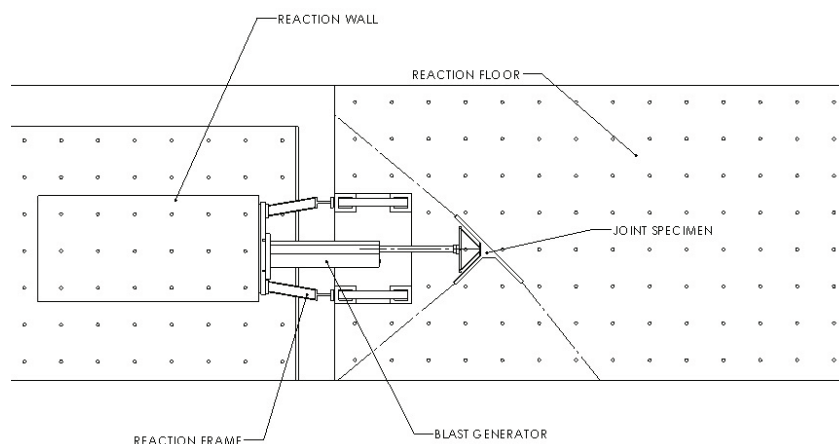


Figure 3.73: Schematic of layout for Composite Joint Tests 3, 4 and 5.

The new blocks were designed to be able to be used for joint tests of other angles, more specifically joints involving 110° and 70° . The 110° configuration was chosen as a probable case for future studies, and the blocks were designed accordingly. The

schematic in Figure 3.74 shows both joints overlaid at the impact distance, and a top view of the block designs.

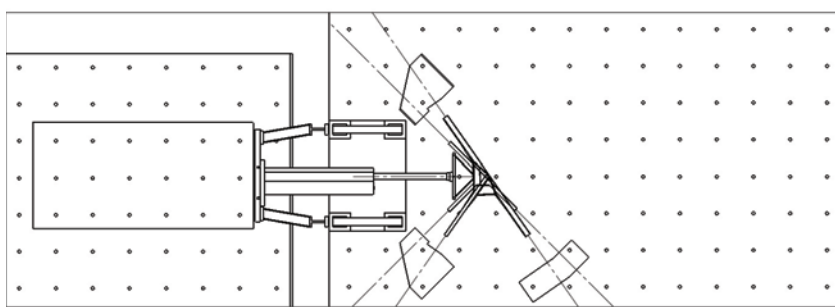


Figure 3.74: Reaction block layout for Composite Joint Tests 3, 4 and 5.

A minimum of twelve inches was kept parallel to the joint arm faces to give room for gripping fixtures. In order to mount gripping fixtures to the blocks and avoid the pullout seen in the previous test, 1 in holes patterns were employed along the height of the blocks through which 0.625 in high strength threads rods were passed. Block outs were added to the back side of the reactions blocks to maintain parallel tie down surfaces, as shown in Figure 3.75.

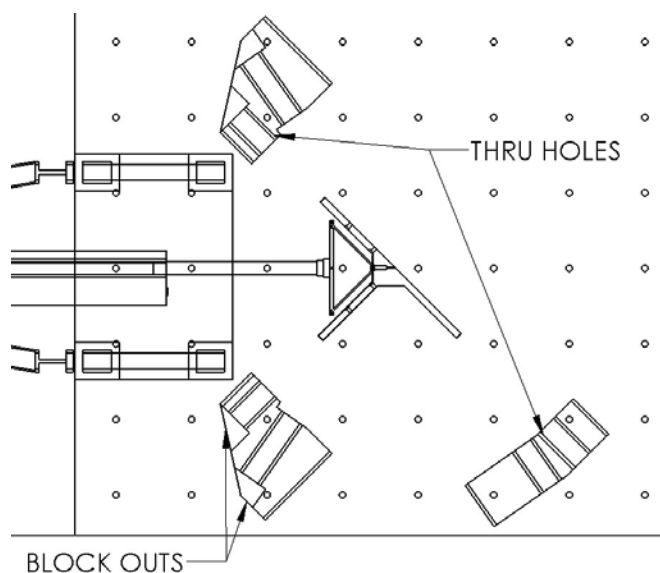


Figure 3.75: Top down section views of reaction block design for Composite Joint Tests 3, 4 and 5.

Another observation made from the loading histories and failure modes seen in Composite Joint Test 2 was that both the side faces and the middle face of the joint were loaded at the same time. This mass design limited the amount of joint *prying action* that would otherwise occur if the panels were loaded first, followed with the delivery of load to the center face of the joint. To investigate this, the impacting mass was modified. A rounded flyer was designed to impact the left and right sides of the flyer first, simulating a charge scenario closer to the center of a room or compartment. A schematic taken from a hydrocode calculation is shown in Figure 3.76, denoting the typical loading path expected from charges located further away from joints in (a), and in (b), demonstrating how to experimentally simulate the phenomena. Using this to guide design, the trapezoidal assembly was replaced with half of a 0.25 in thick, 28 in diameter tube, shown in Figure 3.77.

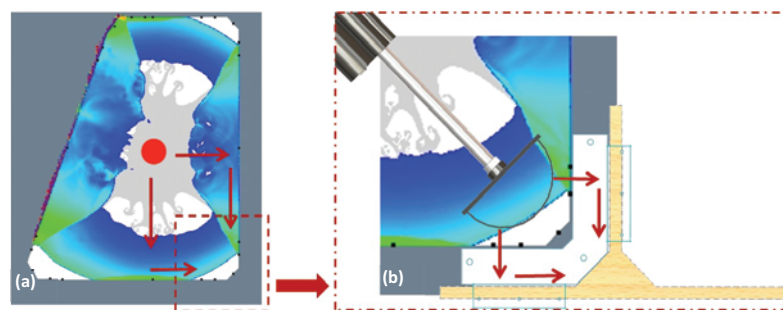


Figure 3.76: Hydrocode calculation (a) and proposed experimental simulation (b).

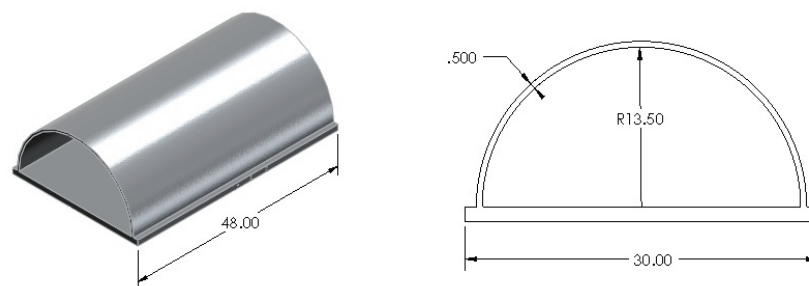


Figure 3.77: Geometry and dimensions of impact mass for Composite Joint Tests 3, 4, and 5.

Composite Joint Tests 3 was conducted using the new reaction blocks and new

mass. To study the effects of gripping fixture variables, web thickness were changed and the summary of new dimensions can be seen in Table 3.11.

Table 3.10: Gripping Fixture Dimensions for Composite Joint Test 3.

CJ Joint Test 3	L_{web} (in)	t_{web} (in)	σ_y (ksi)	w_{foam} (in)	t_{foam} (in)	E_{foam} (psi)
Base Panel	24	0.125	70.0	2.5	1.625	6730
Stem Panel	24	0.125	70.0	2.5	1.625	6730
Back Panel	30	0.25	70.0	2.5	1.625	6730

Strain gauges were placed in the same locations as Composite Joint Tests 1 and 2. Additional load cells were added in the locations seen in Figure 3.78 and a photo of the revised setup can be seen in Figure 3.79.

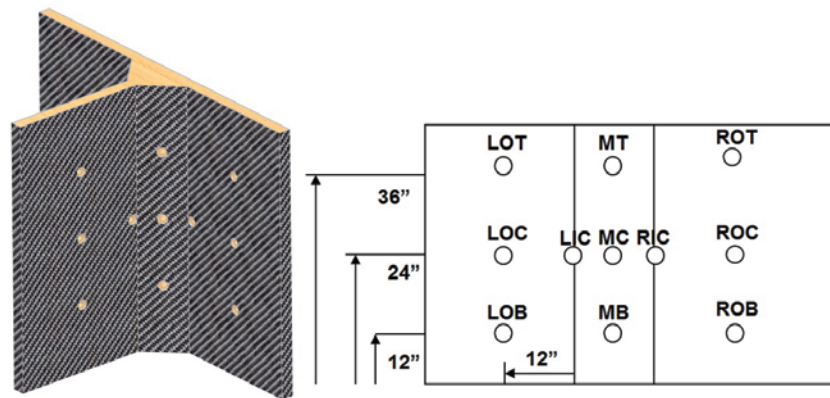


Figure 3.78: Load cell locations for Composite Joint Tests 3, 4, and 5.



Figure 3.79: Composite Joint Test 3.

It should be noted that the shape of the bladder received from the manufacturer for Composite Joint Test 3 did not demonstrate the same tightened shape as Tests 1 and 2. A comparison is shown in Figure 3.80.



Figure 3.80: Comparison of bladders for Composite Joint Test (a) 3 and (b) 2 .

Composite Joint Test 3 was conducted at a target velocity of 669 in/s (17 m/s). The sequence of events taken from the top mounted phantom camera can be seen in Figure 3.81. The force-time histories from the embedded load cells can be seen in Figure 3.82. For clarity, the beginning of the pulses are shown in close up in Figure 3.83.

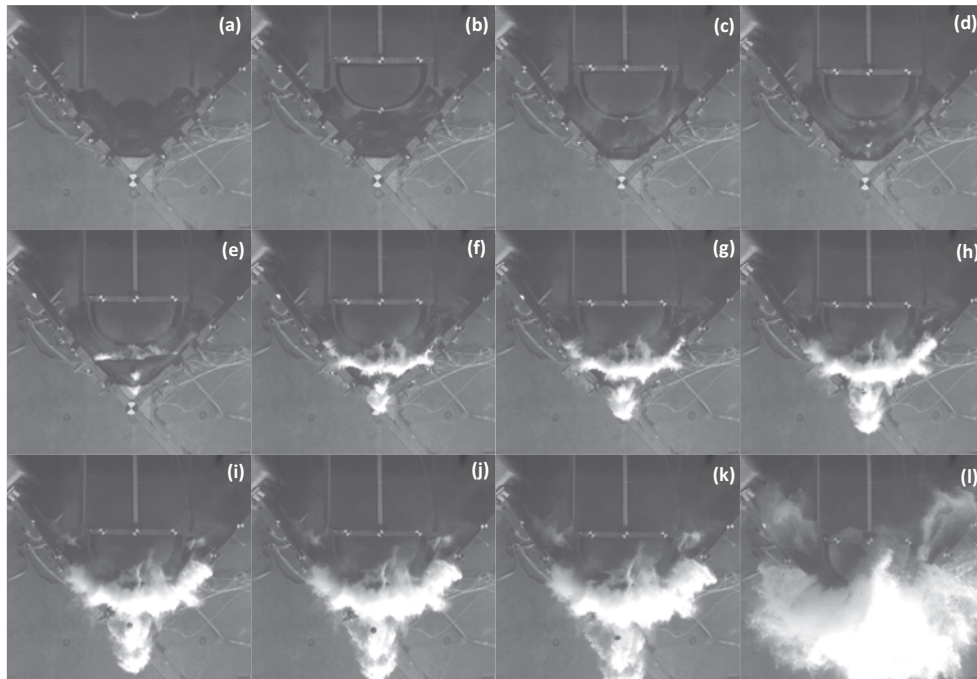


Figure 3.81: Sequence of events during Composite Joint Test 3.

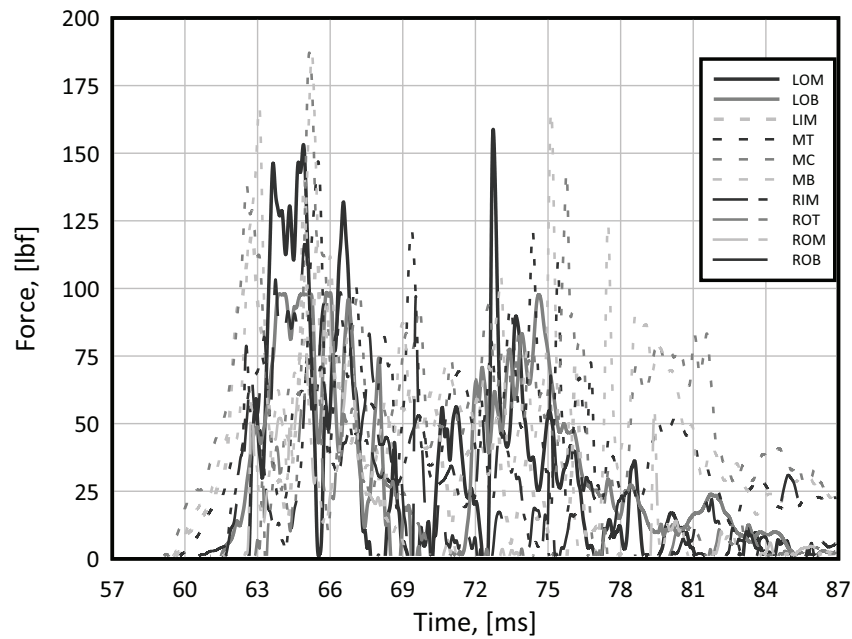


Figure 3.82: Force-time histories for Composite Joint Test 3.

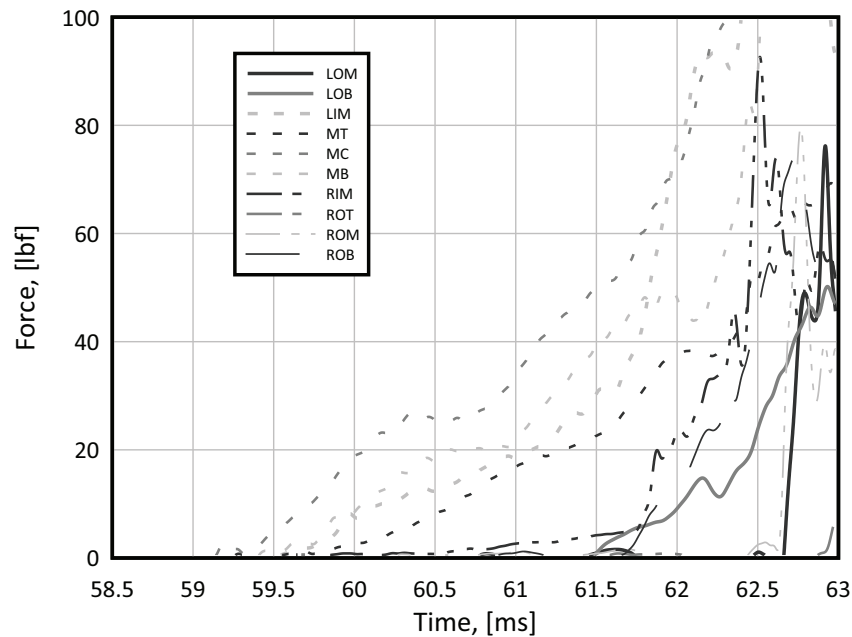


Figure 3.83: Close up of force-time histories for Composite Joint Test 3.

The first observation noted was that the opposite of the intended temporal pulse change occurred, as the middle face of the joint receives load first, beginning at near 59.3

ms and rising to peaks between 124 and 173 lbf over 3 ms. The right and left faces of the joint do not record force until 61.6 ms. This can be largely attributed to the misshapen bladder, as the bulging center compartment of the bladder caused impact sooner than intended. The averaged converted pressure per joint face are shown in Figure 3.84, with impulses following in Figure 3.85.

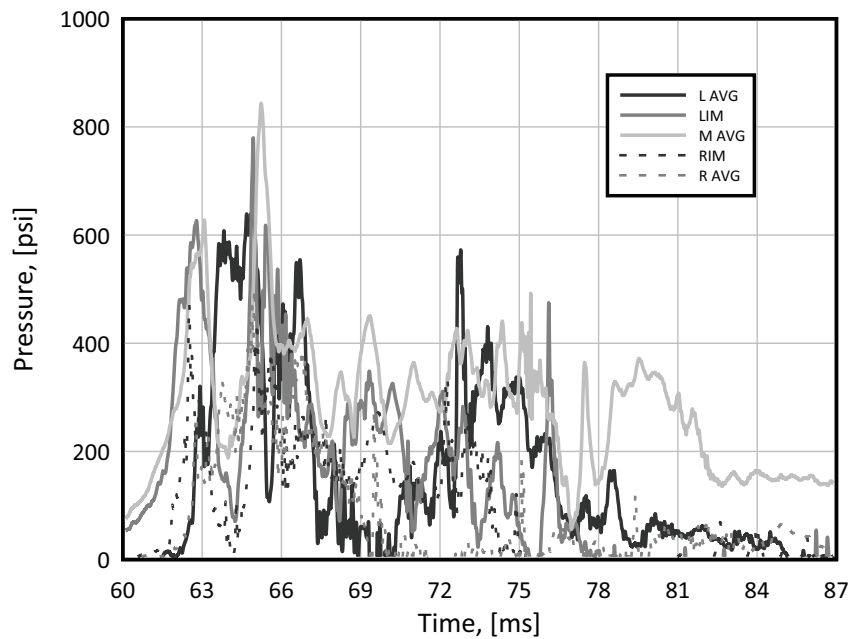


Figure 3.84: Averaged pressure-time histories for Composite Joint Test 3.

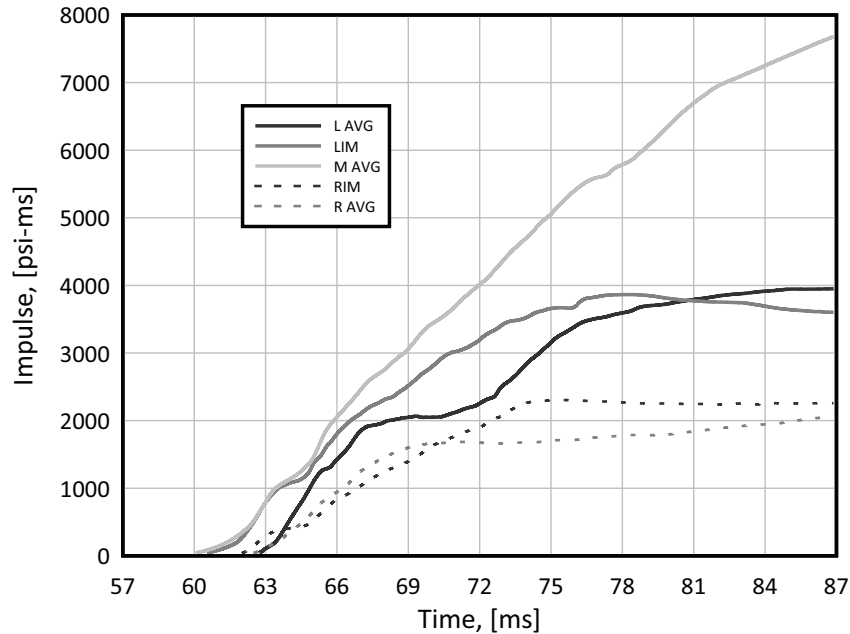


Figure 3.85: Impulses for Composite Joint Test 3.

The pressure-time histories clearly demonstrate the early arrival of the pulse to the center face of the joint as well as left inside load cell (LIM), rising to peaks of just over 600 psi. The right inside middle load cell begin recording force at 62 ms, rising to a peak of 464 psi. All three middle pressure time histories show a significant drop at 65 ms, before showing second peaks ranging between 400 and 800 psi, followed by oscillatory drops to zero over the following 25 ms. The left and right faces of the joint are loaded simultaneously at 62.5 ms, with peak forces of 466 and 630 psi and drops to zero near 70 ms and the left face receiving additional load over the following 15 ms. This is reflected in the impulse plot, as the left face recorded impulses of near double that of the right face, and the middle joint face recording and impulse of almost almost 7700 psi-ms. Strain-time histories from the two panels can be seen in Figure 3.86.

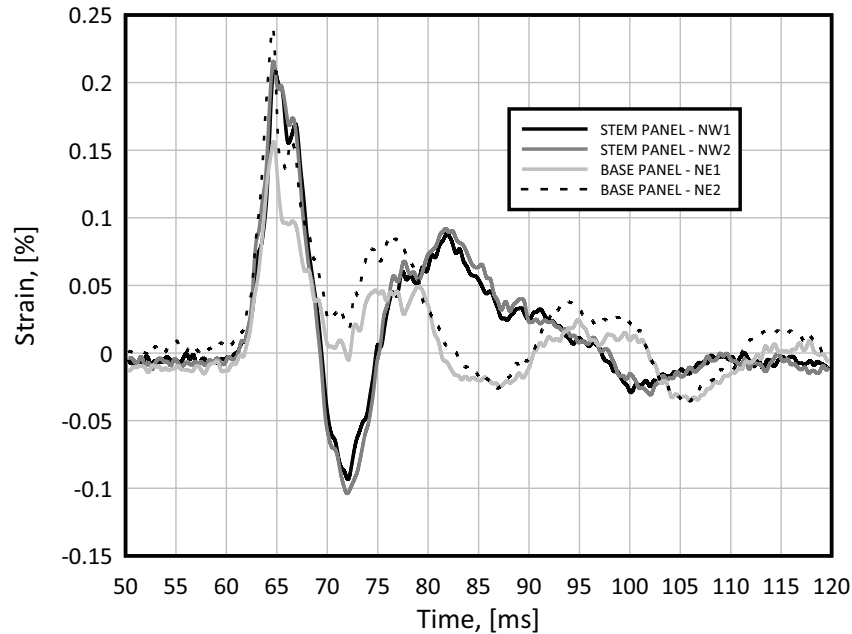


Figure 3.86: Strain-time histories for Composite Joint Test 3.

In the new configuration, the base and stem panel were reversed, with the stem panel now with the strain gauge label of (NW) and the base panel (NE) in the remainder of the strain-time history plots. Both sets of strain gauges denoted peaks of 0.15% to 0.25% strain, rising at similar rates. The stem facesheet drops to zero strain then oscillates in tension for the remainder of the event. The west panel rebounds to a peak compressive strain of 0.1% before oscillating back to zero near 120 ms. Post test inspection of the joint, shown in the photo in Figures 3.87, 3.88, 3.89, revealed a significant amount of damage.



Figure 3.87: Photo of post test damage in Composite Joint Test 3.



Figure 3.88: Photo of post test damage in Composite Joint Test 3.



Figure 3.89: Photo of post test damage in Composite Joint Test 3.

Shear failure is seen through the middle of both triangular sections as well as delamination at three points of the overlaminates. An important observation that could be made from the resultant failure modes was that no shear failure nor delamination along the core-facesheet interfaces was observed, yet the joint reached near breach.

Of critical importance to the Composite Joint Tests was the ability to view initiation and progression of failures. As seen in Composite Joint Test 3, the camera was unable to capture the failure of the joint due to the water dispersion. To remedy this, a polycarbonate shield was mounted on 2 in DWDG bars and placed directly over the specimen. Shown in Figure 3.90, the shield was used to deflect the water and add time of visibility to the phantom camera views during the experiments.



Figure 3.90: Water shield used for Composite Joint Test 4 and 5.

Composite Joint Test 4 was conducted on a virgin joint specimen, at a target velocity of 590 in/s (15 m/s). In an additional effort to increase time of camera visibility after bladder breach by diverting the water in the direction of the baffles, the baffles were turned 90 degrees. The bladder is shown mounted in Figure 3.91.



Figure 3.91: Water bladder with rotated baffles used for Composite Joint Test 4.

To investigate the effect of foam density on axial force, the FR-3707 foam ($\rho = 7 \text{ lb}/\text{ft}^3$) was replaced with an FR-3515 ($\rho = 15 \text{ lb}/\text{ft}^3$). The dimensions used for the gripping fixtures in Composite Joint Test 4 and 5 are seen in Table 3.11 and the sequence of events can be seen in Figure 3.92.

Table 3.11: Gripping Fixture Dimensions for Composite Joint Test 4 and 5.

CJ Joint Test 4,5	L_{web} (in)	t_{web} (in)	σ_y (ksi)	w_{foam} (in)	t_{foam} (in)	E_{foam} (psi)
Base Panel	24	0.125	70.0	2.5	1.625	21920
Stem Panel	24	0.125	70.0	2.5	1.625	21920
Back Panel	30	0.25	70.0	2.5	1.625	21920

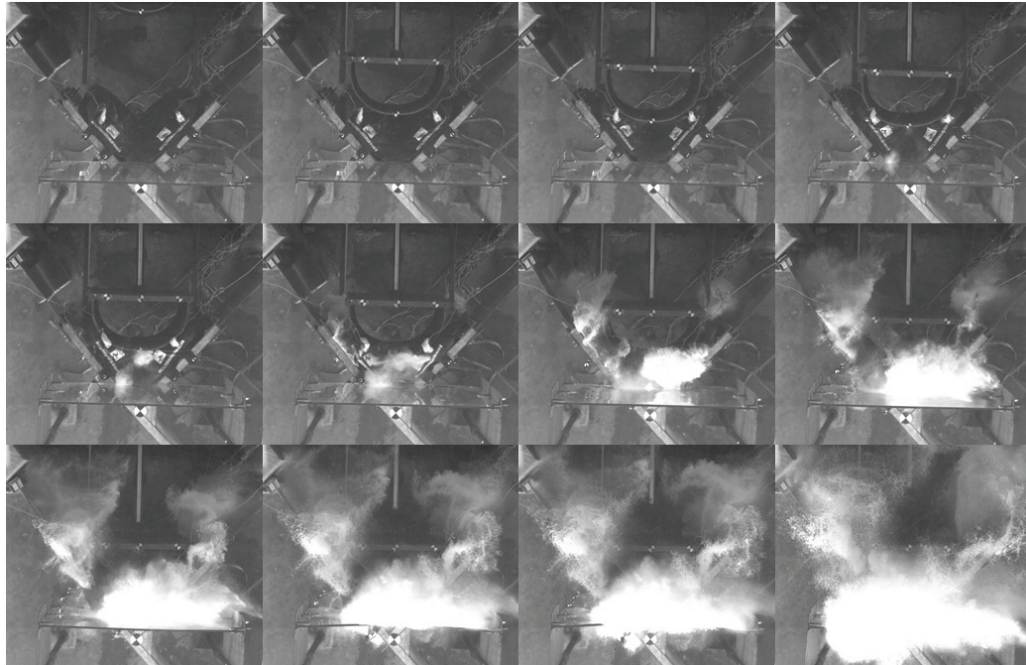


Figure 3.92: Sequence of events during Composite Joint Test 4.

The effect of the water shield is clearly seen as the specimen was able to be seen past its maximum displacement and no failures were observed. Force-time histories from the experiment can be seen in Figure 3.93 and for clarity of force arrival times, Figure 3.94 shows the record zoomed in and color distinguished for each joint face.

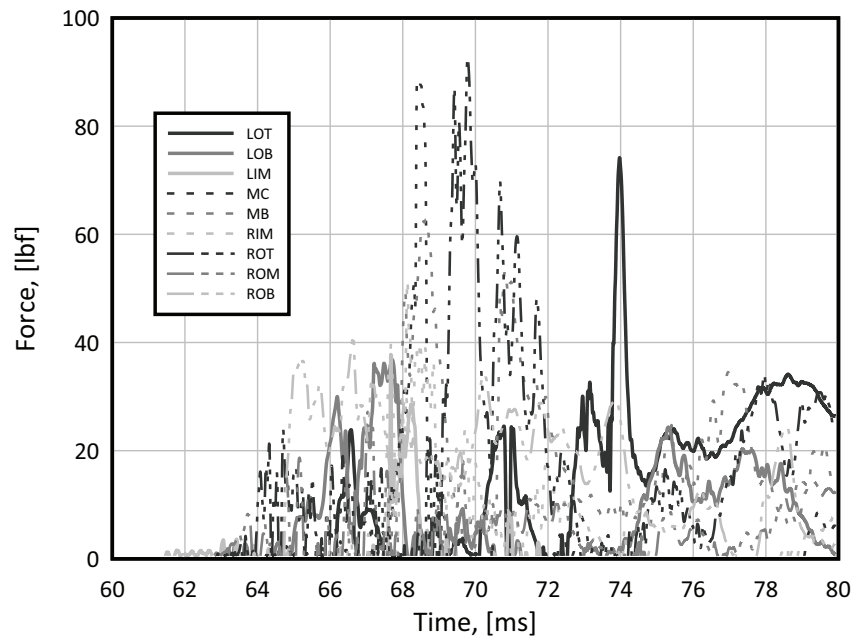


Figure 3.93: Force-time histories for Composite Joint Test 4.

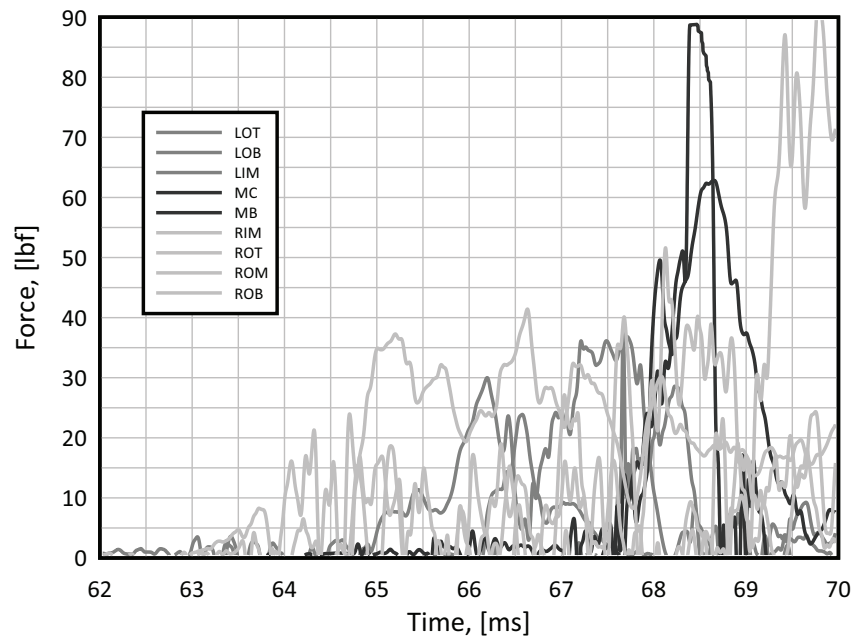


Figure 3.94: Close up of force time history to show load arrival times in Composite Joint Test 4.

The effect of the rounded flyer was immediately noted , as the right and left load

cells show load delivery at 64 and 65 ms, respectively, and force is not recorded at the center load cells until 67.5 ms. Averaged pressure and impulse time histories are shown in Figures 3.95 and 3.96 .

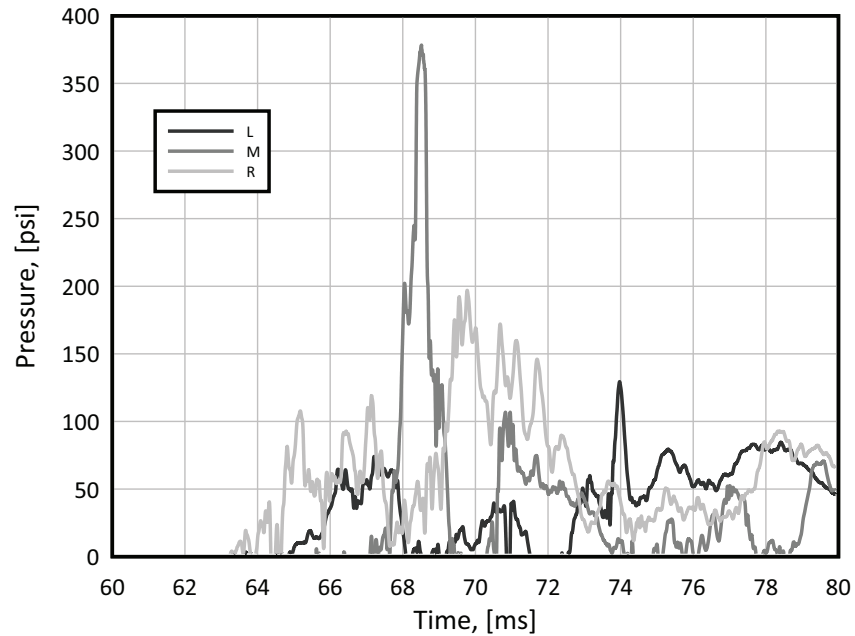


Figure 3.95: Averaged pressure-time histories for Composite Joint Test 4.

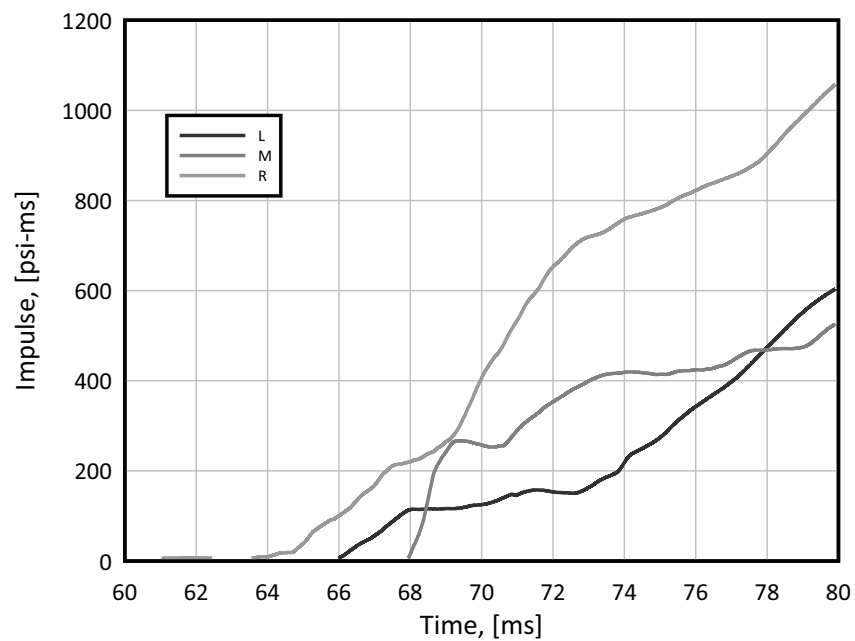


Figure 3.96: Impulses for Composite Joint Test 4.

The arrival of pressures to the panels of the joint before the middle face is made further apparent in the plots, showing rises to pressures of 102 psi at 65 ms for the right face and 66.5 ms to 55 psi for the left, both with durations of 3 to 4 ms before dropping to zero. The middle joint face does not record force until 68.5 ms, reaching a peak of 370 psi and dropping back to zero over 2 ms. The impulses approach 500 and 600 psi-ms for the left and right faces due to the additional reflection from 69 to 80 ms, while the middle load cell recorded an impulse of near 1050 psi-ms. These impulses were far less than those recorded in the previous test, most likely due to the baffle orientation which diverted flow toward the joint. Figure 3.97 shows strain-time histories for the left (east, stem) and right (west, panel) loaded arms.

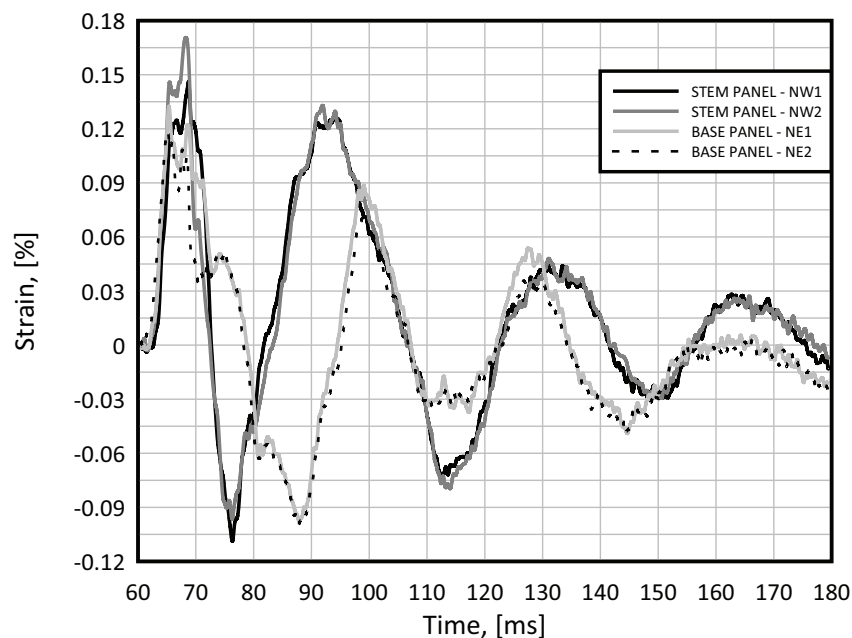


Figure 3.97: Strain-time histories for Composite Joint Test 4.

The strain time histories show rises to 0.15 and 0.17% strain at 61 ms in the stem and base panel, respectively. Both strain histories elastically oscillate back to zero over the remainder of the event in tension and compression.

Because no damage was observed, the specimen was tested again in the same configuration for Composite Joint Test 5, the setup of which is seen from two views in Figure 3.98. Because of the small loads recorded in the previous test, the baffles were returned to the vertical orientation, and an emphasis was placed on the manufacturer to

ensure that the weakly restrained center compartment seen in Composite Joint Test 3 was not present.



Figure 3.98: Composite Joint Test 5.

In Composite Joint Test 5, the target velocity was increased to 1024 in/s (26 m/s) to invoke more damage and closely examine the progression of failure. The sequence of events filmed with the phantom camera can be seen in Figure 3.99.

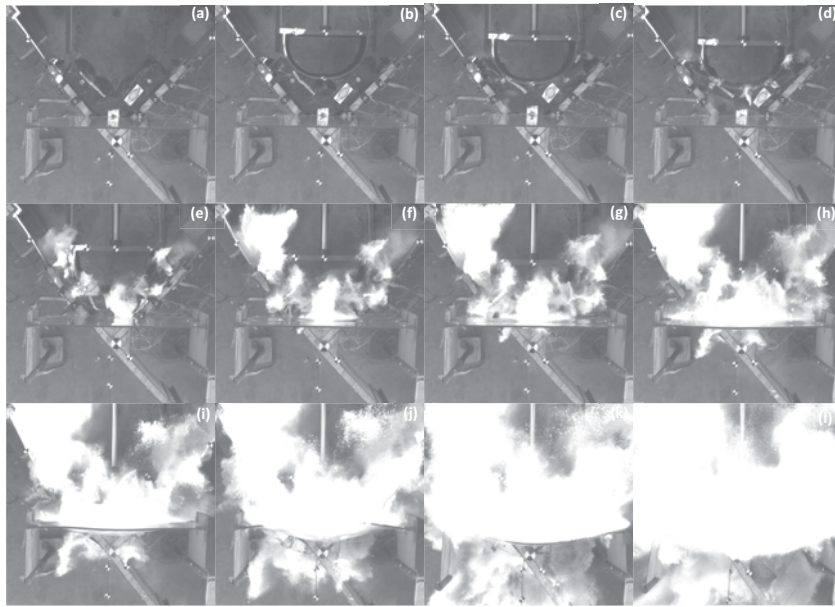


Figure 3.99: Sequence of events during Composite Joint Test 5.

The bladder was impacted to the left and right sides first,(b), followed by load delivery to the center face, seen in (c). The bladder continued to compress in (d) and breach is first seen at the center of the bladder in (e). The specimen continued to displace in (f)-(g). Figures (h)-(k) are enlarged and annotated in Figures 3.100, 3.101, 3.102, and 3.103 to describe the failure progression in detail.

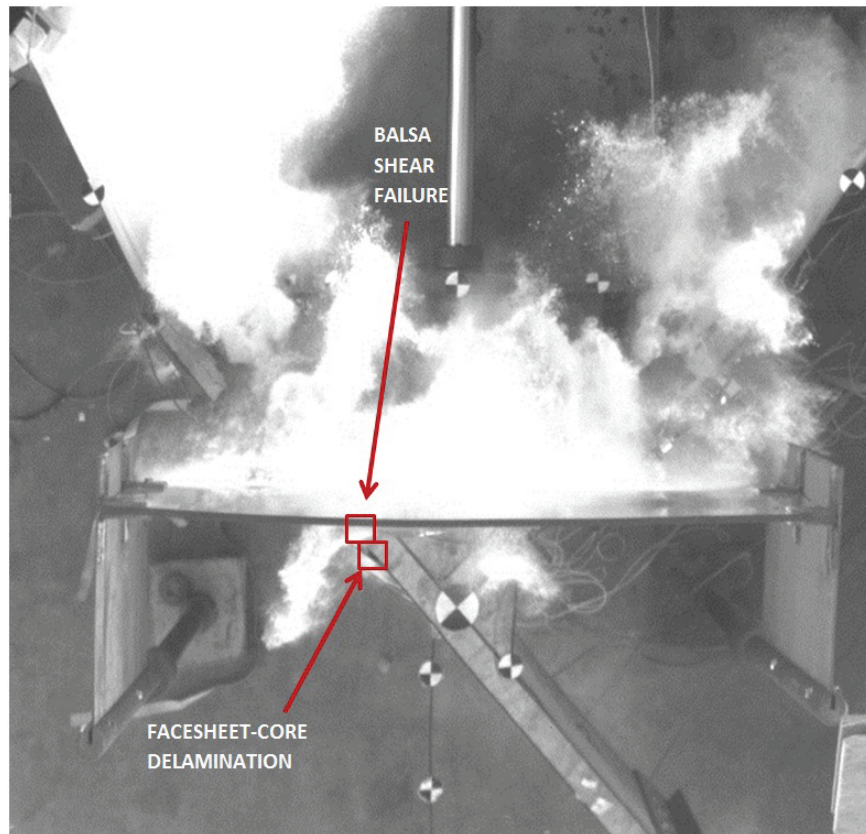


Figure 3.100: Damage progression in Composite Joint Test 5 @ $t = 85.25$ ms.

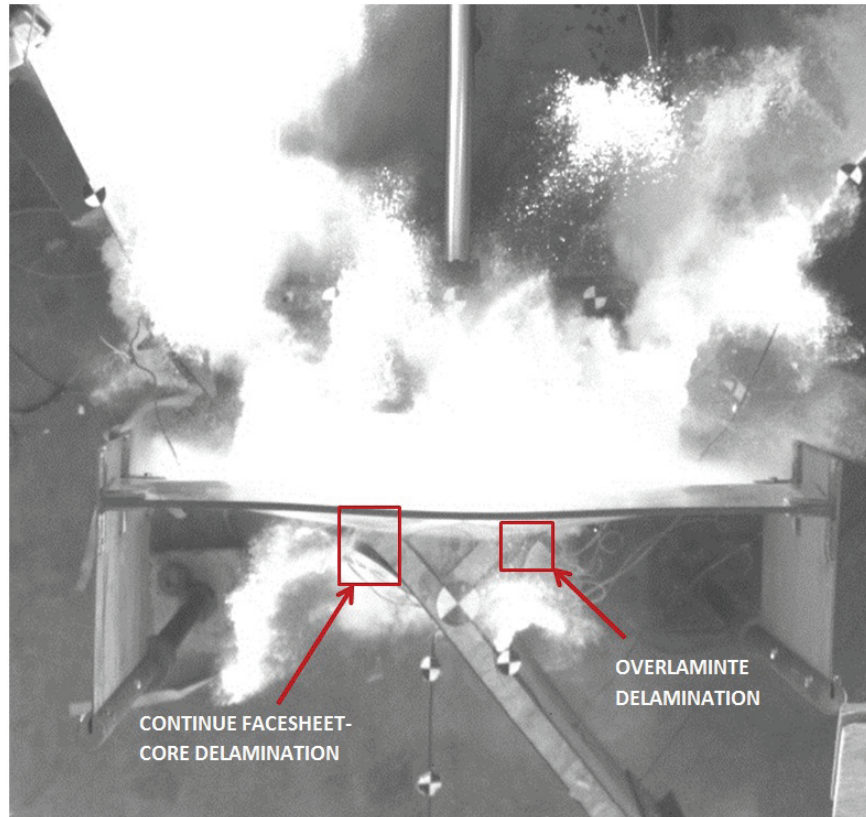


Figure 3.101: Damage progression in Composite Joint Test 5 @ $t = 88.75$ ms.

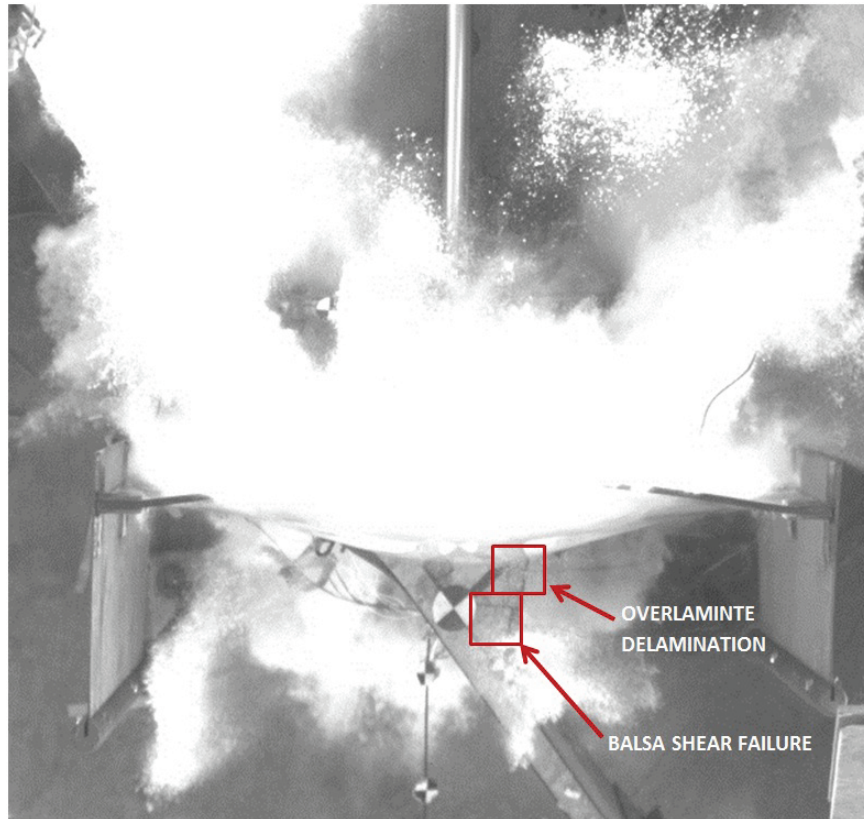


Figure 3.102: Damage progression in Composite Joint Test 5 @ $t = 101.0$ ms.



Figure 3.103: Damage progression in Composite Joint Test 5 @ $t = 114.5$ ms.

Figure 3.100 shows initiation of failure via core shear failure across the loaded base panel (west) arm, 2 in away from the termination point of the where the overlamine begins. The shear failure induced delamination along the core facesheet interface towards the joint. As the delamination continued along the base panel. The bending of the non-continuous stem resulted in initiation of delamination of the overlamine on the back of the joint, seen in Figure 3.101. The overlamine continued to pull away from the joint as the loading continues, seen in Figure 3.102, causing shear failure through the adjacent triangular balsa core. The complete shearing through the triangular balsa core eventually caused the bottom backside overlamine to delaminate from the base panel completely, shown in Figure 3.103, and the stem then pulls away from the base. Examination of Figure 3.104, revealed joint breach, as the stem and base panel were no longer attached. The shear failures in the base panel near the overlamine termination points is shown in Figures 3.105.



Figure 3.104: Photo of post damage in Composite Joint Test 5.



Figure 3.105: Photo of post damage in Composite Joint Test 5.

The measured force-time histories are shown in Figure 3.106, and average converted pressure and impulse-time histories are shown in Figures 3.107 and 3.108.

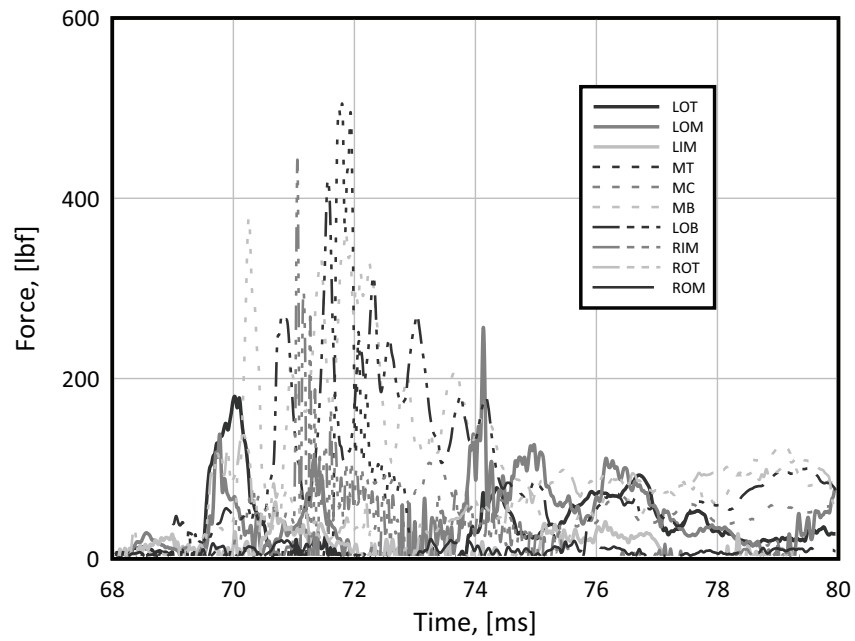


Figure 3.106: Force-time histories for Composite Joint Test 5.

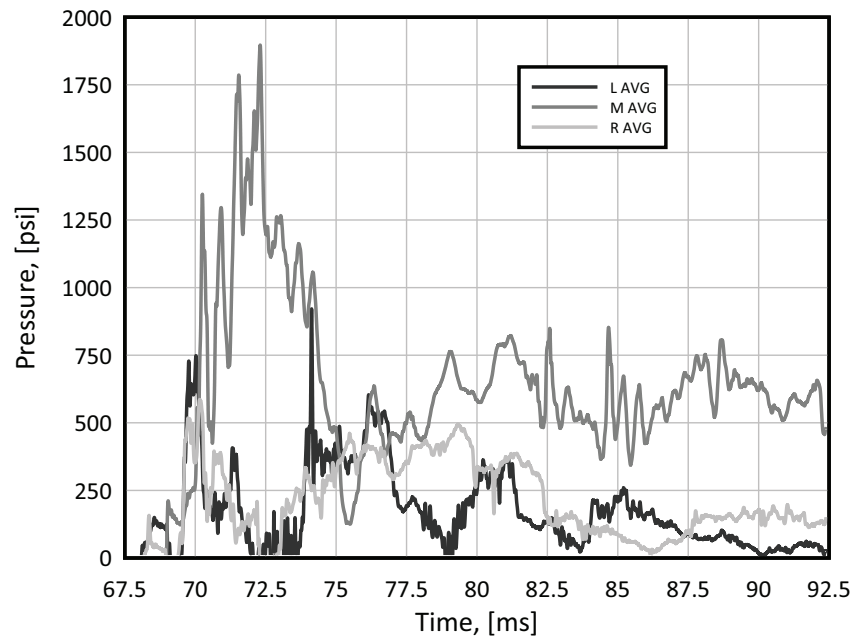


Figure 3.107: Averaged pressure-time histories for Composite Joint Test 5.

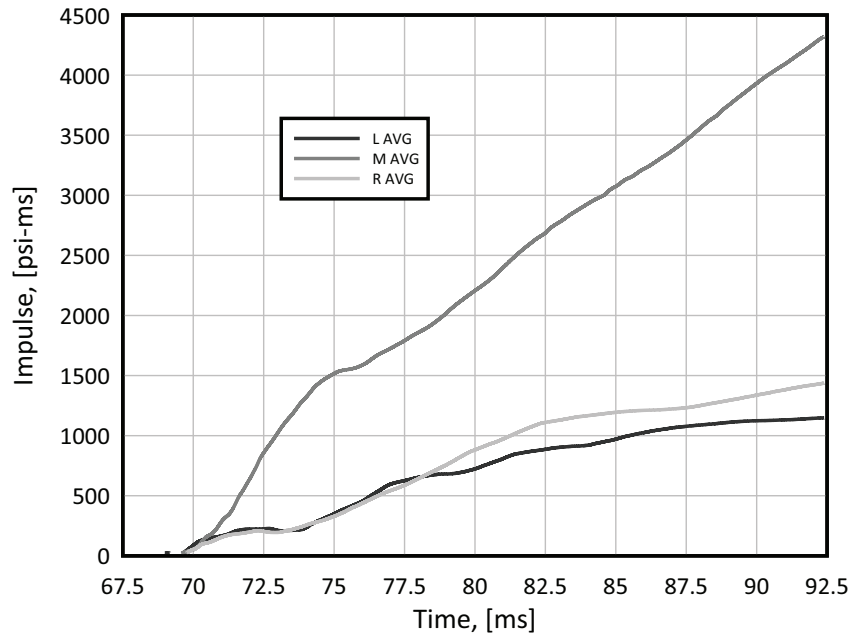


Figure 3.108: Impulses for Composite Joint Test 5.

The base and stem panels begin recording load at 68 ms, reaching peaks of 650 and 496 psi. The pressures drop back to zero at 72.5 ms followed by sequential oscillations leading to impulses of 1405 and 1174 psi-ms. The center face began recording load at 69.5 ms, reaching a peak of 1760 psi over a duration of 6 ms followed by decay load out to 83 ms, leading to an impulse of 4307 psi-ms. Strain-time histories recorded during the experiment can be seen in Figure 3.109 .

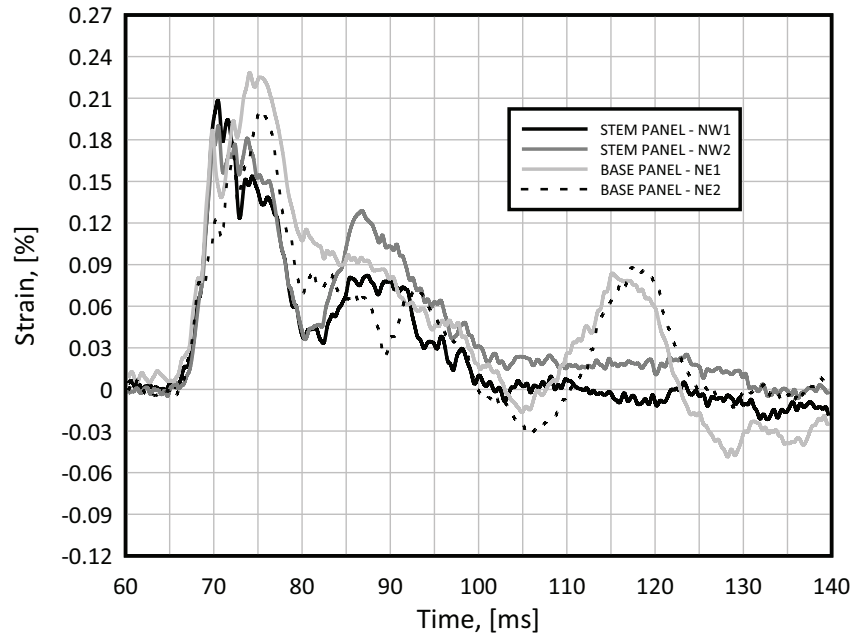


Figure 3.109: Strain-time histories for Composite Joint Test 5.

Both sets of strain gauges on the loaded panels began elongating at 66.7 ms, with the stem reaching a peak of 0.23% bending strain, while the base peaks just beyond 0.2%. Both joint panels record steep decreases in strain until 79 ms, when the stem panel rebounded back up to 0.12% and then gradually descended towards zero strain, while the base continued to drop into compression and not rebounding again until 105 ms and then dropping back down to zero strain.

3.3 Summary

This chapter described the development of methods and procedures for the assessment and testing of structures having complex or non-flat geometries. Through the use of high strength and highly tailorable water bladders, it was shown that force can be transmitted in multiple dimensions and produce pressures and impulses similar in shape to those produced from confined explosions. Through the variation of velocity and impacting mass, peak pressures were able to be controlled. Changing bladder material and internal geometry allowed for the modification of pulse duration, while bladder and impacting mass geometries governed the spatial distribution of applied pressures over

time.

Following the loading medium investigation, a series of tests were conducted in which embedded load cell assemblies were tested to develop appropriate methods for embedment into the composite material. These technologies were incorporated into full scale tests using the UCSD Blast Simulator Facility, first through the testing of surrogate joint specimens to investigate the effects of water bladder and impacting mass assemblies on temporal and spatial pressure distributions. In order to grip the composite joint specimens of interest, a reaction structure and tailorable gripping fixture assemblies were designed. Through the use of high speed video, dynamic load cells and strain gauges, a series of five Composite Joint Tests revealed consistent modes of failure: 1) shear failures through the balsa core material, 2) delamination along core-shear interfaces, 3) shearing of the triangular stiffeners and 4) delamination of the FRP overlaminates.

With the failure mechanisms of interest defined, a series of smaller scale material tests were conducted to assist in the calibration of material models for the use in the simulation of the Composite Joint Tests. The following chapter describes these experiments in detail, all of which were conducted at the various experimental facilities of UCSD's Department of Structural Engineering.

Chapter 4

Material Tests

The Composite Joint Tests presented in the previous chapter revealed four critical structural behaviors contributing to connection breach: bending of the composite panels, shear failure through the balsa core, delamination of the facesheets from the core and ultimately delamination of the FRP overlaminates from the base and/or stem facesheets. In an effort to develop a predictive numerical model of joint behavior, a series of material tests were conducted to obtain data necessary for the calibration of finite element material models.

To investigate the performance of the composite sandwich material in bending, 96 in long sandwich beams were tested to failure both statically and dynamically. In a series of 20 in long beam bend tests, shear failure criteria of the balsa core material was investigated at various strain rates. Delamination at the core-facesheet interface was examined through the conduction of bend tests on pre-slit sandwich beam specimens which isolated the coherence parameters of the sandwich assembly. The following chapter presents the results from these material tests which were conducted in a collaborative effort including UCSD graduate students Antony Chen [7] and Daniel Whisler [39].

4.1 Bending Properties

4.1.1 Quasi-Static Bend Tests

The first set of bend tests were conducted at the UCSD Powell Laboratories using a 2.67 MN capacity Satek 810 material test machine. Four 96 in specimens were put under 4-pt bending with simply supported conditions and tested to failure quasi-statically (QS) at a rate of 0.017 in/s. A photo of the setup can be seen in Figure 4.1.

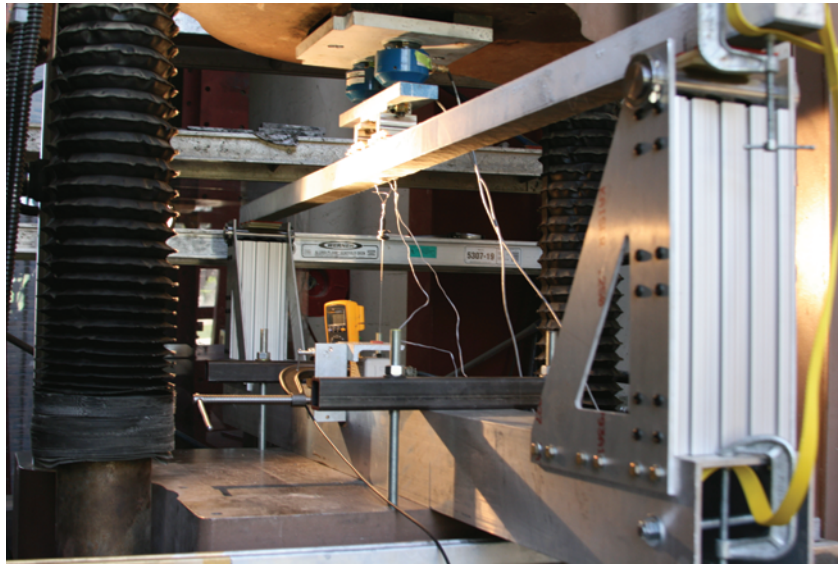


Figure 4.1: QS Bend Test setup.

The load frame was composed of a 90 in long, 6 in x 6 in x .25 in aluminum HSS section affixed with 18.5 in x 12 in x .25 in thick triangular support brackets and 1.5 in aluminum rollers. The specimen was placed on 3.5 in x 3.5 in x .625 in thick glass-epoxy laminate/rubber spreader plate assemblies to alleviate local crushing of the composite facesheets. For load measurement, the Satek machine was mounted with two 222 kN Interface load cells attached to a 6 in x 3 in x .5 in aluminum plate and 0.75 in roller assembly. Two additional spreader plates were placed between the loading rollers and the top of the specimen. A schematic of the setup can be seen in Figure 4.2.

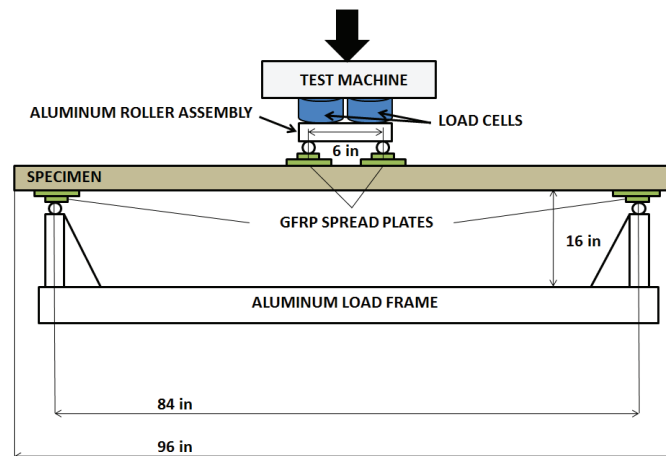


Figure 4.2: QS Bend Test geometry.

A total of three experiments were conducted and video was taken with a Phantom camera in the time ranges of failure. Bending strains were recorded at the midspan of the back (tension) side and front (compression) side of the beam using 350 $\bar{U}$ model TML FLA-6-350-1L strain gauges. A 15 in range string pot was used to measure specimen mid-span displacement. A typical sequence of events for the QS Bend Tests can be seen in Figure 4.3. Force-displacement and strain-displacement plots for all three tests are shown in Figures 4.4 and 4.5, respectively.

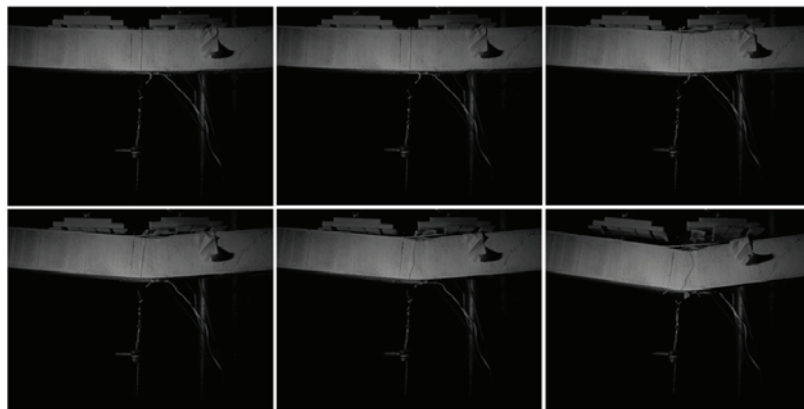


Figure 4.3: Sequence of events during QS Bend Tests.

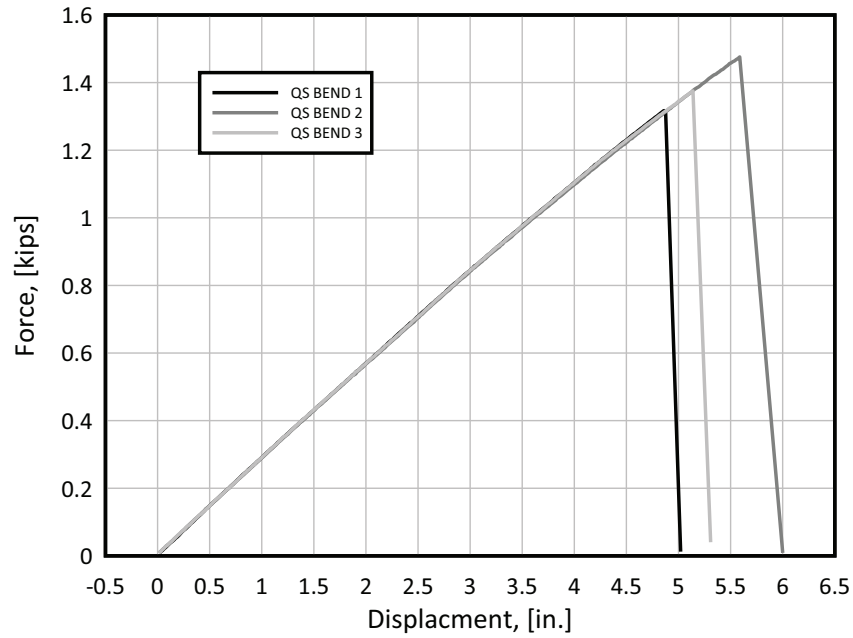


Figure 4.4: Force-displacement plots for QS Bend Tests.

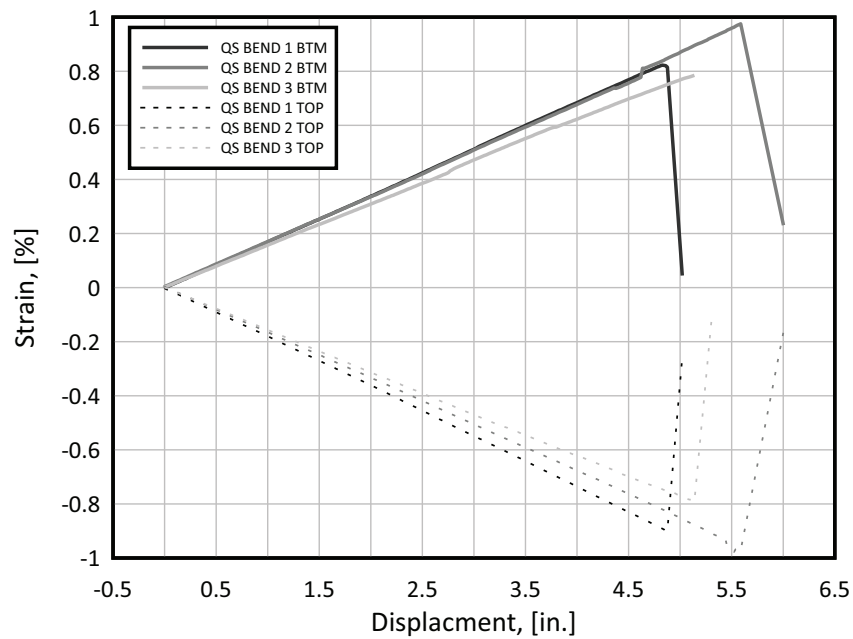


Figure 4.5: Strain-displacement plots for QS Bend Tests.

In QS Bend Test 1, the specimen displaced 4.85 in, reached a maximum midspan compressive strain of 0.90% and maximum tensile strain of 0.82% before buckling in

the top facesheet 4 in outside of the right roller at a load of 1.32 kips. The facesheet failure triggered delamination along the core-facesheet interface towards the midspan followed by shear failure through the core. A photo of the specimen after the test is shown in Figure 4.6.

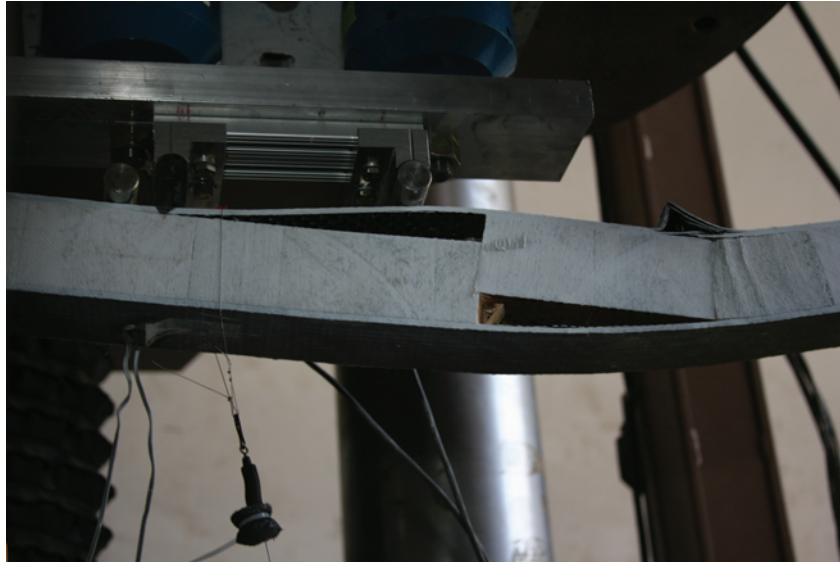


Figure 4.6: Post test damage for QS Bend Test 1 demonstrating both compressive buckling of the top facesheet as well as shearing of the core.

The specimen in QS Bend Test 2 demonstrated similar compressive failure in the top facesheet at a load of 1.47 kips and displacement of 5.6 in, but this time directly under the aluminum roller and spreader plate, shearing the core underneath the FRP failure location and causing delamination along the bottom side of the beam. The top face sheet reached a maximum compressive strain of 0.97% and maximum tensile strain of 0.98%. A photo of the specimen after QS Test 2 is shown in Figure 4.7.

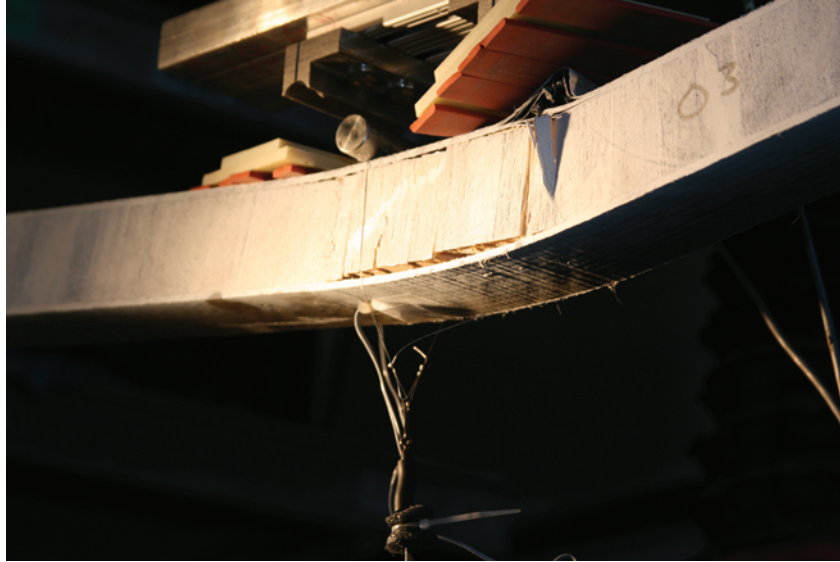


Figure 4.7: Post test damage for QS Bend Test 2 demonstrating compressive buckling of the top facesheet and delamination.

Initial compressive failure in QS Bend Test 3 occurred at a load of 1.37 kips and a displacement of 5.1 in in the top FRP facesheet near the center of the beam. The maximum recorded compressive and tensile strains were 0.79% and 0.78%, respectively. The failure triggered delamination at the core-facesheet interface followed by further composite failure along the delamination line until forming a hinge near the midpoint. A photo of the specimen after QS Test 3 is shown in Figure 4.8.

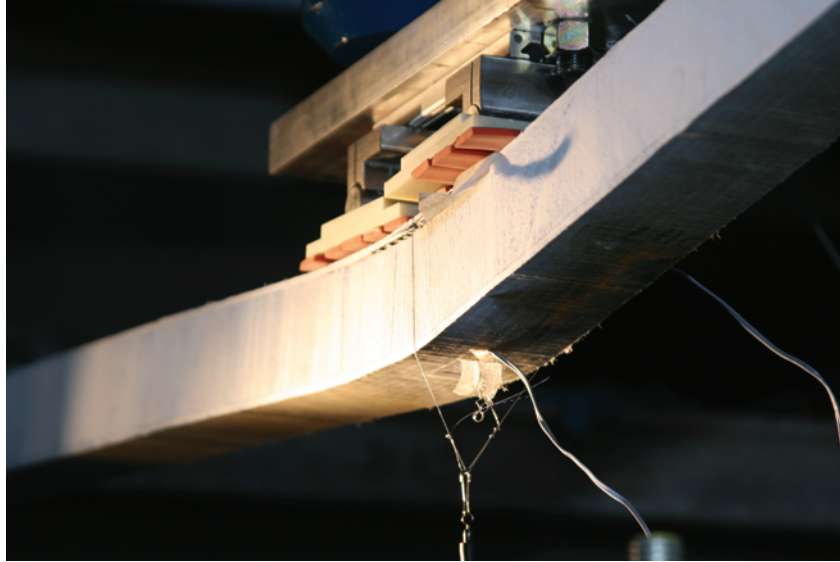


Figure 4.8: Post test damage for QS Bend Test 3 denoting compressive failure and hinge formation.

The following section describes a set of dynamic tests conducted on beam specimens of the same geometry using the UCSD Blast Simulator.

4.1.2 Dynamic Bend Tests

The next set of bend experiments were conducted dynamically using the Blast Simulator. The setup was designed to use an existing concrete block reaction block to which the same aluminum frame used in the quasi-static setup was mounted. In between the frame and block, two 50 kip model 1220 Interface load cells were placed to measure reaction force. The frame was mounted vertically and the specimen was mounted in a similar fashion as the quasi-static configuration. A photo of the setup can be seen in Figure 4.9.



Figure 4.9: Blast Simulator configuration for Dynamic Bend Tests.

For load application, a 16 in x 16 in x 0.75 in steel plate was attached to the Blast Generator rod. The specimen was mounted with a similar plate, roller and spreader plate assembly as used in the quasi-static setup, with four notable changes. A Dytran 1060 V1 500 lb load cell was mounted onto the plate for load measurement, and a 3 in x 3 in x 1 in thick piece of structural foam was taped to the top of the load cell to dampen high frequency noise. The loading assembly was affixed to the specimen via nylon straps to compliantly hold the vertically mounted specimen in place during impact. To direct failure closer to the midspan of the beam, the specimens were dog-boned 6 in from each side of the center. A photo of the machined specimens can be seen in Figure 4.10 and Figure 4.11 shows the the loading assembly setup before impact.

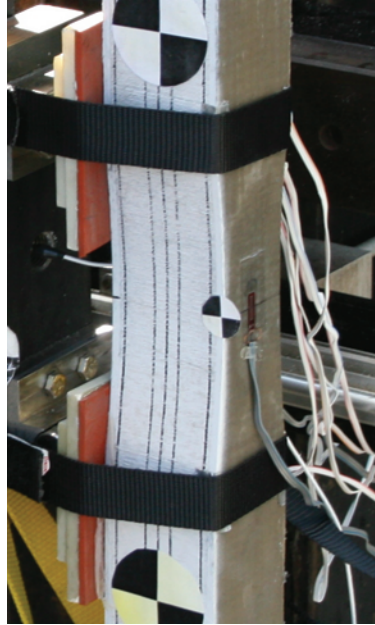


Figure 4.10: Dog-bone specimen for Dynamic Bend Tests .



Figure 4.11: Impact plate assembly for Dynamic Bend Tests.

A total of three specimens were tested dynamically in this configuration at a

speed of 394 in/s (10 m/s). In Bend Test 1 and 2, the impacting plate began 6 in away from the loading assembly while the impacting plate began in contact for Test 3. Strain gauges were mounted at the midspan of the front and back facesheet at the midspan and video was taken with Phantom cameras at 5,000 frames/sec. A typical sequence of events through the course of the dynamic bend experiments can be seen in Figure 4.12 which shows the entire beam, while Figure 4.13 shows a zoomed in view taken a slight angle to highlight depth.

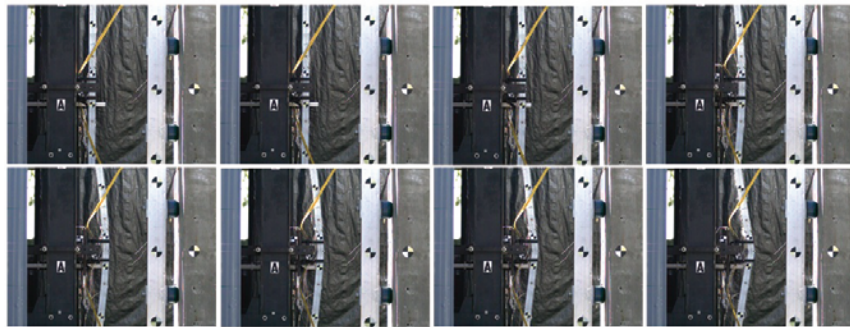


Figure 4.12: Side view sequence of events during Dynamic Bend Tests.

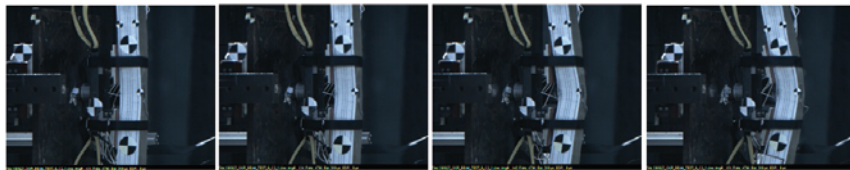


Figure 4.13: Angled view of sequence of events during Dynamic Bend Tests.

The three dynamic tests exhibited similar characteristics in terms of overall deformation: at impact, the specimen displaced as it went into bending, reached a critical strain in the front face sheet and compressively buckled, forming a hinge at the center and causing delamination at the interface along with core shear failures along the length. Post test photos for each test are shown in Figure 4.14(a)-(c). Figure 4.15 denotes force-time histories recorded from the front load cells for each test and Figure 4.16 shows reaction load cell forces recorded from the two back load cells.

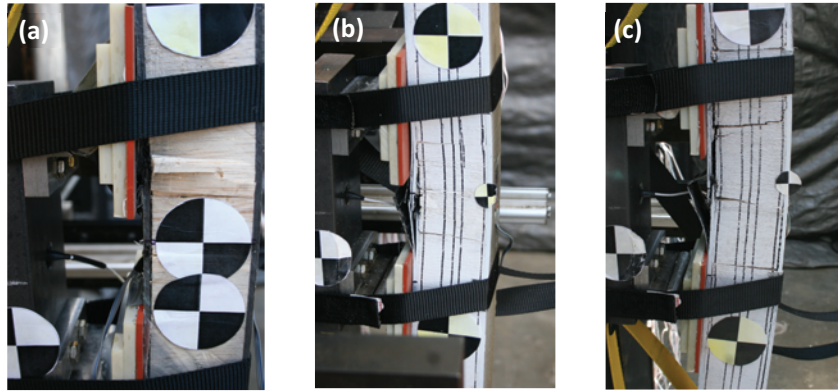


Figure 4.14: Post test photos for Dynamic Bend Tests (a) 1, (b) 2, and (c) 3.

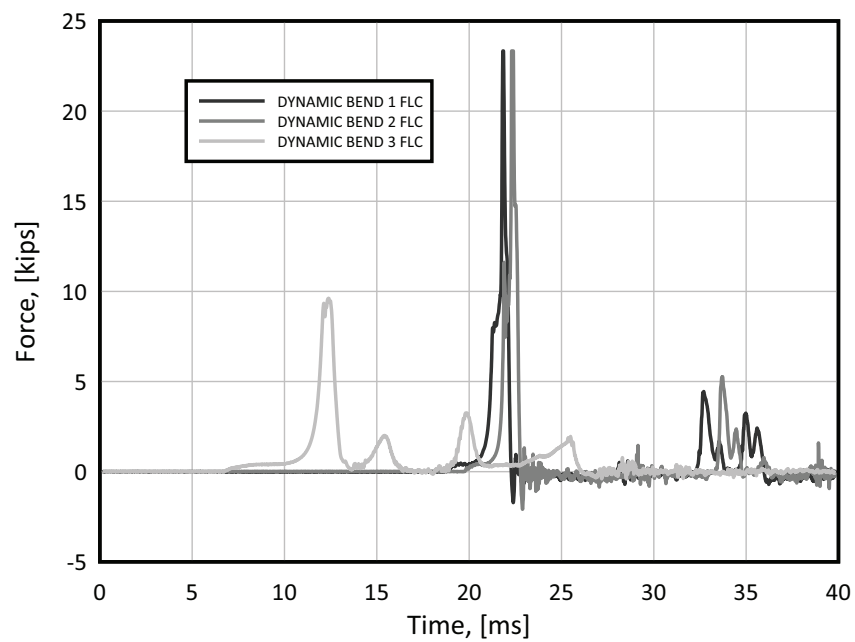


Figure 4.15: Front load cell force-time histories for Dynamic Bend Tests 1-3.

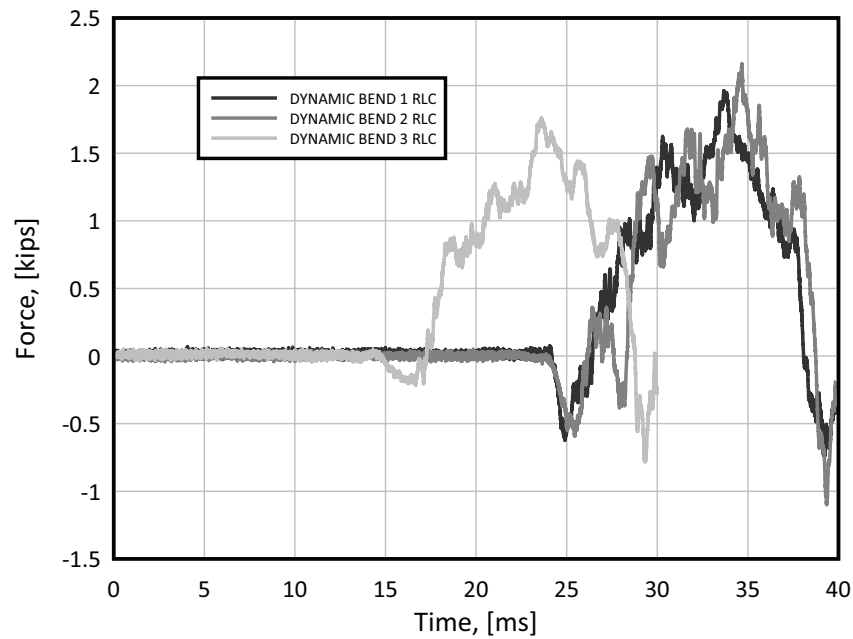


Figure 4.16: Reaction load cell force-time histories for Dynamic Bend Tests 1-3.

Tests 1 and 2 show similar readings, with a rise to roughly 7.5 kips before a very sharp peak up to near 25 kips at 23 ms, and almost asymptotic drop of load immediately following. The sharp peak is not present in Test 3, with smooth rise to a maximum of 9.4 kips. Test 1 and 2 reached peaks close to 2 kips, with a durations between 12 and 14 ms, while a peak of 1.75 kips over a duration of 10 ms is seen in the faster Test 3. Strain-time histories are shown in Figure 4.17.

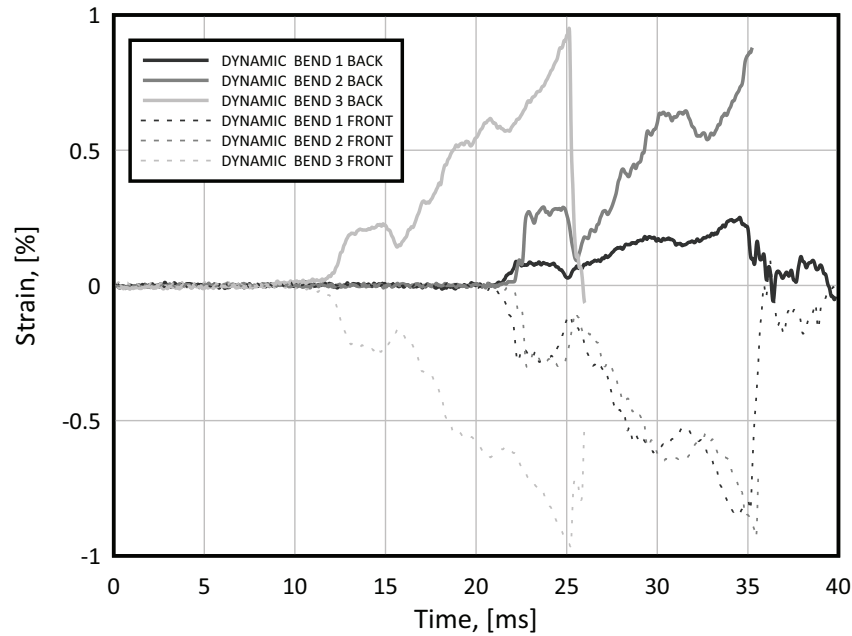


Figure 4.17: Strain time histories for Dynamic Bend Tests 1-3.

Maximum compressive strains between 0.85% and 1% were seen at facesheet failure, similar to that seen in the quasi static tests, however with the addition of the dog-bone, failure was seen much close to the midspan of the specimen. Although Test 1 did not show high tensile strains (due to excessive shearing of the core), Tests 2 and 3 reached peak tensile strains approaching 1%.

4.2 Shear Properties

4.2.1 Quasi-Static Shear Tests

A third set of bend experiments were conducted to investigate shear characteristics using 20 in. long sandwich specimens. A schematic of the experimental setup can be seen in Figure 4.18.

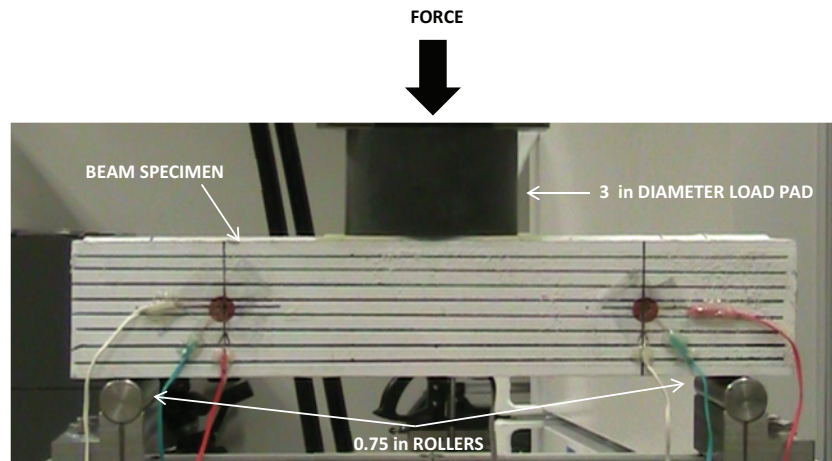


Figure 4.18: Schematic of QS Shear Tests.

The specimens were loaded using a servohydraulic 100 kN MTS 810 material test system (uniaxial tension/compression test machine) and were simply supported by two 0.75 in steel rollers, while a 3 in diameter urethane cylinder was used to distribute the load and avoid localized failure. Applied force was measured with the MTS test machine's built in load cell, and the experiments were run at crosshead speeds of 0.0033 in/s. Bending strains in the bottom facesheet were recorded at the midspan of the beam using a 350 Ω model TML FLA-6-350-1L strain gauge. Shear strains were measured in the core using 45° rosettes placed at the midplane 2.5 in away from either end. A laser extensometer was used to measure displacements at center of the beam. A schematic showing the location of instrumentation is shown in Figure 4.19.

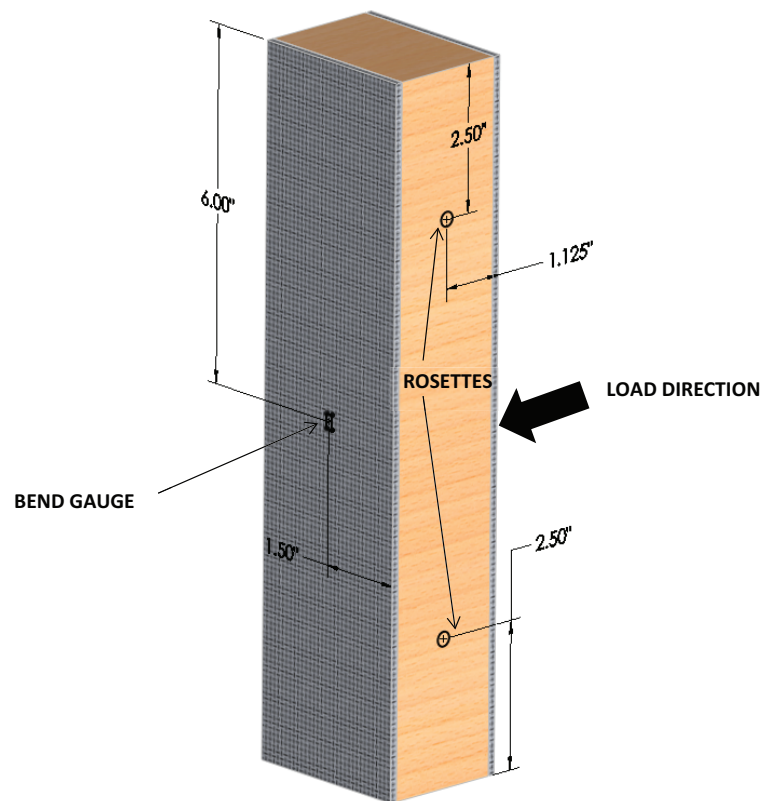


Figure 4.19: QS Shear Test instrumentation locations.

A total of six quasi-static tests were run at load rates ranging between 0.08 and 0.122 kip/s. Live footage was captured using a Samsung HD video camera. A typical sequence of events can be seen in Figure 4.20.

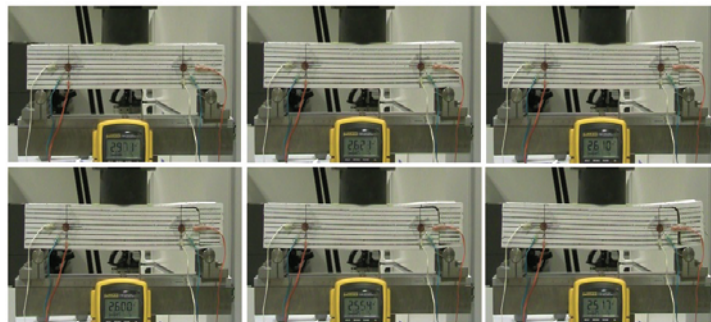


Figure 4.20: Typical sequence of events for QS Shear Tests 1-6.

Failure in the short beam specimens were typically characterized by shear failure

through the balsa core near one of the two supports, followed by delamination along the impact side facesheet-core interface towards the midspan and along the backside facesheet towards the supports. Force-displacement curves for all six tests can be seen in Figure 4.21. The instantaneous drops in force at the peaks of the curves demonstrate the point of initial shear failure and the continued displacement at the reduced load is characteristic of delamination.

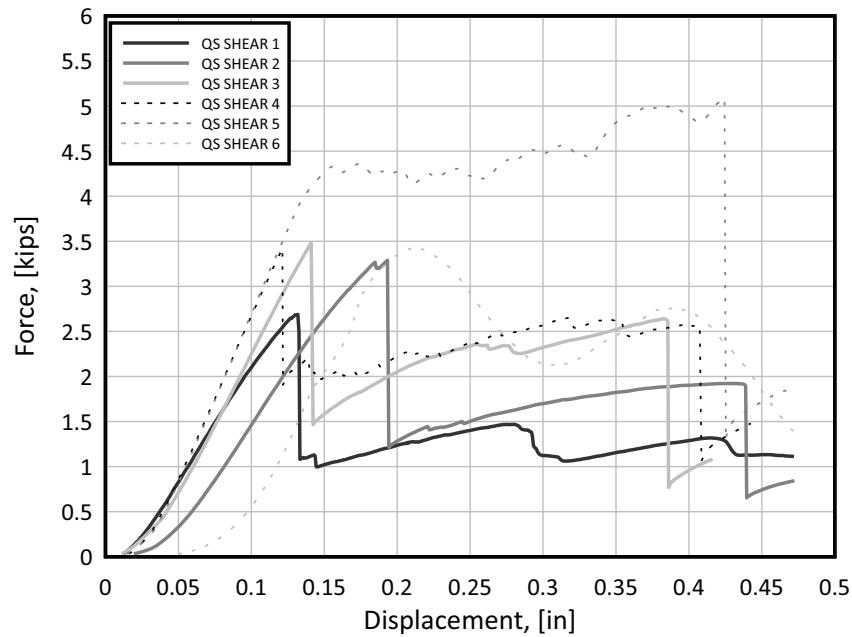


Figure 4.21: Force displacement results for QS Shear Tests 1-6.

Variations of peak force ranged from 2.7 to 4.3 kips at displacements between 0.12 to 0.19 in. Tests 1-4 show sharp drop offs to near half of the peak loads, at which point the strength of the adhesive at the core-facesheet interface pick up the loads. A plot of strains recorded from the back bending gauge and shear strains from the rosettes in QS Shear Test 2 can be seen in Figure 4.22, denoting core shear strains to failure of 0.6% and a maximum bending strain in the back FRP facesheet of 0.2%. Strain is then plotted against displacement in Figure 4.23.

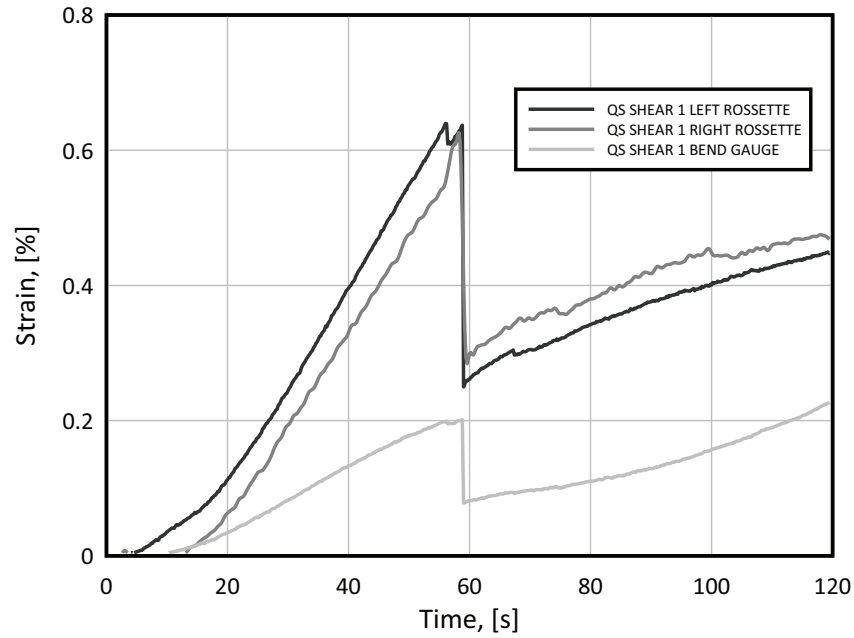


Figure 4.22: Bending and shear strain-time histories for QS Shear Test 2.

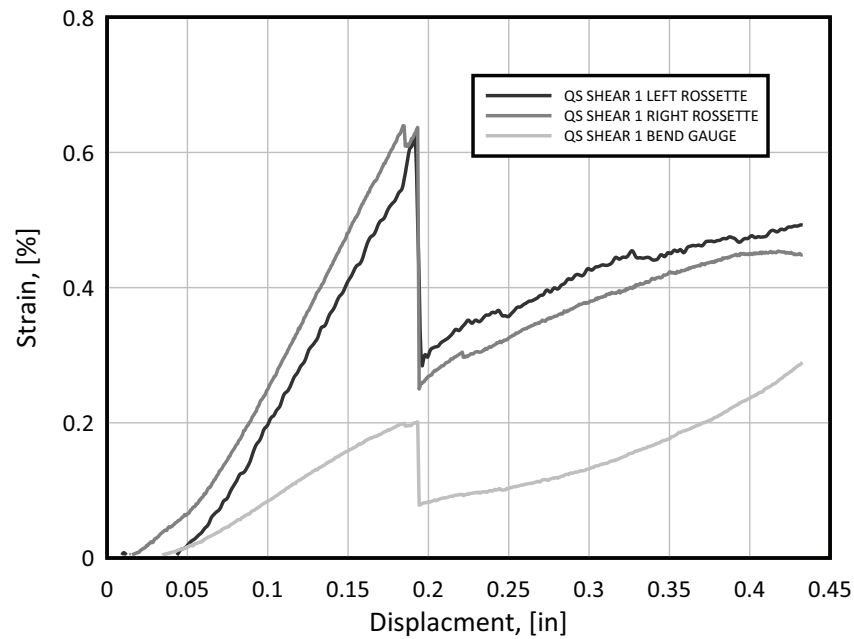


Figure 4.23: Bending and shear strain vs displacement for QS Shear Tests 2.

Data from the complete set of quasi static tests are summarized in Table 4.1 following the descriptions of the Intermediate Speed and Dynamic Bend Tests in the

next two sections.

4.2.2 Intermediate Speed Shear Tests

A total of nine intermediate tests were run at load rates ranging from 168 to 276 kips/s. The tests were filmed using Phantom cameras at speeds of 5,000 frames/sec. An example of the intermediate speed deformation sequence can be seen in Figure 4.24 and load displacement curves for all ten tests can be seen in Figure 4.25.

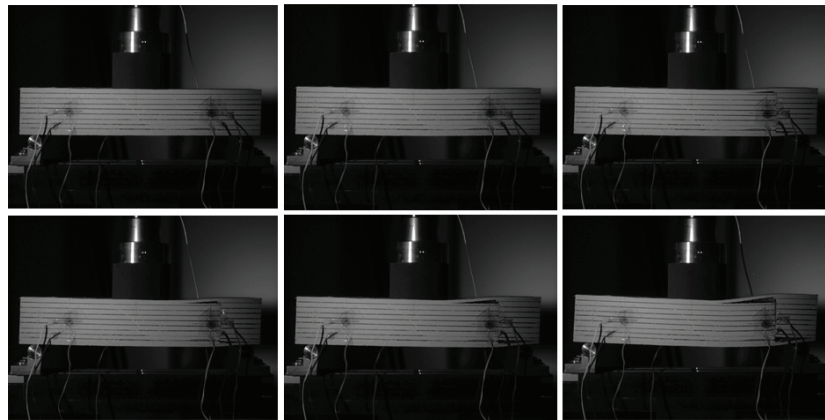


Figure 4.24: Typical sequence of events for IS Shear Tests 1-9.

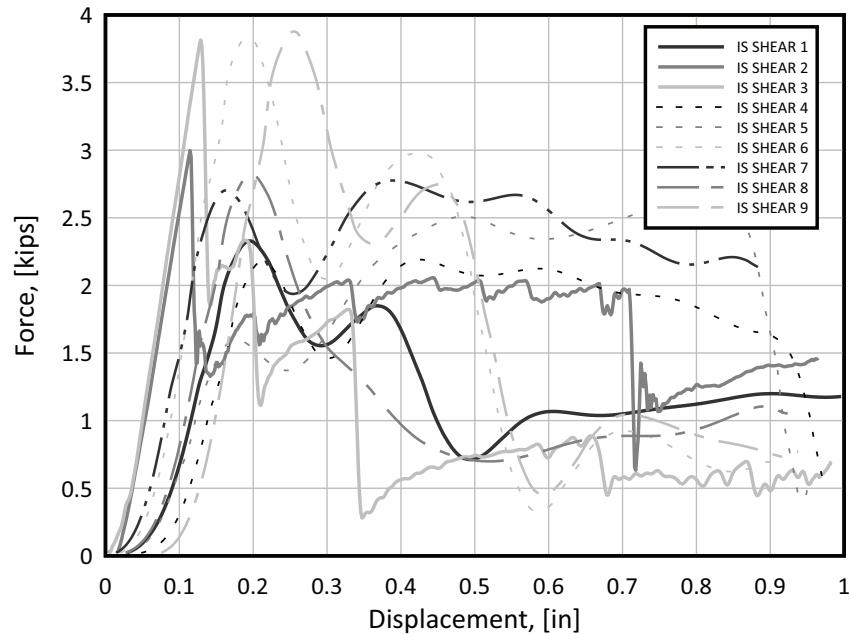


Figure 4.25: Force-displacement results for IS Shear Tests 1-9.

For the intermediate speed tests, loads were recorded using a 111 kN Dytran 1060V5 piezoelectric force sensor and strains were taken in same locations as the QS tests. Displacements at shear failure were recorded at a range between 0.11 and 0.26 in and peak forces of 2.33 to 3.85 kips. Tests 2 and 3 demonstrate the sharp peaks as seen in QS Test 1-4, while the rest of the intermediate speed tests show softer rises and rounded peaks as seen in QS Tests 5 and 6. Plots of strain gauge measurements from IS Bend Test 6 can be seen in Figure 4.26, showing core shear strains to failure of approximately 0.74% and 0.63% in the left and right rosettes, respectively, and a maximum bending strain of 0.26% in the back FRP facesheet. Strain displacement histories are shown in Figure 4.27 and a summary of the results from the intermediate speed experiments can also be found in Table 4.1.

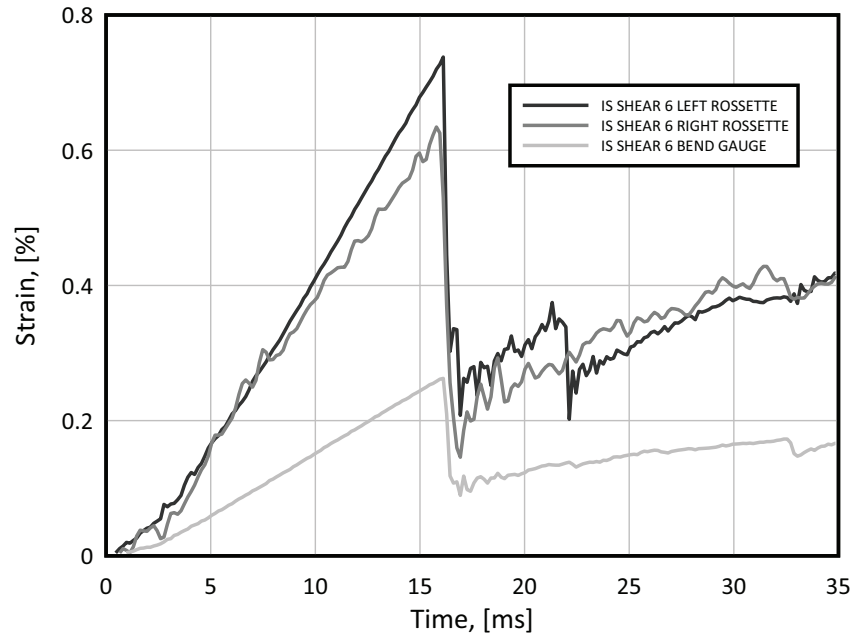


Figure 4.26: Strain time histories for IS Shear Test 6 denoting as shear strain to failure of approximately 0.6%.

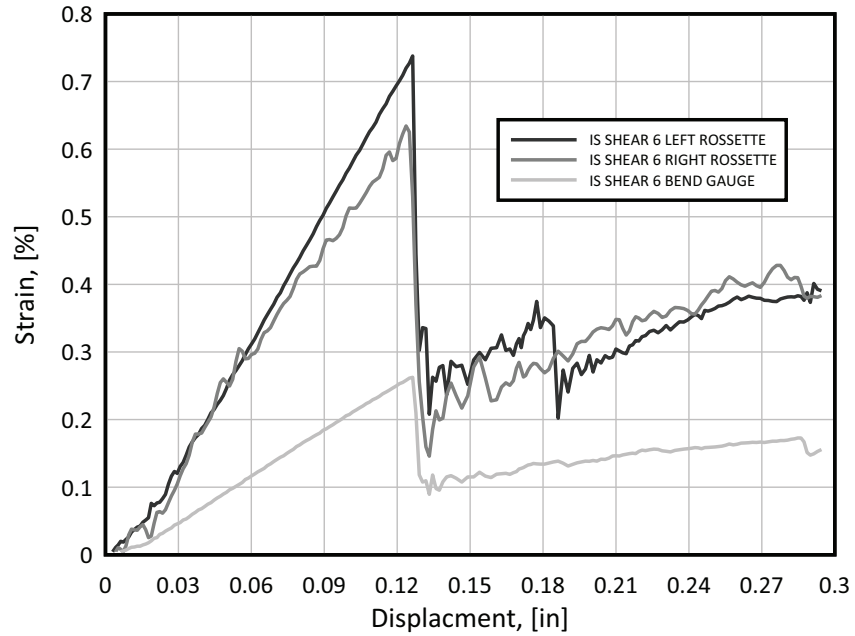


Figure 4.27: Strain displacement results for IS Shear Tests 1-9.

4.2.3 Dynamic Shear Tests

The set of Dynamic Shear Tests were conducted using UCSD's Gas Gun Facility, shown in Figure 4.28. The gas gun is powered by pressurized nitrogen which is released into the breech along aluminum tube via an ultra fast helium gas actuated valve [7]. The gas sends an aluminum body projectile mounted with soft structural foams and lightweight flexible fins seen in Figure 4.29 towards specimens mounted onto an aluminum frame.

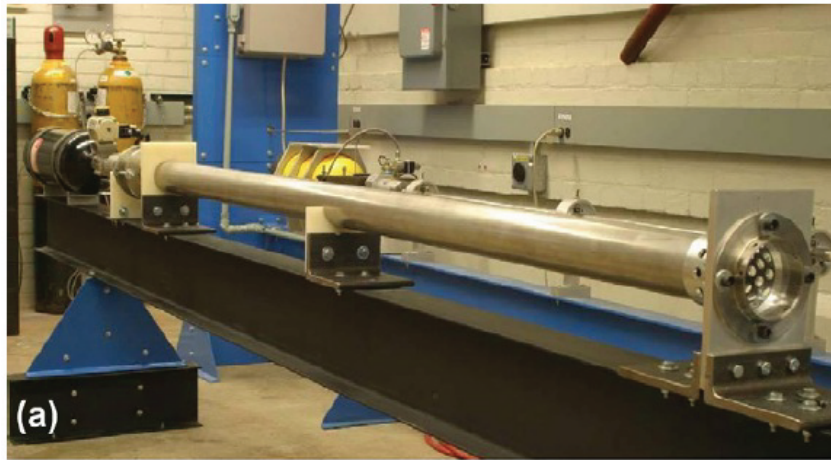


Figure 4.28: UCSD Gas Gun Facility.

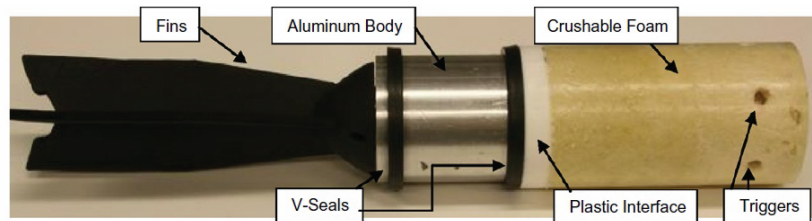


Figure 4.29: Example of Gas Gun projectile.

The projectiles were first launched at target velocities towards a dynamic load cell, shown in Figure 4.30, to measure associated loads. A typical pulse from the projectile assembly is shown in Figure 4.31.

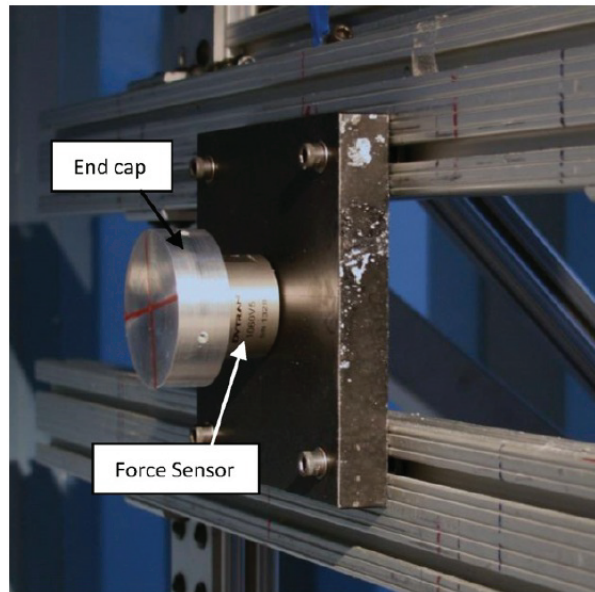


Figure 4.30: Load cell used for load-velocity calibration.

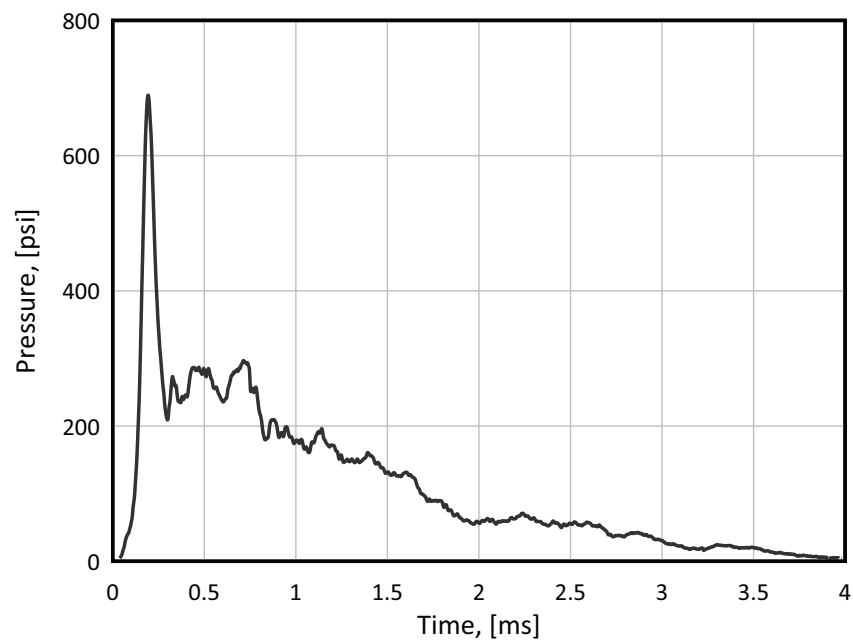


Figure 4.31: Example of pressure pulse from Gas Gun projectile.

Strains and displacements were recorded at similar locations to the quasi-static and intermediate speed shear experiments, and details of their placements can be seen in Figure 4.32. A photo and schematic of the sandwich specimen configuration can be

seen in Figure 4.33.

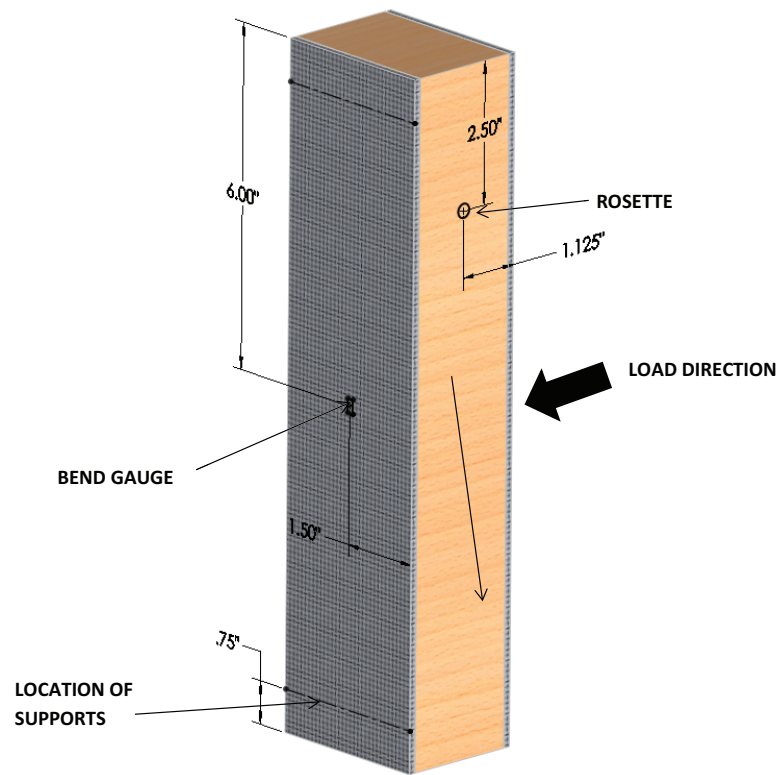


Figure 4.32: Instrumentation placement for Dynamic Bend Tests.

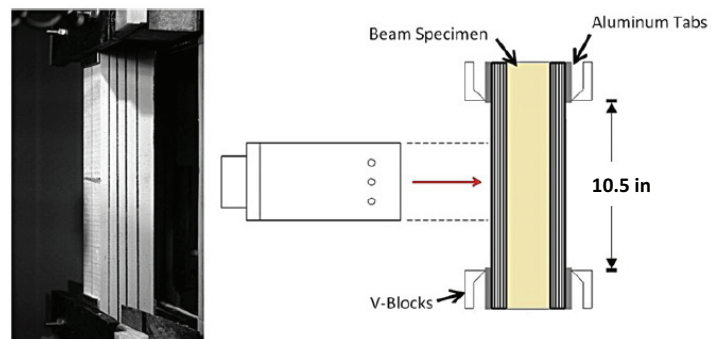


Figure 4.33: Photo and schematic of Dynamic Bend Tests specimens.

A total of four gas gun experiments were conducted and Phantom cameras were used to capture video. A typical sequence of events is shown in Figure 4.34.

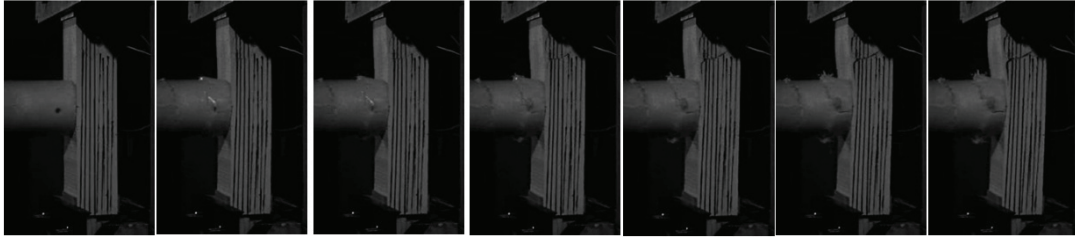


Figure 4.34: Typical sequence of events during Dynamic Bend Tests.

In all gas gun experiments, core shear cracks occurred near one of the two supports, propagated through the cross section of the core, which were followed by delamination along the impact side facesheet-core interface towards the midspan and along the backside facesheet towards the supports. No damage was apparent in the FRP facesheets in any of the experiments. As an example of typical results, core shear strains and facesheet bending strains from Dynamic Bend Test 3 are shown in Figure 4.35.

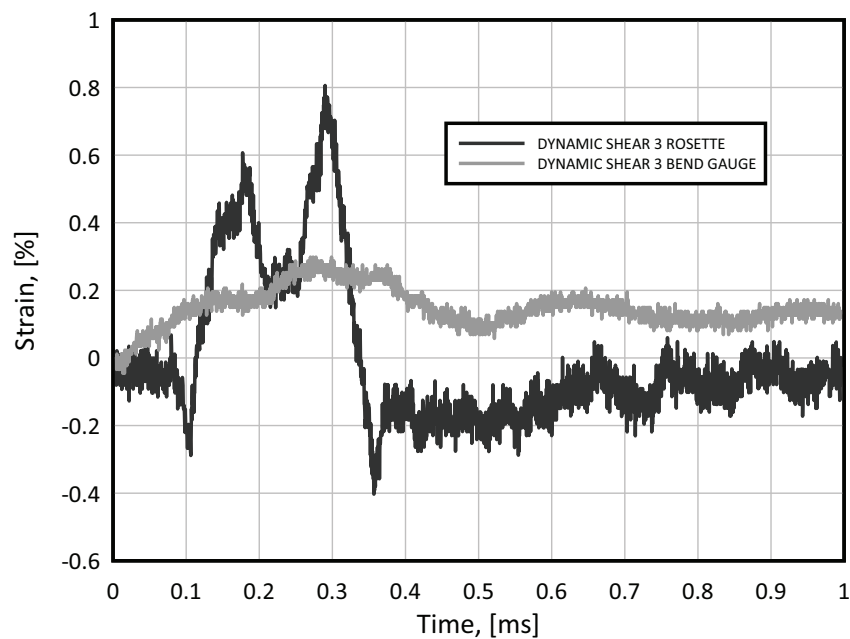


Figure 4.35: Strain-time histories for Dynamic Bend Test 3.

A summary of results from the QS, IS and Dynamic Bend Tests can be found in Table 4.1, followed by 4.36 which plots logarithmic strain rate vs. strain to failure for all of the experiments.

Table 4.1: Summary of composite sandwich Shear Test Results.

Spec. ID	Load Rate kip/s	Bend Strain Rate 1/s	Shear Strain Rate 1/s	Peak Force kips	Peak Bend Strain %	Failure Strain %
QS1	0.100	6.08E-05	1.75E-04	3.485	0.185	0.616
QS2	0.114	4.15E-05	1.57E-04	3.424	0.125	0.427
QS3	0.122	6.96E-05	1.94E-04 (L) 1.35E-04 (R)	5.092	0.292	0.697 (L) 0.582 (R)
QS4	0.085	5.21E-05	3.94E-04 (L) 2.64E-04 (R)	2.689	0.176	1.020 (L) 0.842 (R)
QS5	0.080	4.93E-05	1.34E-04 (L) 1.38E-04 (R)	3.290	0.201	0.622 (L) 0.637 (R)
QS6	0.083	5.40E-05	7.49E-04 (L) 2.00E-04 (R)	2.698	0.175	1.280 (L) 0.941 (R)
IS1	NA	0.184	0.395	NA	0.305	0.726
IS2	NA	0.171	0.449	NA	0.185	0.436
IS3	272.019	0.164	0.268		0.233	0.368
IS4	NA	0.188	1.410 (L) 0.824 (R)	NA	0.300	1.930 (L) 1.401 (R)
IS5	346.206	0.183	0.402 (L) 0.508 (R)	4.899	0.263	0.627 (L) 0.738 (R)
IS6	269.771	0.136	1.540 (L) 0.156 (R)	3.598	0.212	1.350 (L) 0.216 (R)
IS7	274.267	0.159	0.368 (L) 0.818 (R)	2.997	0.194	0.438 (L) 1.070 (R)
IS8	276.515	0.188	0.582 (L) 0.527 (R)	3.815	0.274	0.840 (L) 0.838 (R)
IS9	175.576	NA	0.479 (L) 0.763 (R)	3.599	NA	0.543 (L) 1.011 (R)
IS10	168.157	0.139	0.288 (L) 0.964 (R)	2.313	0.136	0.311 (L) 0.932 (R)
GG1	NA	NA	14.1	10.7	0.276	0.739
GG2	NA	NA	17.3	16.6	0.195	0.704
GG3	NA	NA	15.46	13.261	0.276	0.541
GG4	NA	NA	13.77	15.947	0.312	0.673

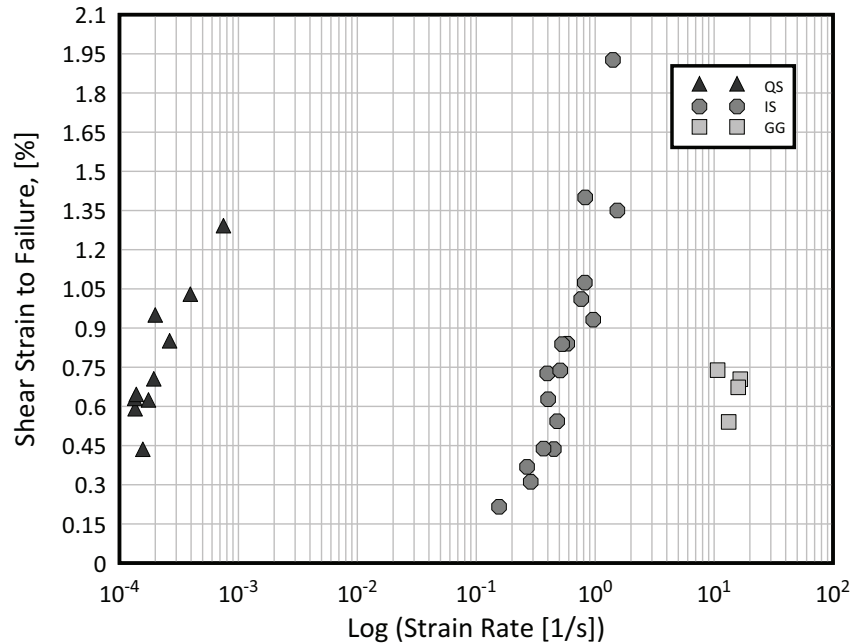


Figure 4.36: Failure strains as a function of strain rate for QS, IS and Dynamic Shear Tests.

4.3 Delamination Properties

4.3.1 Delamination Tests

The final set of material studies conducted concerned delamination strength, i.e. the forces required to break the FRP facesheet to balsa core interfacial bond. To decouple the delamination phenomena from the shear failure (the short beam shear tests showed an almost instantaneous progression of delamination after balsa shear cracking), a 0.25 in slit was cut into short beam specimens 5 in from the end of the 20 in specimen and then tested in bending. This cut or *pre-shear* isolated delamination as the primary mode for failure in the specimen and would assist in the calibration of the numerical models discussed in later chapters. The specimen was placed in a similar bending setup as the QS and IS Shear Tests, with two differences. Instead of the cylindrical urethane pad, a single 0.75 in steel roller affixed with a laminate spreader plate was used for loading and additional spreader plates were placed under the specimen at the supports. The setup and notched specimen can be seen in Figure 4.37.

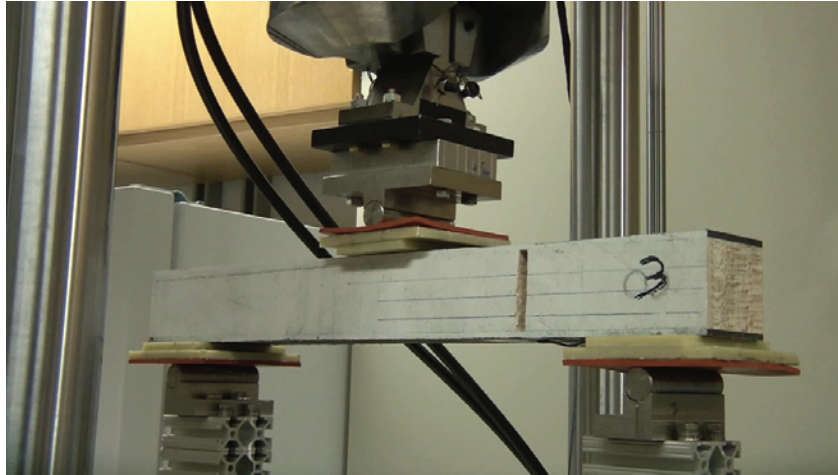


Figure 4.37: Delamination Test setup.

The test was displacement controlled and conducted at a rate of 0.08 in/sec and video was recorded using a Samsung HD camera. Load and displacement were taken from the testing machine and a strain gauge was placed at the midspan on the back (tensile) CFRP facesheet. An example of a sequence of events during the delamination tests can be seen in Figure 4.38. Force-time plots for the three tests can be seen in Figure 4.39, while Figure 4.40 shows the strain histories.

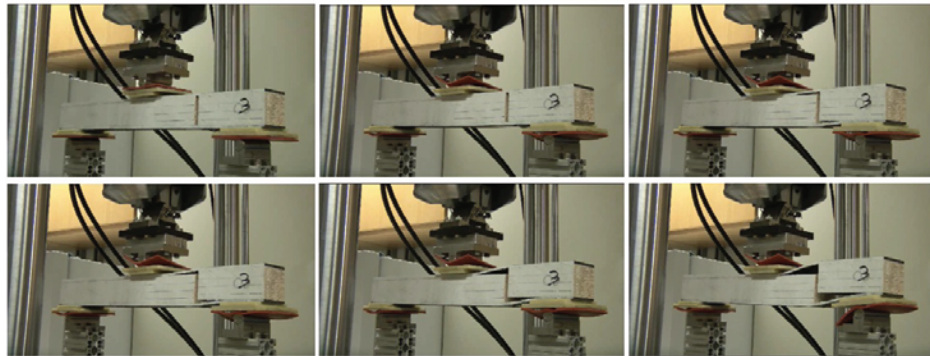


Figure 4.38: Sequence of events during Delamination Test 2.

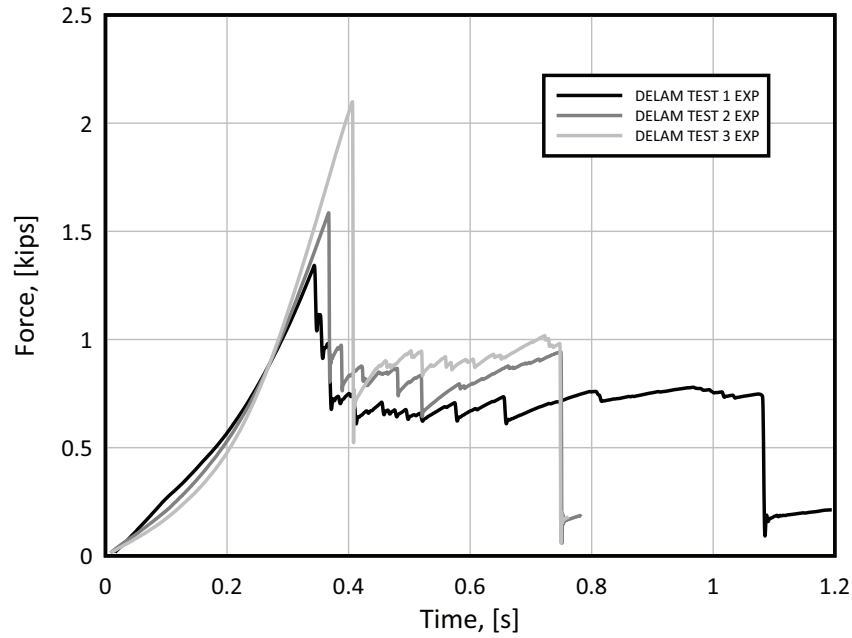


Figure 4.39: Force-time plots for Delamination Tests 1-3.

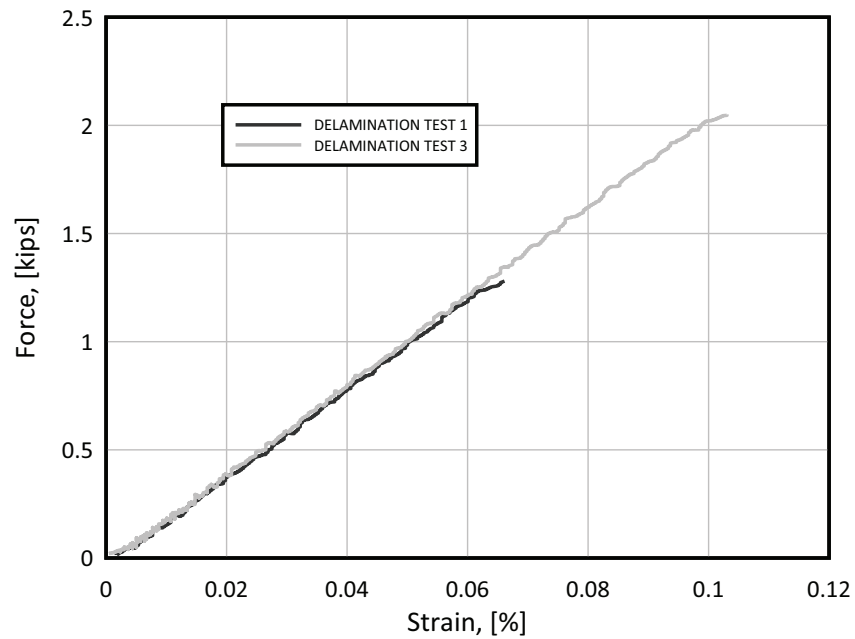


Figure 4.40: Strain-displacement plots for Delamination Tests 1 & 3.

All three tests demonstrated similar behavior, with delamination occurring along both interfaces, towards the center of the specimen along the top and towards the sup-

ports along the bottom. The delamination continues along both until the bottom interface is completely undone at which point the test terminates. Delamination Test 1 demonstrated a stiffer response than Tests 2 and 3, failing at 0.15 in at a load of 1.58 kips followed by a sharp drop to roughly 1 kip before the adjacent interface strength holds a fairly constant load to a maximum displacement of .95 in. Tests 2 and 3 showed similar stiffness characteristics, however Test 2 failed at peak force of 1.34 kips at a displacement of 0.26 in while Test 3 reached a load of 2.1 kips and displacement of 0.32 in before delamination. In turn, Test 3 demonstrated a drop in force of almost 1.4 kips before continuing to displace to a maximum of displacement of 0.97 in. Test 2 dropped only 0.6 kips before continuing to displace out to a maximum displacement of 0.83 in. Strain time histories from the bending gauge for Tests 1 and 3 are show consistent slopes, while the no data was recorded from the strain gauge during Test 2.

4.4 Summary

The preceding documented the experimental results from a series of tests conducted to investigate the bending, shear and delamination characteristics of the CFRP and balsa sandwich structure material at quasi-statics and dynamic rates. The QS Bend Tests demonstrated near identical stiffness and in general similar peak forces and strains, with an average compressive strain to failure of 0.85%. The Dynamic Bend tests revealed some rate dependance in the facesheet material, most notable a 10% increase in average compressive failure strains. The QS, IS and Dynamic Shear Tests showed that failure initiation in the balsa core material was not rate dependant, however, as seen previously in Figure 4.36, the strain to failure values are widespread across the strain rate regime, largely due to the tiled manufacturing technique used frequently is balsa panel construction discussed in Chapter 2. This will be investigated in greater detail in the following chapter where finite element material models of the experiments are calibrated. The Delamination Tests presented a method in which to decouple core shear failure and delamination phenomena experimentally. The measured forces required to initiate core-facesheet separation as well as delamination progression was also used for numerical calibration.

Chapter 5

Numerical Model Development & Calibration: Material Tests

Finite element material model studies for each of the experiments presented in Chapter 4 were developed for use in the numerical simulations of the Composite Joint Tests. Simulations were run using the general purpose 3D finite element code LS-DYNA [21], an explicit Lagrangian code which incorporates a standard central difference time integration scheme.

In all of the simulations, selective reduced (S/R), eight node continuum elements were used with single point integration. Elements sizes varied depending on length of the specimen and mesh details are reviewed prior to the presentation to each set of simulations. To inhibit hourglassing i.e. mesh distortion, LS DYNA's type 3 and 4 hour-glass control with HGE coefficient (QM) set to 0.01 for the balsa core and composite facesheets respectively.

As discussed in Chapter 2, the CFRP facesheets were modeled using *MAT_COMPOSITE_DAMAGE and *MAT_WOOD was implemented to model the balsa core. At the interface of the two materials, *CONTACT_AUTOMATIC_ONE_WAY_SURFACE_TO_SURFACE_TIEBREAK was employed.

Tables 5.1, 5.2, and 5.3 summarize the initial material properties and tiebreak parameter estimates used to model the sandwich structure. The results from the the simulations presented are summarized in an an updated version of the tables at the end of the chapter.

Table 5.1: Initial CFRP facesheet property estimates

Density, ρ , lbm/in^{-3}	1.46e-4
Tensile modulus, E_A, E_B, E_C , Msi	6.1, 6.1, 1.39
Poisson's ratio, $\nu_{BA}, \nu_{CA}, \nu_{CB}$	.029, .088, .088
Shear modulus, G_{AB}, G_{BC}, G_{CA} , Msi	2.2, 1.6, 1.6
Longitudinal tensile strength, X_T , ksi	148
Transverse tensile strength, Y_T , ksi	152
Transverse compressive strength, Y_C , ksi	97.5
Out-of-plane tensile strength, S_N , ksi	4.9
Shear strength, S_C , ksi	8.14
Transverse shear strength, S_{YZ}, S_{XZ} , ksi	7.7, 7.32

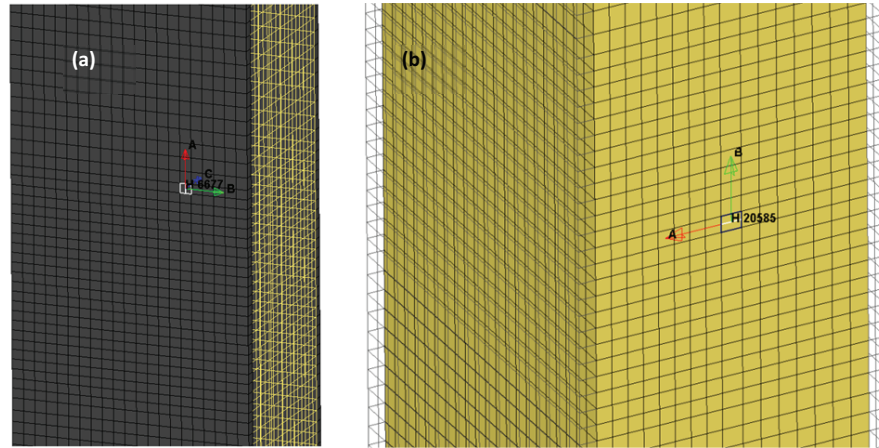
**Figure 5.1:** Computationally assigned material directions (a) CFRP facesheets (b) balsa core.

Table 5.2: Initial balsa core property estimates [3]

Stiffness:	
Density, ρ , lbm/in^{-3}	1.42e-5
Parallel normal modulus, E_L , ksi	518
Perpendicular normal modulus, E_T , ksi	22
Parallel shear modulus, G_{LT} , ksi	29
Perpendicular shear modulus, G_{TR} , ksi	11
Parallel major Poisson's ratio, PR	.25
Strength:	
Parallel tensile strength, X_T , psi	1920
Parallel compressive strength, X_C , psi	1878
Perpendicular tensile strength, Y_T , psi	57
Perpendicular compressive strength, Y_C , ksi	340
Parallel shear strength, S_{XY} , ksi	433
Perpendicular shear strength, S_{XZ} , ksi	576
Damage:	
Perpendicular fracture energy in tension, $G_{f_{I\perp}}$, psi-in	0.342
Perpendicular fracture energy in shear, $G_{f_{II\perp}}$, psi-in	0.457
Parallel fracture energy in tension, $G_{f_{I\parallel}}$, psi-in	36.278
Parallel fracture energy in shear, $G_{f_{II\parallel}}$, psi-in	48.442

Table 5.3: Initial tiebreak contact parameters estimates

Normal failure stress, NFLS	1040
Shear failure stress, SFLS	520
Critical interface failure distance, PARAM	-

5.1 Delamination Test Simulations

The first set of experiments modeled numerically were the Delamination Tests. Failure at the interface of the sandwich materials was observed in all of the experiments of Chapter 4, and the method of pre-slitting the balsa core to simulate an existing shear failure isolated the delamination failure mode, making tiebreak parameter calibration more efficient.

A schematic of the simulation and comparison to the experimental setup is shown in Figure 5.2 (a) and (b).

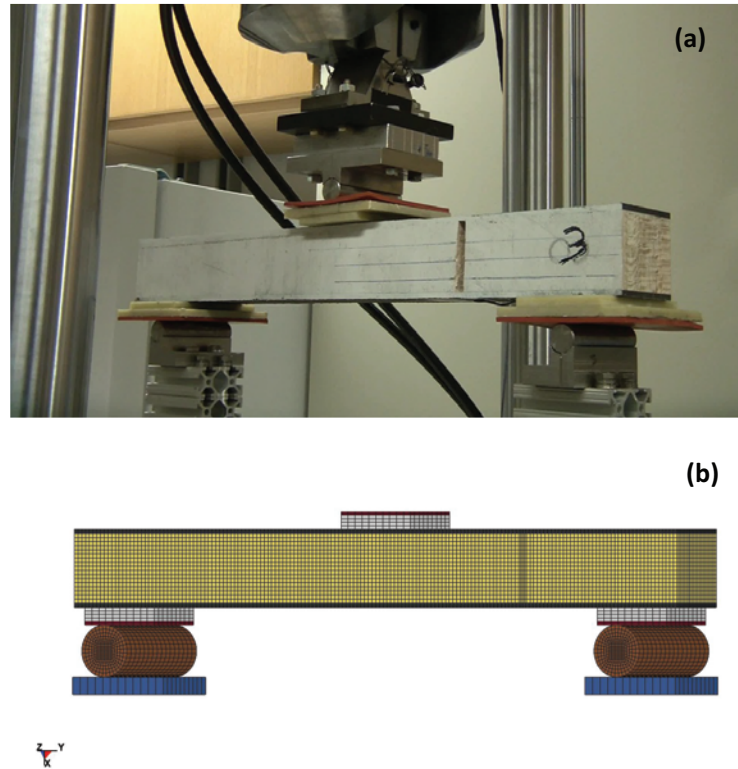


Figure 5.2: Delamination Test(a) and Simulation (b).

The model consisted of 89,000 solid elements and the specimen mesh had maximum aspect ratios of 1.2 for the core and 1.5 for the facesheets.

The steel rollers, roller supports and glass-laminate load plates were modeled using *MAT_ELASTIC using typical reported values for A36 steel and manufacturer reported values for the laminate material. The rubber pads were modeled using a *MAT_LOW_DENSITY_FOAM obtained from a model calibrated by [27].

The simulation was run in displacement control using *BOUNDARY_PRESCRIBED_MOTION_SET using displacement histories recorded from experiment. The displacements were applied to a node set specified on the top surface of the glass laminate spreader plate, shown in Figure 5.3. Also shown are imposed fixed boundary conditions that were applied to the bottom side of the roller support.

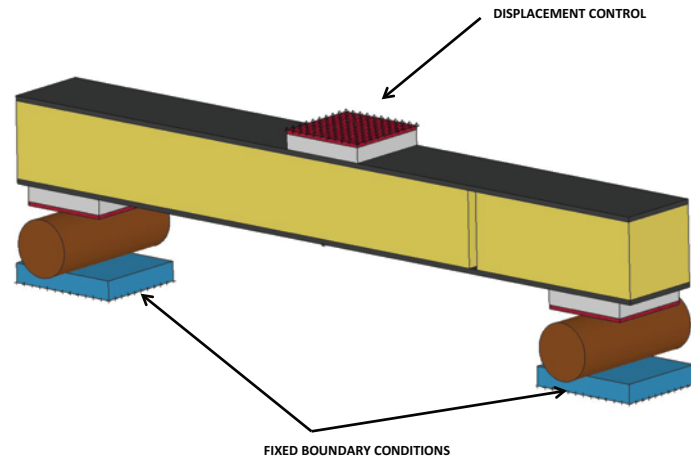


Figure 5.3: Displacement application and boundary conditions for Delamination Test Simulations.

The tiebreak contact surface was modeled along the inside faces of the composite facesheet and outside faces of the balsa core, as shown in Figure 5.4.

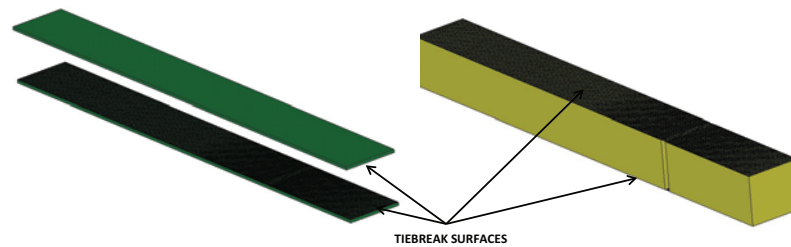


Figure 5.4: Tiebreak surfaces in Delamination Test Simulations.

Additional contacts were applied using `*CONTACT_AUTOMATIC_SURFACE_TO_SURFACE` at the locations of contact between the rubber pads and facesheets, the lower glass laminate and roller & the roller/support interface, all of which are highlighted in Figure 5.5.

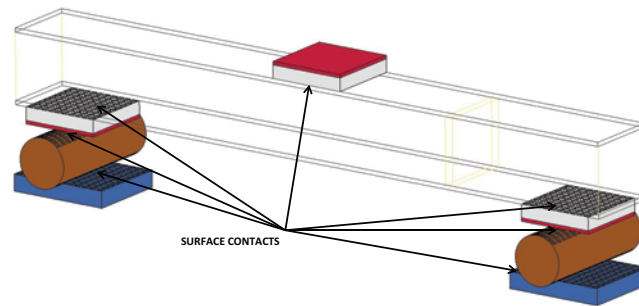


Figure 5.5: Surface contacts in Delamination Test Simulations.

To measure force, LS-DYNA's ASCII output option *DATABASE_RCFORC was used, which output the resultant interface force at the supports. Strains were requested at the midspan of the bottom facesheet for comparison to the experimental strain gauge output. The location of the load and strain outputs are shown in Figure 5.6.

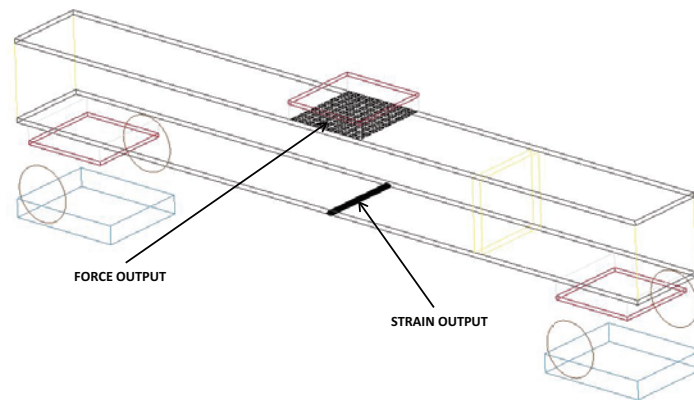


Figure 5.6: Load and strain outputs for Delamination Test Simulations.

The sequence of events for Delamination Test 3 and its corresponding simulation are compared in Figure 5.7.

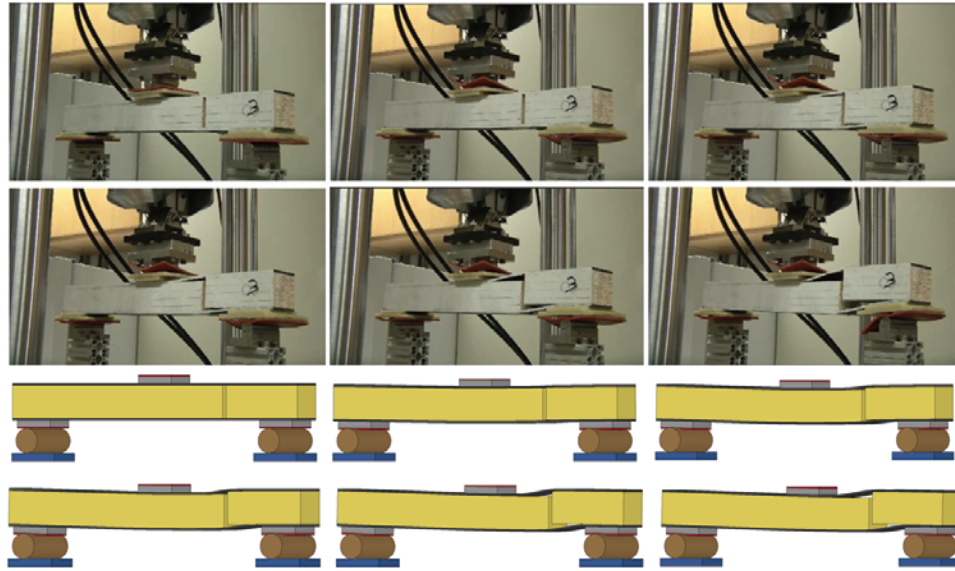


Figure 5.7: Comparison of Delamination Test 3 Simulation and experiment.

Resultant force-time histories for each of the experiments are compared to simulation results in Figure 5.8.

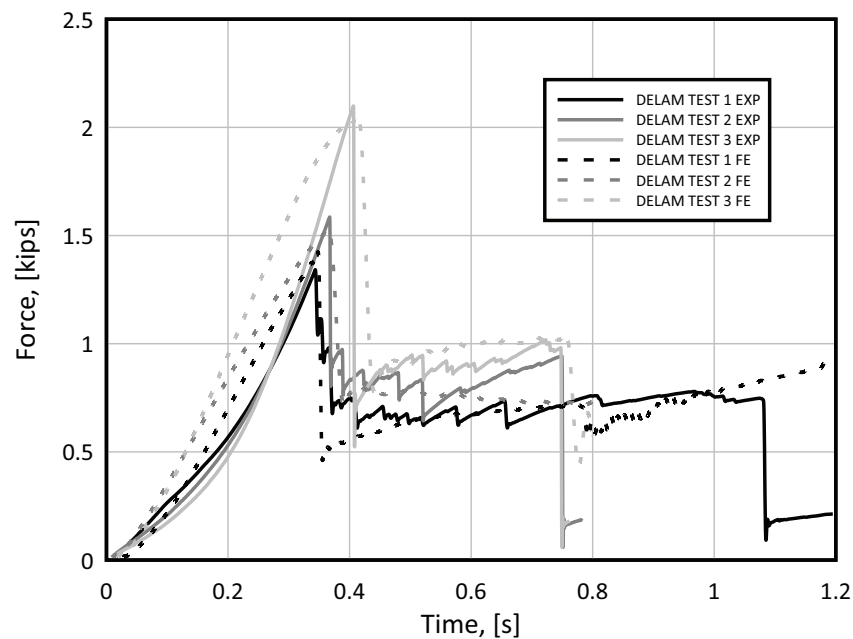


Figure 5.8: Delamination Tests experimental and calculated force histories comparisons.

From the plot, Delamination Test Simulations 2 and 3 show good correspondence with experiment, denoting peak forces of 1.52 and 2.05 kips, respectively, compared to the observed 1.57 and 2.09 kips. At delamination initiation, the damage model behaves well, dropping to 0.8 kips in Test 3 compared to 0.73 kips seen in experiment and 0.9 kips compared to 0.78 kips in Test 2. The recorded forces from Test 1 show a stepwise decay over a longer period of time than seen in Tests 2 and 3, however the model is able to capture within 10% of the peak force in Test 1 and follows closely to experiment at approximately 0.5 s.

The slope differences from zero force up to initial failure between the simulations and experiment were readily observed. It was found that this was a function of the hyperelastic nature of the rubber pads used to alleviate stress concentrations on the loaded composite facesheets. The model proved capable of simulating initial failures and continued delamination progression characteristics, and calibrating the rubber model was not in the scope of this research.

The value of 0.0325 used for PARAM was obtained through multiple trials. Typically, values ranging from 0.02-0.1 are used for degradation parameters [8] and for this set of tests the result was found acceptable.

5.2 Bend Test Simulations

Bending simulations of both the QS and Dynamic Bend Tests were also conducted. The simulated setup for both test speeds was similar, consisting of approximately 60,000 solid elements and a specimen mesh with a maximum aspect ratio of 1.5.

5.2.1 Quasi-Static Bend Test Simulations

The experimental and numerical setups for the QS Bend Tests are shown in Figure 5.9.

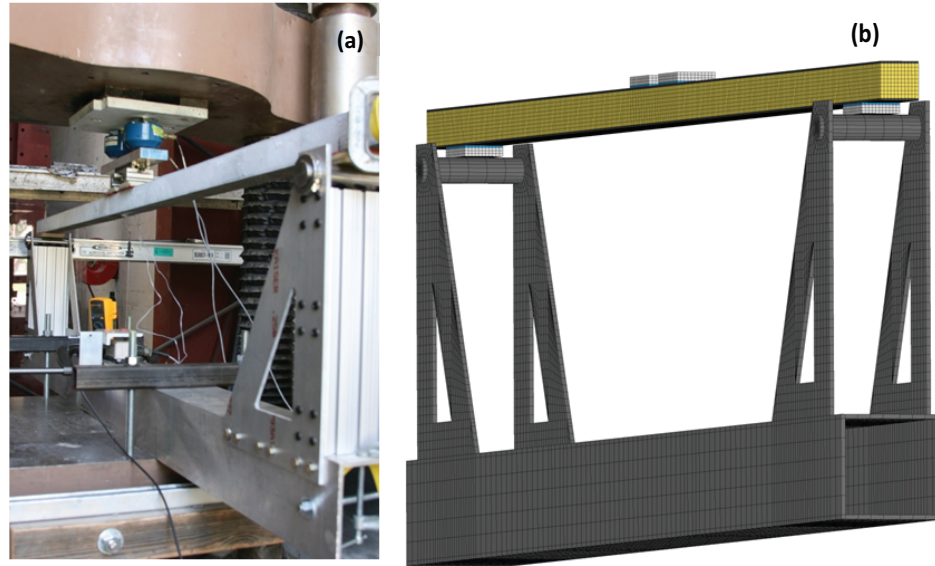


Figure 5.9: QS Bend Test(a) and Simulation (b).

The aluminum frame, roller supports and glass-laminate were modeled using *MAT_ELASTIC using typical reported values for aluminum 6061-T6 and the glass-laminate/rubber assembly was modeled in the same fashion as the delamination simulations.

The quasi static experiment was conducted at a rate of approximately 0.016 in/s, however with a mesh size of approximately 0.25 in in each direction, it was impractical to run the calculation at the experimental rate. Instead, a pressure was applied to the top face of the simulated glass-laminate/rubber spreader plate assembly at a rate of 1 psi/s. The loaded area is highlighted in Figure 5.10 along with the fixed boundary conditions that were imposed on the underside of the support frame.

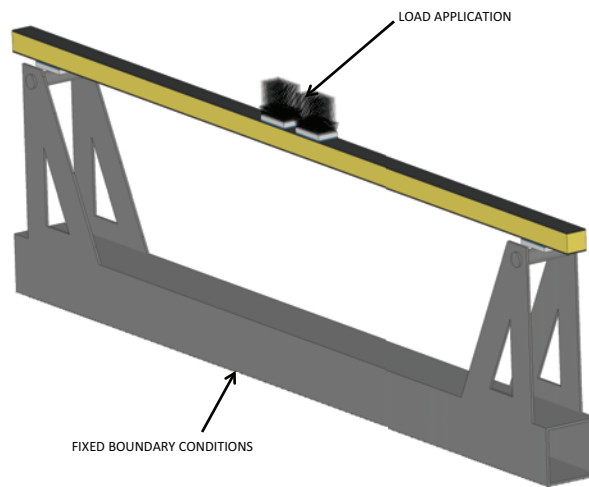


Figure 5.10: Load application and boundary conditions for QS Bend Test Simulations.

For comparison to experiment, strains and displacements were requested at the midspan of the bottom and top facesheet, shown in Figure 5.11.

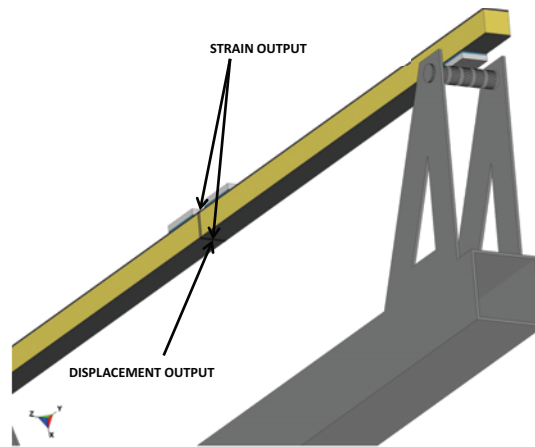


Figure 5.11: Strain and displacement output locations for QS Bend Test Simulations.

The sequence of events for QS Bend Test 3 and its corresponding simulation are compared in Figure 5.12 and strain-displacement histories from the simulations are compared to each experiment in Figure 5.13.

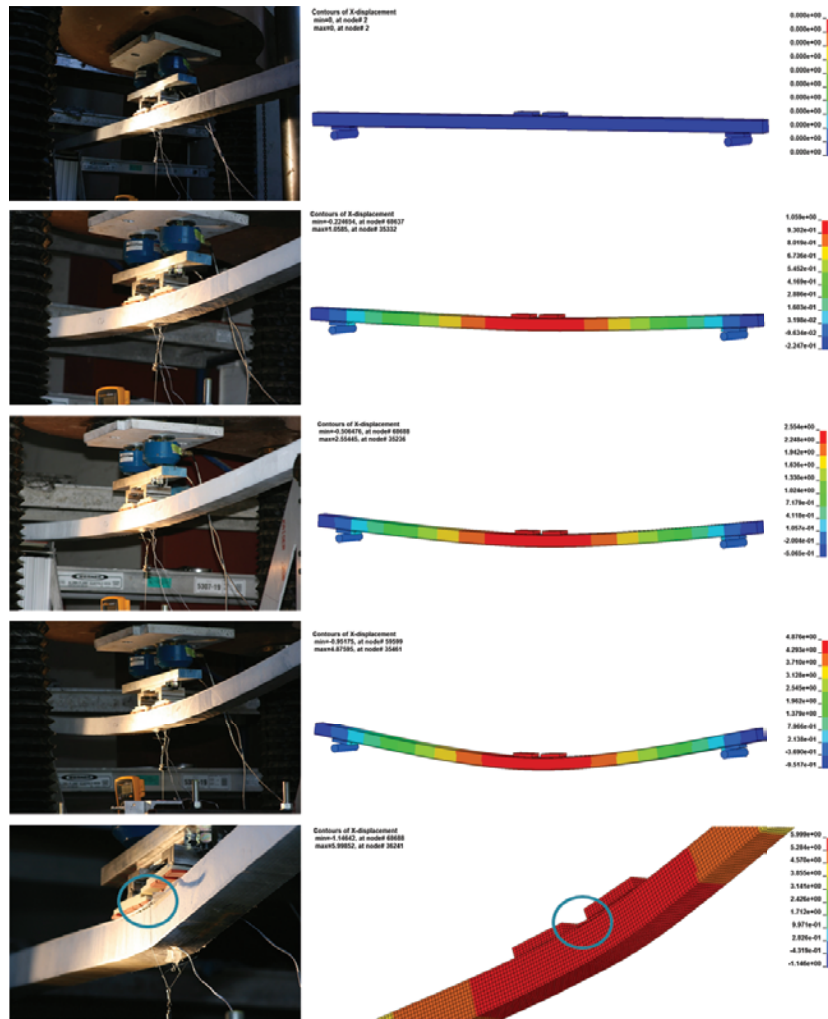


Figure 5.12: Comparison of QS Bend Tests and Simulation.

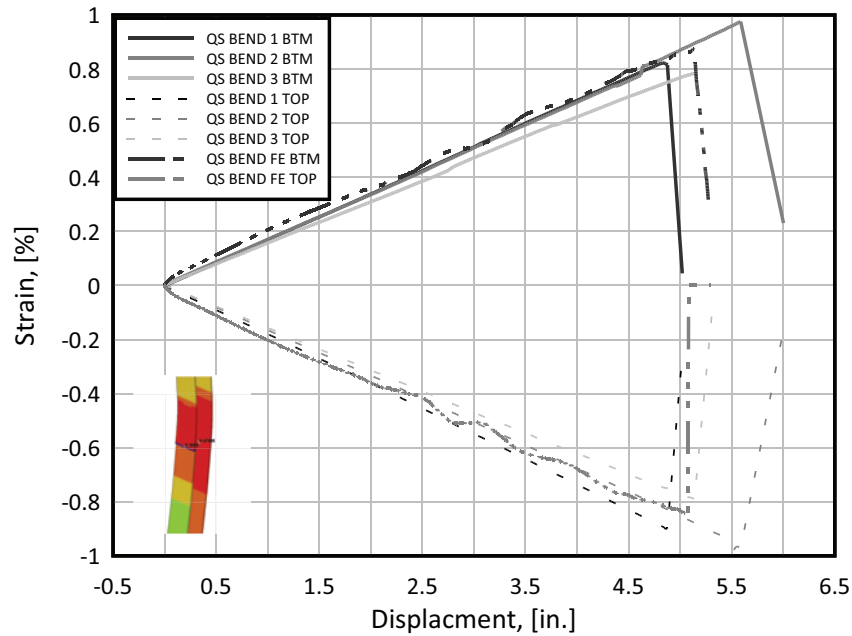


Figure 5.13: Strain-displacement of QS Bend Test Simulation and experiment.

The model showed consistency with experiment in terms of stiffness and strength, reaching a maximum displacement of 5.07 in before failing at the midpoint of the top facesheet at a compressive strain of 0.85%. The simulation fell within the bounds of QS Bend Tests 1 and 2, as also did Test 3, in terms of both displacement and maximum tensile and compressive strains.

5.2.2 Dynamic Bend Test Simulations

The experimental and numerical setups for the Dynamic Bend Tests are shown in Figure 5.14.

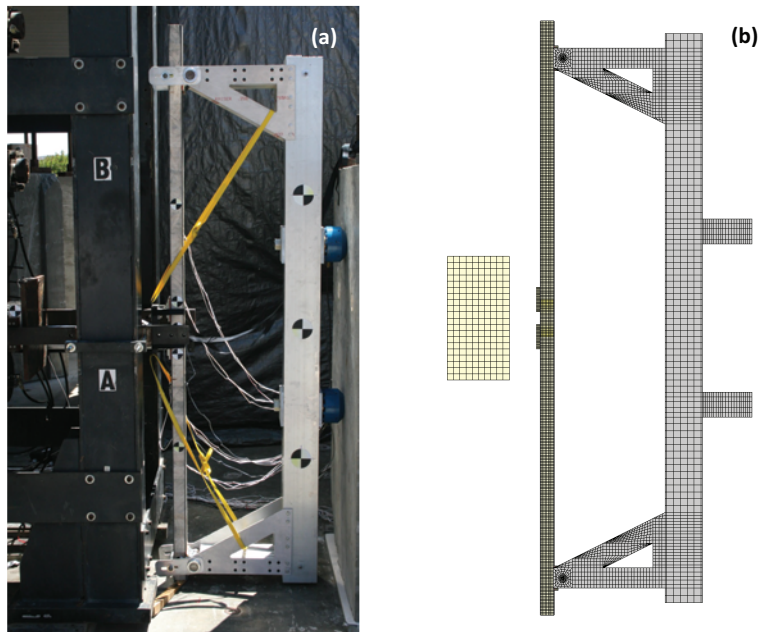


Figure 5.14: Dynamic Bend Test(a) and Simulation (b).

The aluminum frame and spreader plates were modeled using the same material models as the QS Bend Test Simulations.

The load impactor mass/load plate assembly was simulated as a lumped mass and given velocities obtained from integration of the accelerations recorded by the accelerometer mounted on the impacting mass. The velocity-time histories used in each simulation are plotted in Figure 5.15.

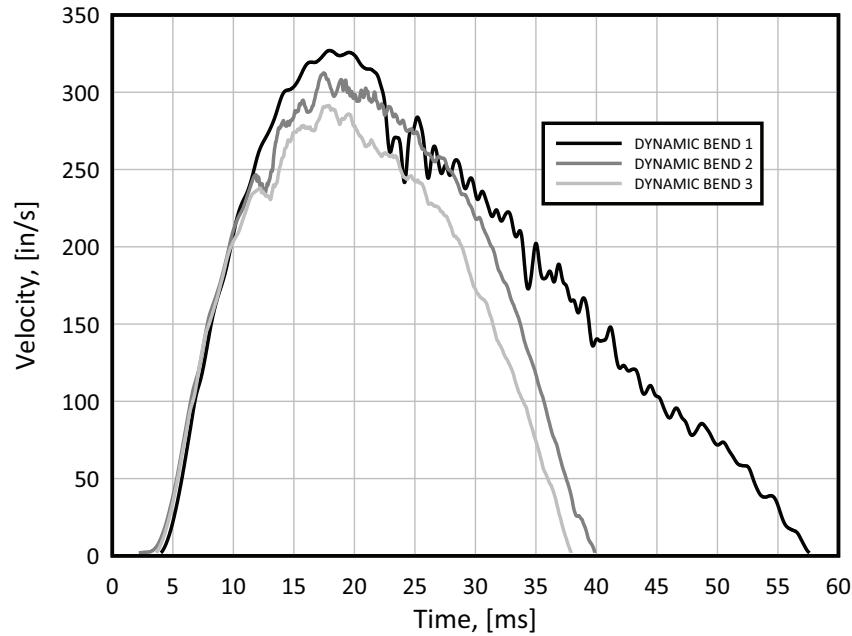


Figure 5.15: Velocity-time histories applied to Dynamic Bend Test Simulations.

To extract forces, the back reaction load cells were simulated as steel blocks. Through the designation of an element and an adjacent node set, LS-DYNA's *DATABASE_CROSS_SECTION_SET enables the user to create section cuts through parts and output resultant forces and moments from the *DATABASE_SECFORC ASCII function. The section cuts were made at the locations of the load cell representation, shown in Figure 5.16, which also denotes the location of the applied fixed boundary conditions and element sets used for strain output. .

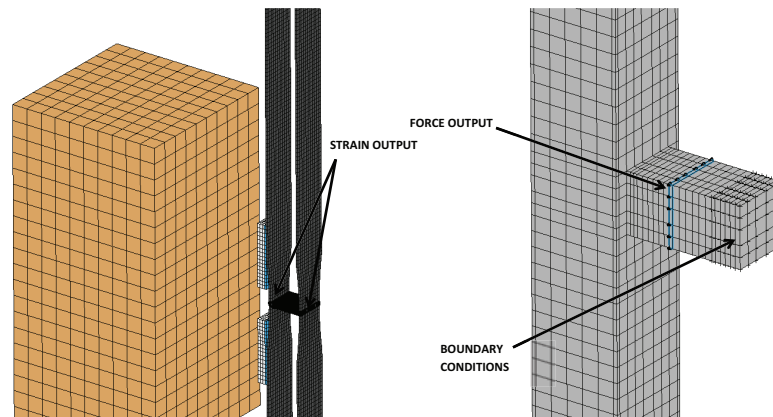


Figure 5.16: Numerical representation of reaction load cells, strain gauges and boundary conditions in Dynamic Bend Test Simulations.

The sequence of events for Dynamic Bend Test 2 and its corresponding simulation are compared in Figure 5.17.

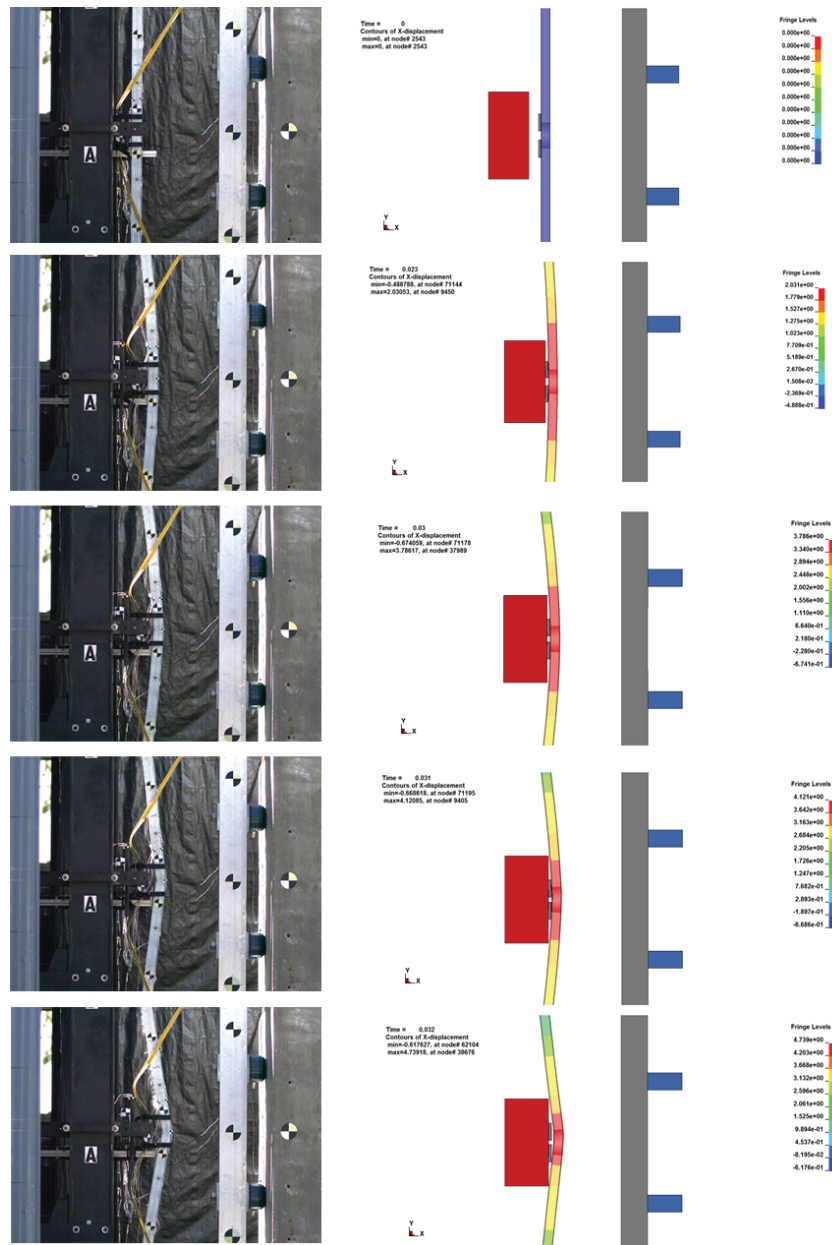


Figure 5.17: Dynamic Bend Test 2 Simulation and experiment.

Resultant force and strain time histories for each of the simulations are compared to each experiment in Figure 5.18 and Figure 5.19.

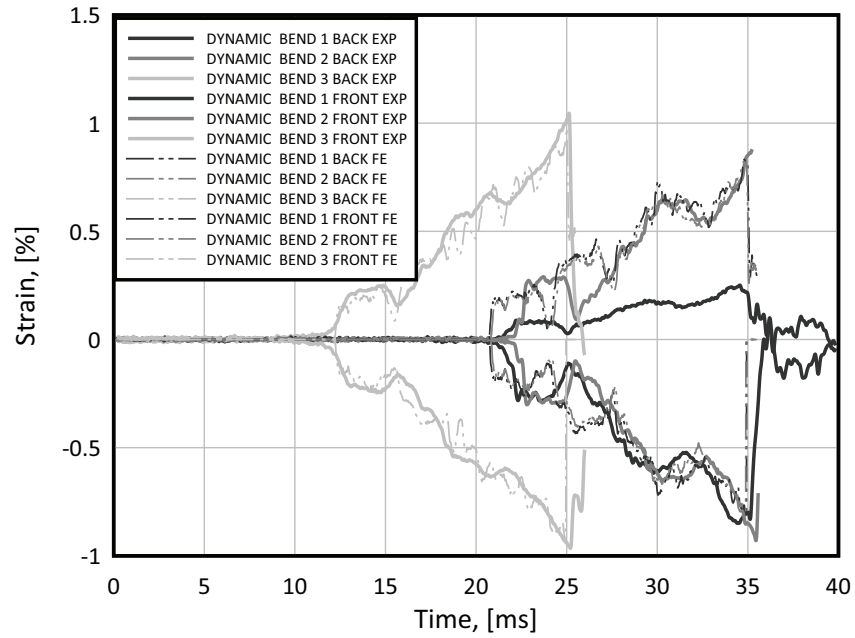


Figure 5.18: Strain time histories of Dynamic Bend Test simulations compared to experiment.

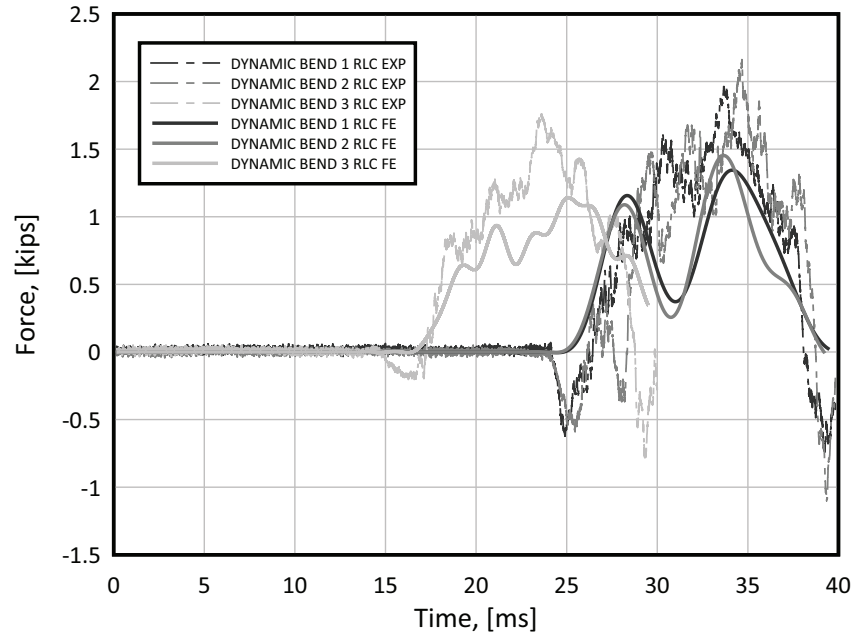


Figure 5.19: Simulated reaction force-time histories of Dynamic Bend Tests 1-3 compared to experimental results.

The simulation of Dynamic Bend Test 3 demonstrated the closest match to experiment, following the measured strain time histories closely until compressive failure at 0.94%. Tests 1 and 2 show good correlation with maximum compressive strains to failure observed empirically, while the discrepancy seen in the tensile strain history for Test 1 was attributed to the unexpected shear failure that occurred through the core. As discussed in Chapter 2, the tiled nature of the core manufacturing process can cause defects leading to unexpected failures such as this. The discrepancy between time of impact seen in Tests 1 and 2 can be accounted for by the fact that in Tests 1 and 2, the impacting mass started between 2 and 3 in from the load assembly mounted to the specimen, whereas in Test 3 they began initially in contact. Discussed further in [39], there was a short time span at which the load fixture was accelerating faster than the BG, which were not modeled separately in the simulation. Also, the foam on the load assembly was not simulated, and the crushing due to impact also may have played a role in the observed temporal differences.

The simulated reaction load cells were used as a check in initial trials. The peak forces measured during the impact by the model fell within 10% of the experiment, and the result was considered sufficient for numerical validation.

5.3 Shear Test Simulations

Only the IS and Dynamic Shear Tests were modeled for shear property calibration. Rate effects investigations were made using the Dynamic Shear Test data at the end of the chapter. Moreover, as with the QS Bend Test, the quasi-static displacement rates were impractical for use in explicit calculations. The setup for both test speeds were similar and consisted of approximately 80,000 solid elements, while the specimen mesh maintained a maximum aspect ratio of 1.5.

5.3.1 Intermediate Speed Shear Test Simulations

The experimental and numerical setups for the QS Shear and Intermediate Tests are shown in Figure 5.20.

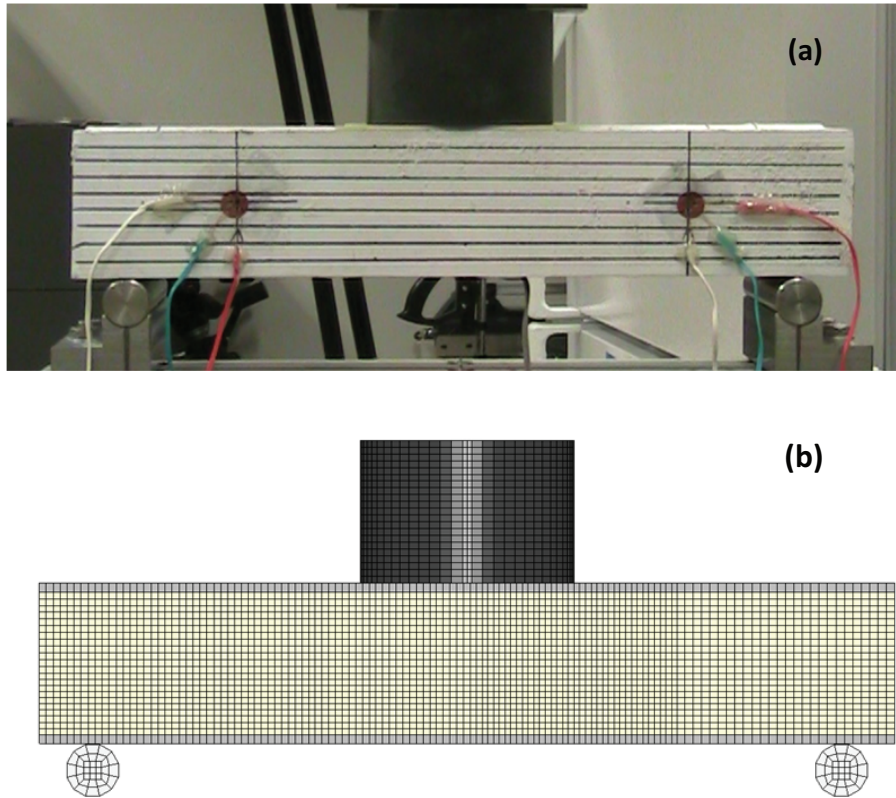


Figure 5.20: IS Shear Test (a) and Simulation (b).

The steel rollers were modeled using the same material model as used in the previous simulations. The urethane pad was simulated using a `*MAT_LOW_DENSITY_FOAM` obtained from a model calibrated by [27].

The IS Shear Test Simulations were ran using displacement control at a rate of 10 in/s, similar to the rates of the experiments. The location of velocity assignment, surface contacts and fixed boundary conditions along the bottom of the steel rollers are shown in Figure 5.21.

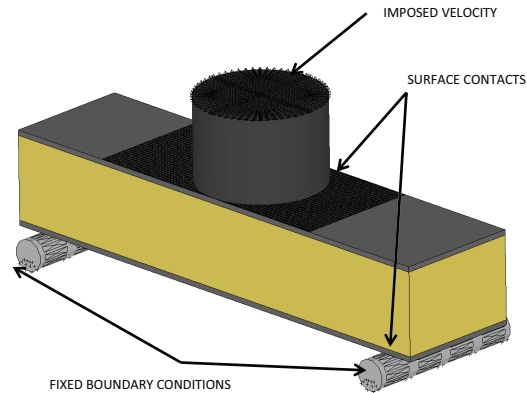


Figure 5.21: Location of velocity application, surface contacts and boundary conditions for IS Shear Test Simulations.

For comparison to the strain gauge used in experiment, element sets were requested at the midspan of the bottom facesheet as well as the location of the rosette to measure shear strains. Both output areas are depicted in Figure 5.22, along with the tiebreak surfaces at the specimen material interfaces.

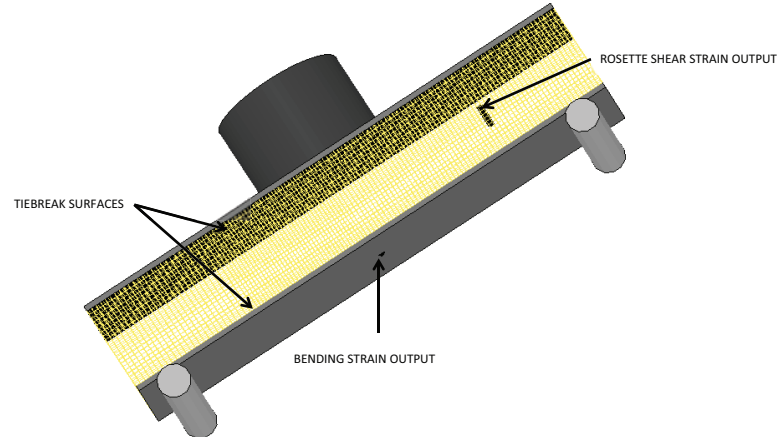


Figure 5.22: Locations of tiebreak surfaces and strain outputs for IS Shear Test Simulations.

The sequence of events for IS Shear Test 2 and its corresponding simulation are compared in Figure 5.23.

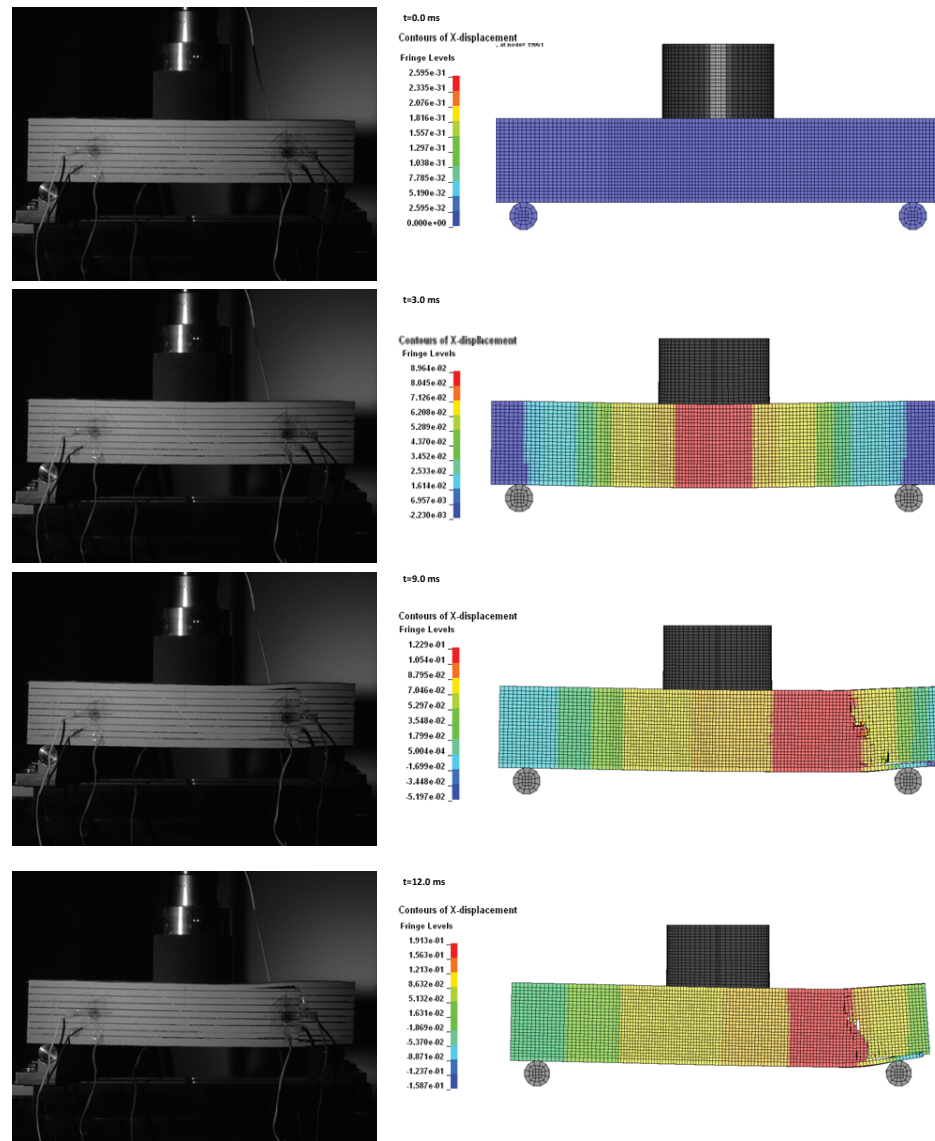


Figure 5.23: IS Shear Test 2 Simulation displacements and comparison to experiment.

Figure 5.35 plots the simulated shear strains against experimental measurements.

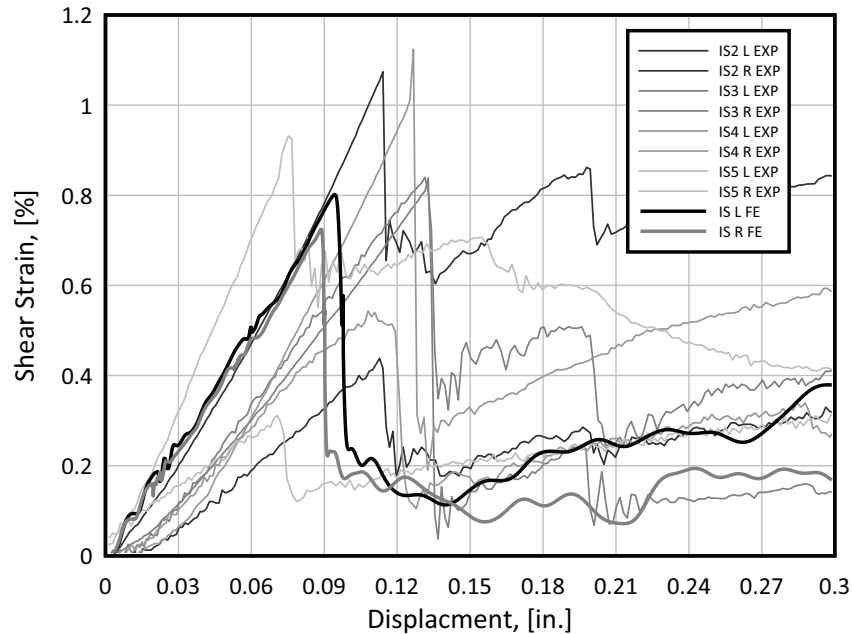


Figure 5.24: Shear strain-displacement correspondence between simulation and IS Shear Tests 2-5.

The shear strain-displacement histories for the experiment fall within the wide range of shear stiffnesses observed from the rosettes. Peak shear strains of 0.72% and 0.80% were also within the bounds of the experimentally observed strains to failure.

These quantitatively acceptable strain-displacement curves were highly dependant on the fracture energy inputs for damage modeling and were therefore examined more closely. The following analysis and discussion scrutinizes the damage propagation in the transversely orthotropic wood model in detail, as the qualitative failure characteristics of the core material proved to be extremely critical to accurately simulating failure modes in the Composite Joint Tests.

5.3.2 Core Material Model Discussion

The key to the proper implementation of LS-DYNA's wood model using balsa was the understanding of the damage formulation. The model was initially developed in an effort to model wood posts used for roadside safety barriers. The experimental data used for model calibration was taken from impacts perpendicular the grain, which

causes *parallel* damage and results in what [25] refers to as *catastrophic* failure. This is because cracking occurs *across* the grain leaves very little to no residual strength in the material.

Balsa wood used in sandwich core materials has its grain oriented in the out of plane direction, and shear failures were observed *parallel* to the grain, which resulted in *perpendicular* damage. The model assumes that splitting along the grain is assumed as non-catastrophic, as the wood can still retain high levels of tensile and bending resistance.

By default, the model degrades all six components of the stress tensor under parallel damage and automatically erodes right before reaching a value of 1.0. The model only degrades three of the six stress components when accumulating perpendicular damage, and therefore the element does not automatically erode [24]. In order to accurately simulate the shear failure observed in experiment, the flag IRATE was necessary to be set a value of 1, which allows the element to erode under perpendicular damage.

As reviewed briefly in Chapter 2, the damage model for wood is based on fracture energies, which is defined as the critical strain energy dissipated per unit of newly created fracture surface area. For three dimensional problems, Mode I and II fracture energies are related to fracture energies through the following analytical expression [24],

$$G_{fI} = C_I K_I^2 \quad (5.1)$$

$$G_{fII} = C_{II} K_{II}^2 \quad (5.2)$$

where C1 and C2 are constants related to the moduli of an orthotropic material through

$$C_I = \left(\frac{S_{11}S_{22}}{2} \right)^{1/2} \left[\left(\frac{S_{22}}{S_{11}} \right) + \left(\frac{2S_{12} + S_{66}}{2S_{11}} \right) \right]^{1/2} \quad (5.3)$$

$$C_{II} = \frac{S_{11}}{\sqrt{2}} \left[\left(\frac{S_{22}}{S_{11}} \right) + \left(\frac{2S_{12} + S_{66}}{2S_{11}} \right) \right]^{1/2} \quad (5.4)$$

in which S_{ij} are reciprocals of the elastic moduli.

From [40] values of K_I and K_{II} of $100.1 \text{ psi} - \text{in}^{1/2}$ and $254.8 \text{ psi} - \text{in}^{1/2}$ were obtained experimentally in the perpendicular modes. The user manual notes that good

correlation to test data was made to southern yellow pine and douglas fir using default parallel-to-the-grain fracture energies of roughly 106 times the fracture energies in the perpendicular modes [24]. This assumption was made initially for the balsa wood simulations, and the estimates are shown in Table 5.3. Although these values did lead to element erosion when input into the simulations of the IS Shear Tests, qualitative analysis of the simulations proved that this assumption did not correlate well to test results. An example is seen in the comparisons made to experiment in Figure 5.25(a), where excessive erosion is observed in a mixed perpendicular/parallel damage mode in (b). Further inspection into the evaluation of the model completed by Murray [25], revealed that the estimate of $G_{f_{\parallel}} = 106G_{f_{\perp}}$ showed good correlation for data from *quasi-static* tests, however did not fall in acceptable performance envelopes for *dynamic* cases. The study notes that a factor of $G_{f_{\parallel}} = 50G_{f_{\perp}}$ fit well with empirical data for dynamic load rates. When used for the simulation of balsa wood, improved performance of the IS Shear simulation was observed and shown in (c), which denotes decreased parallel damage.

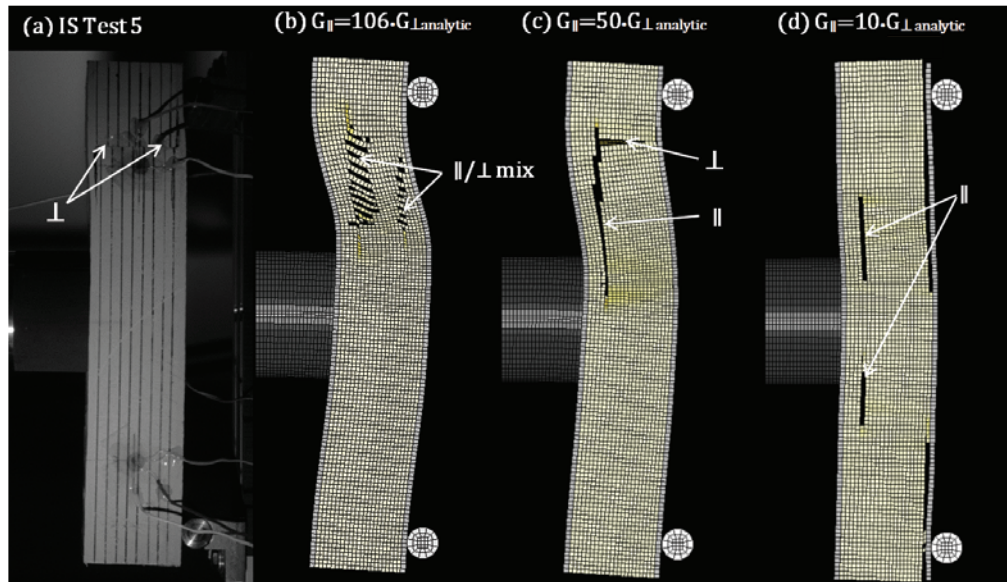


Figure 5.25: Comparison of (a) IS Test 5 with finite element results using $G_{f_{\parallel}} =$ (b) $106G_{f_{\perp}}$, (c) $50G_{f_{\perp}}$, (d) $10G_{f_{\perp}}$ and $G_{f_{\perp}}$ values from 5.2 .

To investigate the effects that the analytically derived value of $G_{f_{\parallel}}$ had on performance of the IS Shear Test simulations, a study was done using 66% and 33% of the theoretical $G_{f_{\parallel}}$, holding the ratio of $G_{f_{\parallel}} = 10G_{f_{\perp}}$ constant. The qualitative comparison

to experiment is made in Figure 5.26.

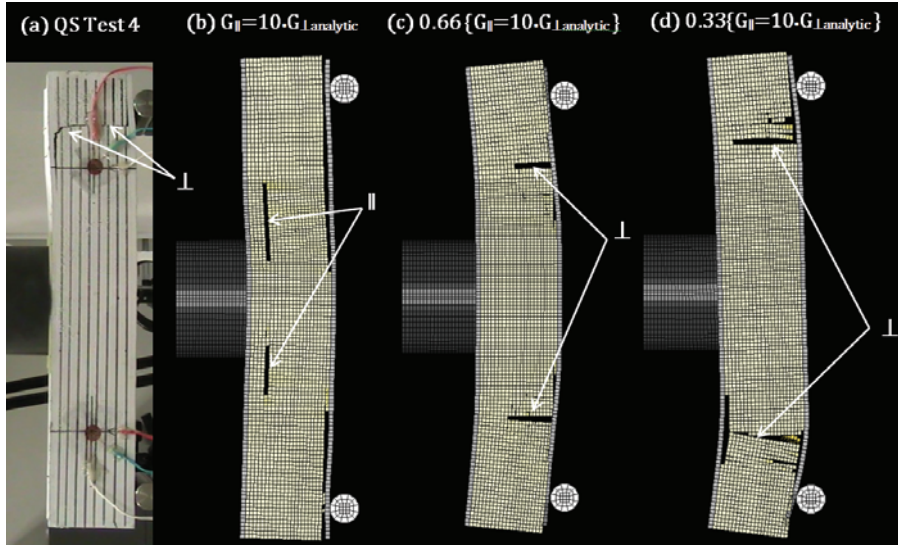


Figure 5.26: Comparison of (a) experiment to (b) derived $G_{f_{||, \perp}}$, (c) $2/3$ of derived $G_{f_{||, \perp}}$, and (d) one third of $G_{f_{||, \perp}}$ keeping the ratio of $G_{f_{||}} = 10G_{f_{\perp}}$ constant.

Reducing the derived value of the parallel fracture energy demonstrated improved correlation to the QS and IS Shear Tests as damage propagated across the grain, near the roller supports. To check the effect of reducing $G_{f_{||}}$ against the $G_{f_{||}} = 50G_{f_{\perp}}$ and $G_{f_{||}} = 106G_{f_{\perp}}$ user manual correlated data, the three cases were simulated holding the reduction of one-third constant. The results are illustrated in Figure 5.27.

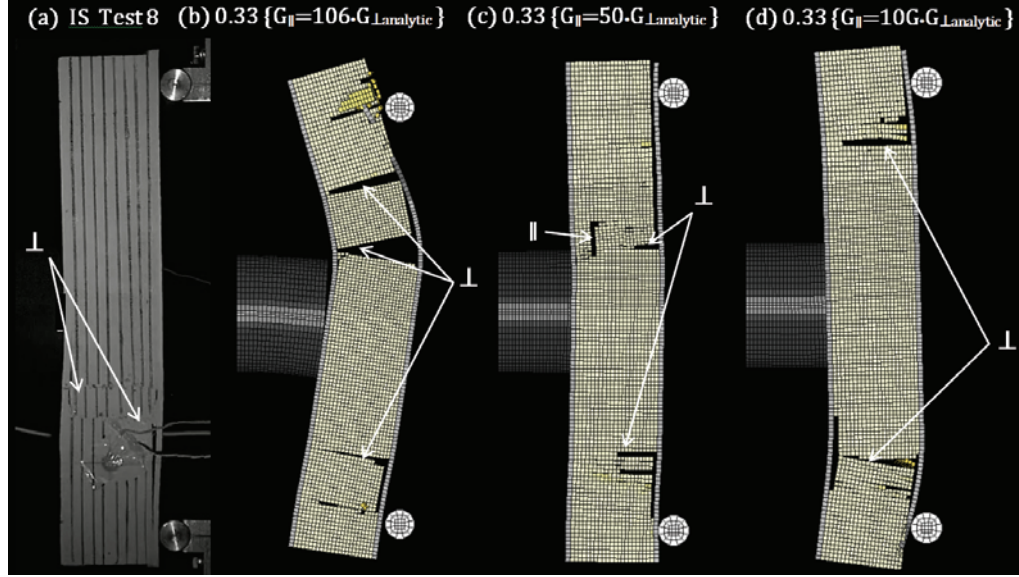


Figure 5.27: Comparison of IS Test 8 failure mode with numerical results using $0.33 \times$ (a) $G_{f_{||}} = 106 G_{f_{\perp}}$, (b) $G_{f_{||}} = 50 G_{f_{\perp}}$, (c) $G_{f_{||}} = 10 G_{f_{\perp}}$.

All three cases demonstrate damage propagation in the grain direction, however the higher estimates for $G_{f_{||}}$ produced increased damage. The simulation using the factor of $50 G_{f_{\perp}}$ denoted the presence of isolated parallel damage as well, shown in (b). As mentioned, [25] states that the reduced approximation of the parallel fracture energy correlated better with experimental data when loaded dynamically. This is further examined using the Dynamic Shear Test simulations in the next section.

The variations of $G_{f_{||}}$ and $G_{f_{\perp}}$ are compared to experimental strain displacement curves in Figure 5.28.

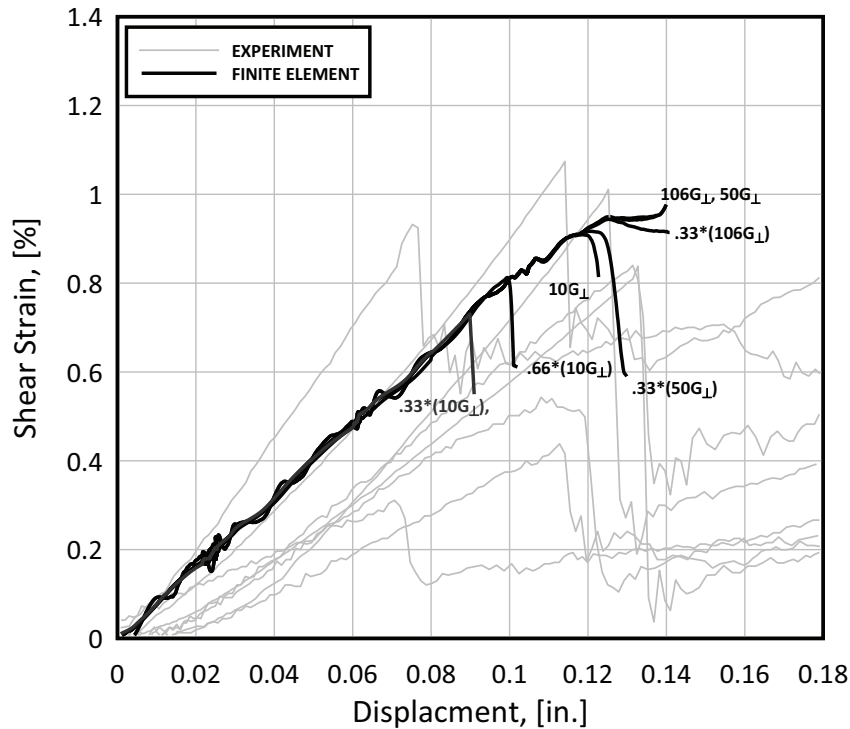


Figure 5.28: Strain-displacement histories of parametric study varying fracture energies compared to experiment.

All simulations show similar slopes, however varied in peak strains to failure. As the ratio of $G_{f\parallel}$ to $G_{f\perp}$ increases, higher peak strains to failure were reached, demonstrated with $G_{f\parallel}=106G_{f\perp}$ and $G_{f\parallel}=50G_{f\perp}$ reaching maximum strains of 0.9% using the theoretical and reduced values of $G_{f\perp}$. Although the increased values show good correlation with the upper bounds of the IS Shear Test spread of data quantitatively, the preceding discussion showed that these approximations did not coincide with the perpendicular damage mode dominated experimental failures. The maximum values of 0.81% strain attained by using the reduced fracture energies of $0.66G_{f\perp}$ and estimating $G_{f\parallel}=10G_{f\perp}$ fell very close to the averaged experimental shear strains to failure shown in Table 5.2, which for the IS Shear Tests was 0.81% and for the QS Shear Tests was 0.76%.

An additional case of parametric simulations were next conducted, in an effort to minimize the reduction of fracture energy estimates and maintain the perpendicular damage modes seen empirically. The IS Shear Simulations were conducted at reduc-

tions ranging from 25% to 85% of the analytical estimates at 10% increments, keeping $G_{f_{\parallel}}=10G_{f_{\perp}}$ constant. The resultant shear strain-displacement histories are shown in Figure 5.29.

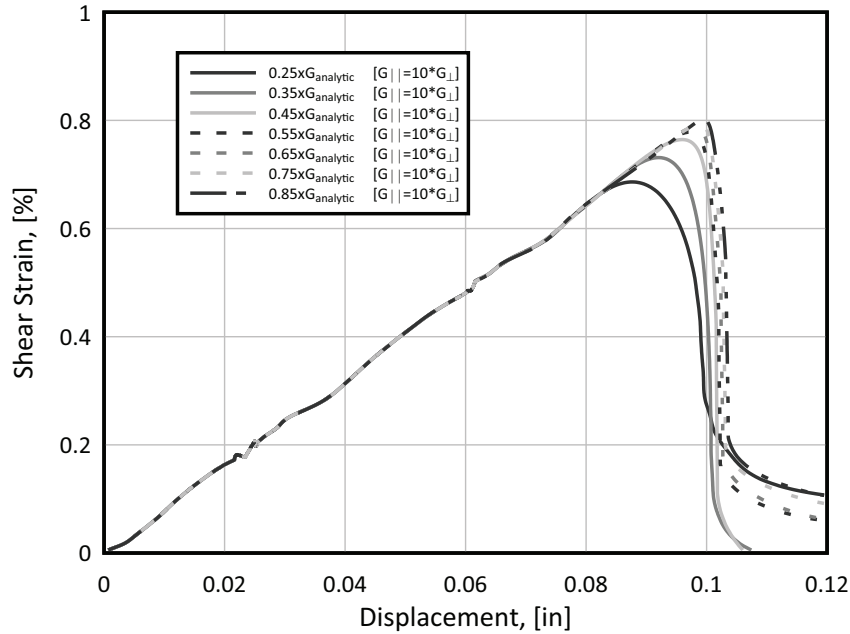


Figure 5.29: Strain-displacement histories comparing reduction of analytical fracture energies keeping $G_{f_{\parallel}}=10G_{f_{\perp}}$ constant.

From 55% to 85% reductions of the derived $G_{f_{I\perp}}$ and $G_{f_{II\perp}}$ values, the effects on peak shear strain to failure are minimal and lie within the bounds of the QS and IS Shear Tests averages. At further reductions, the effect on strain to failure is more profound and the plot shows more gradual decays in strain at failure. Qualitatively, the simulations showed strong tendencies of parallel damage in the 25% to 55% reduction ranges, but as the derived values were approached, mixed parallel and perpendicular damage was observed. The behaviors are illustrated in Figure 5.30.

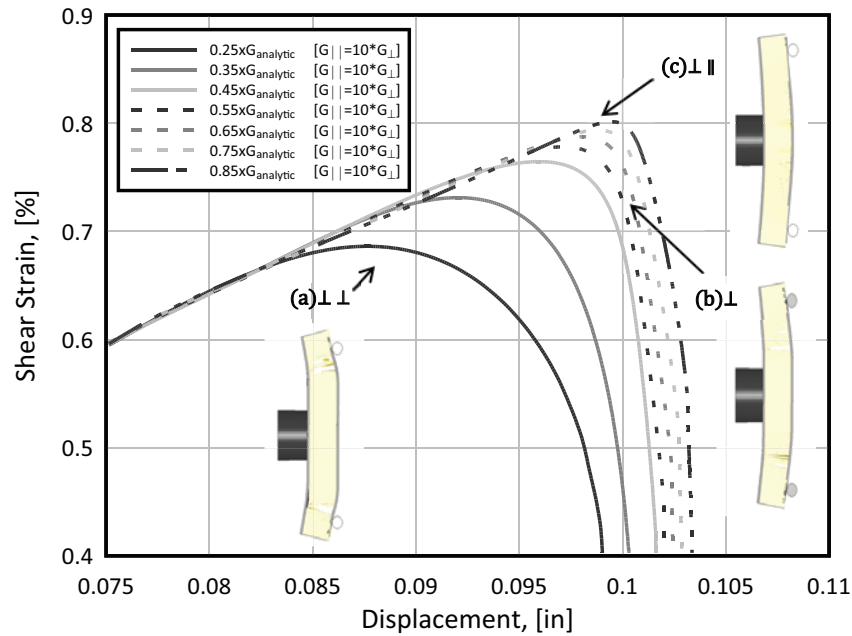


Figure 5.30: Close-up of maximum strains observed in simulations, highlighting reduction ranges of (a) strongly perpendicular damage dominated, (b) perpendicular damage and (c) mixed perpendicular/parallel damage.

The simulations run at 55% and 65% of the derived values for $G_{f\parallel}$ and $G_{f\perp}$ demonstrated the minimum amount of reduction necessary to achieve experimentally observed results when assuming $G_{f\parallel} = 10G_{f\perp}$. These estimates demonstrated both quantitative and qualitative correspondence to the empirically observed failure progression of the balsa core in the QS and IS Shear Tests.

5.3.3 Dynamic Shear Test Simulations

The experimental and numerical setups for the Dynamic Shear Tests are shown in Figure 5.31.

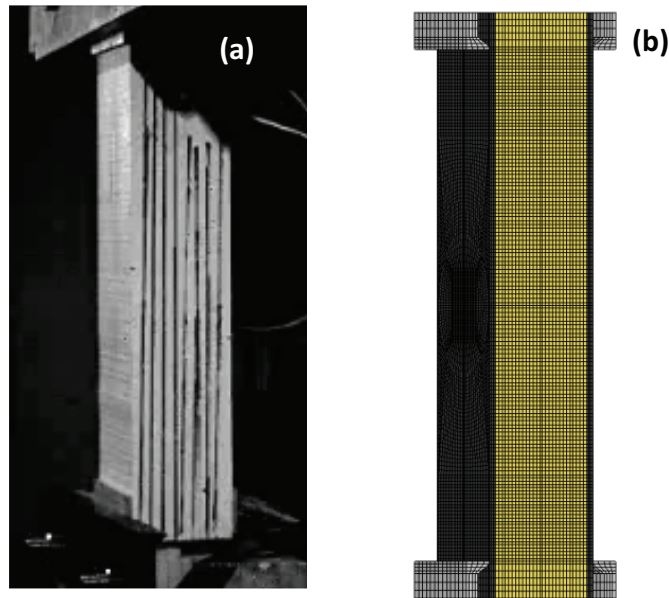


Figure 5.31: Dynamic Shear (a) Test and (b) Simulation.

The steel rollers and tiebreaks were modeled using the same material parameters as used in the previous simulations.

Applied loads were taken from pressure time histories recorded from the dynamic load cells impacted with the foam/flyer assembly and strain outputs were requested in the same locations as in the IS Shear Test Simulations. The location of load application and element sets for the strain gauge representations as well as the fixed boundary conditions imposed on the steel supports are depicted in Figure 5.32.

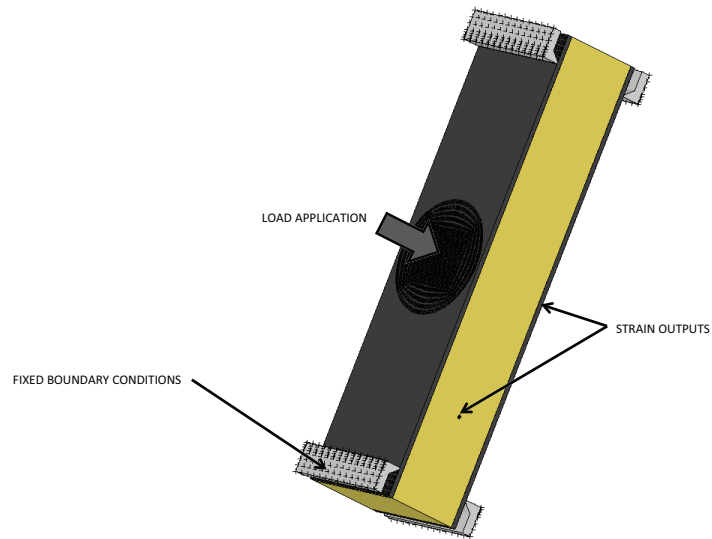


Figure 5.32: Load application, strain outputs and boundary conditions for Dynamic Shear Test Simulations.

As in the IS simulations, tiebreak contact surfaces were applied in between the CFRP facesheets and balsa core, which are shown in Figure 5.33 along with the surface contact between the outer facesheets and steel supports.

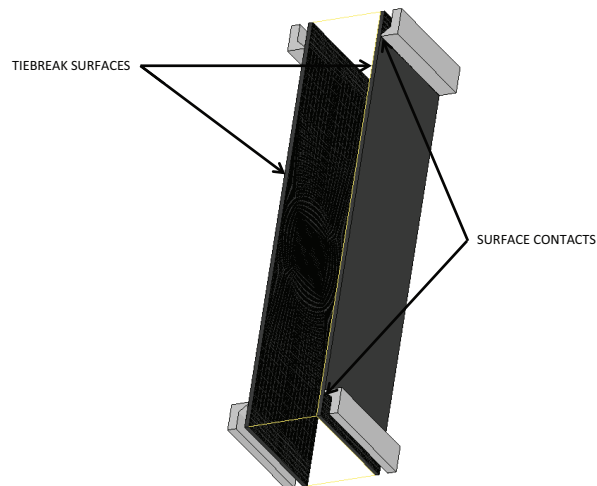


Figure 5.33: Tiebreak and surface contacts for Dynamic Shear Test Simulations.

The sequence of events for Dynamic Shear Test 3 and its corresponding simulation are compared in Figure 5.34.

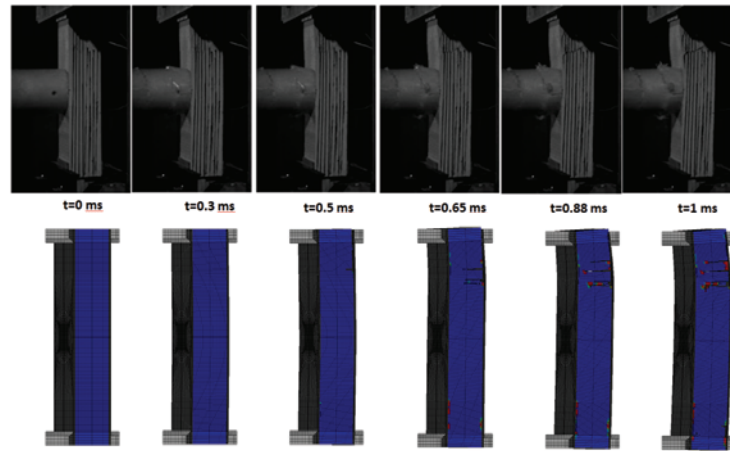


Figure 5.34: Dynamic Shear Test 3 Simulation and experiment.

Figure 5.35 plots the simulated shear and bending strains against experimental measurements.

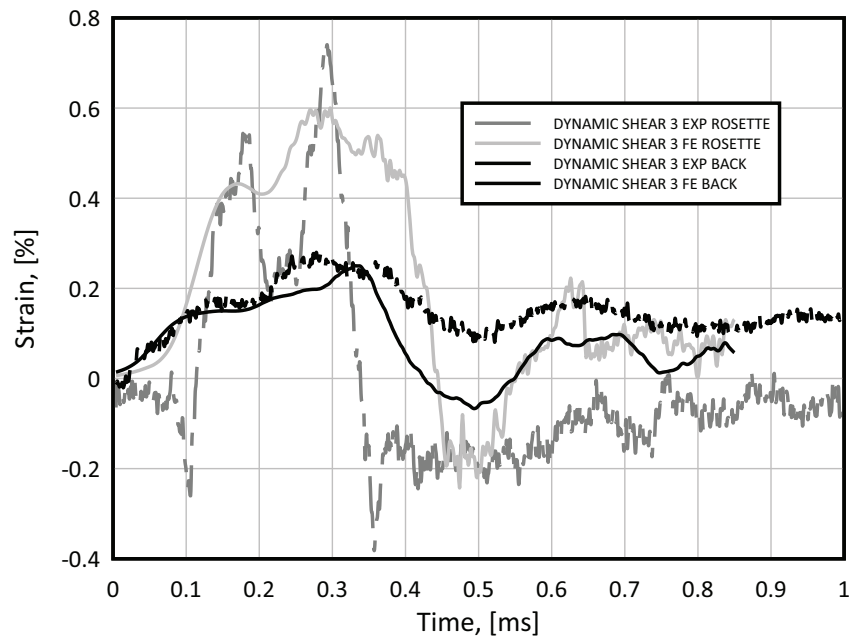


Figure 5.35: Shear and bending strain-time history comparison between simulation and Dynamic Shear Tests 3.

The general characteristics from both gauges are captured in the simulation. The shear strain history from the model shows a more gradual rise to a peak of 0.6% and approximately half a second longer duration. The bending gauge strain histories from the simulation are consistent with experiment. As discussed in the previous section, part of the rationale for the drop in the ratio of $G_{f_{\parallel}}$ to $G_{f_{\perp}}$ was to be based on [25] that claimed better correlation to experimental data under dynamic loads. The results from the Dynamic Shear Test simulation fell within an acceptable range to make the assumption that reductions in $G_{f_{\parallel}}$ was appropriate for the balsa wood core.

5.4 Summary

The updated material properties are shown in Tables 5.4, 5.5, and 5.6.

Table 5.4: Updated CFRP facesheet property estimates

Density, ρ , lbm/in-3	1.46e-4
Tensile modulus, E_A, E_B, E_C , Msi	6.1, 6.1, 1.39
Poisson's ratio, $\nu_{BA}, \nu_{CA}, \nu_{CB}$	.029, .088, .088
Shear modulus, G_{AB}, G_{BC}, G_{CA} , Msi	2.2, 1.6, 1.6
Longitudinal tensile strength, X_T , ksi	148
Transverse tensile strength, Y_T , ksi	152
Transverse compressive strength, Y_C , ksi	97.5
Out-of-plane tensile strength, S_N , ksi	4.9
Shear strength, S_C , ksi	8.14
Transverse shear strength, S_{YZ}, S_{XZ} , ksi	7.7, 7.32

Table 5.5: Updated balsa core property estimates

Stiffness:	
Density, ρ , lbm/in-3	1.42e-5
Parallel normal modulus, E_L , ksi	518
Perpendicular normal modulus, E_T , ksi	22
Parallel shear modulus, G_{LT} , ksi	29
Perpendicular shear modulus, G_{TR} , ksi	11
Parallel major Poisson's ratio, PR	.25
Strength:	
Parallel tensile strength, X_T , psi	1920
Parallel compressive strength, X_C , psi	1878
Perpendicular tensile strength, Y_T , psi	57
Perpendicular compressive strength, Y_C , ksi	340
Parallel shear strength, S_{XY} , ksi	433
Perpendicular shear strength, S_{XZ} , ksi	576
Damage:	
Perpendicular fracture energy in tension, $G_{f_{I\perp}}$, psi-in	.1278
Perpendicular fracture energy in shear, $G_{f_{II\perp}}$, psi-in	.17313
Parallel fracture energy in tension, $G_{f_{I\parallel}}$, psi-in	1.278
Parallel fracture energy in shear, $G_{f_{II\parallel}}$, psi-in	1.7313

Table 5.6: Updated tiebreak contact parameters estimates

Normal failure stress, NFLS	500
Shear failure stress, SFLS	250
Critical interface failure distance, PARAM	.0325

These calibrated parameters were used as inputs for the numerical simulations of the Composite Joint Tests presented in Chapter 6.

Chapter 6

Numerical Model Development & Validation: Composite Joint Tests

The focus of this chapter and main objective of this research was to develop a finite element model of the Composite Joint Tests presented in Chapter 3. The observed failure modes provided guidance into criteria of focus for the subsequent material level experiments discussed in Chapter 4, which in turn enabled the calibration of the finite element material models examined in Chapter 5.

This criteria included behavior of the sandwich material in bending and strain limits of the CFRP facesheets, characterization of the balsa core material with emphasis on shear failure and damage accumulation, and the interfacial strength and damage properties that initiate delamination.

The following presents five finite element simulations of each of the Composite Joint Tests. First, a description of the model and assumptions are reviewed, followed by the details of each simulation and a comparison to results.

6.1 Composite Joint Model Setup

The composite joint model consisted of 50,000 continuum elements and was run under plane strain conditions. The specimen mesh maintained an aspect ratio of 1.1 in all of the simulations. Figure 6.1 shows a comparison of the experimental setup and numerical representation.

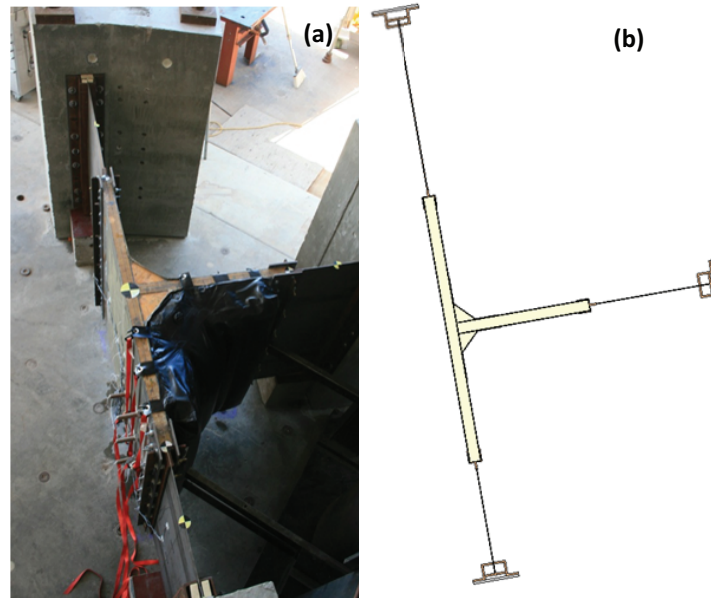


Figure 6.1: Composite Joint Test (a) and Simulation (b).

As prescribed in the material test simulations, the material directions in both the CFRP facesheets and balsa core needed to be specified. However, unlike the material tests that were composed of beams spanning in one direction, the composite joints were composed of two sandwich panels joined together with a triangular balsa stiffener and an overlamine on each side of the stem. The grain in the triangular core stiffeners was at 45° to each of the panels and the overlamine ran parallel from the stem panel, across the stiffener and parallel again to the base panel. The material orientation designations for each part of the joint are illustrated in Figure 6.2. The grain direction in the balsa is highlighted in red in (b), which is also the through the thickness direction in the CFRP facesheets and overlamine, highlighted in blue in (c).

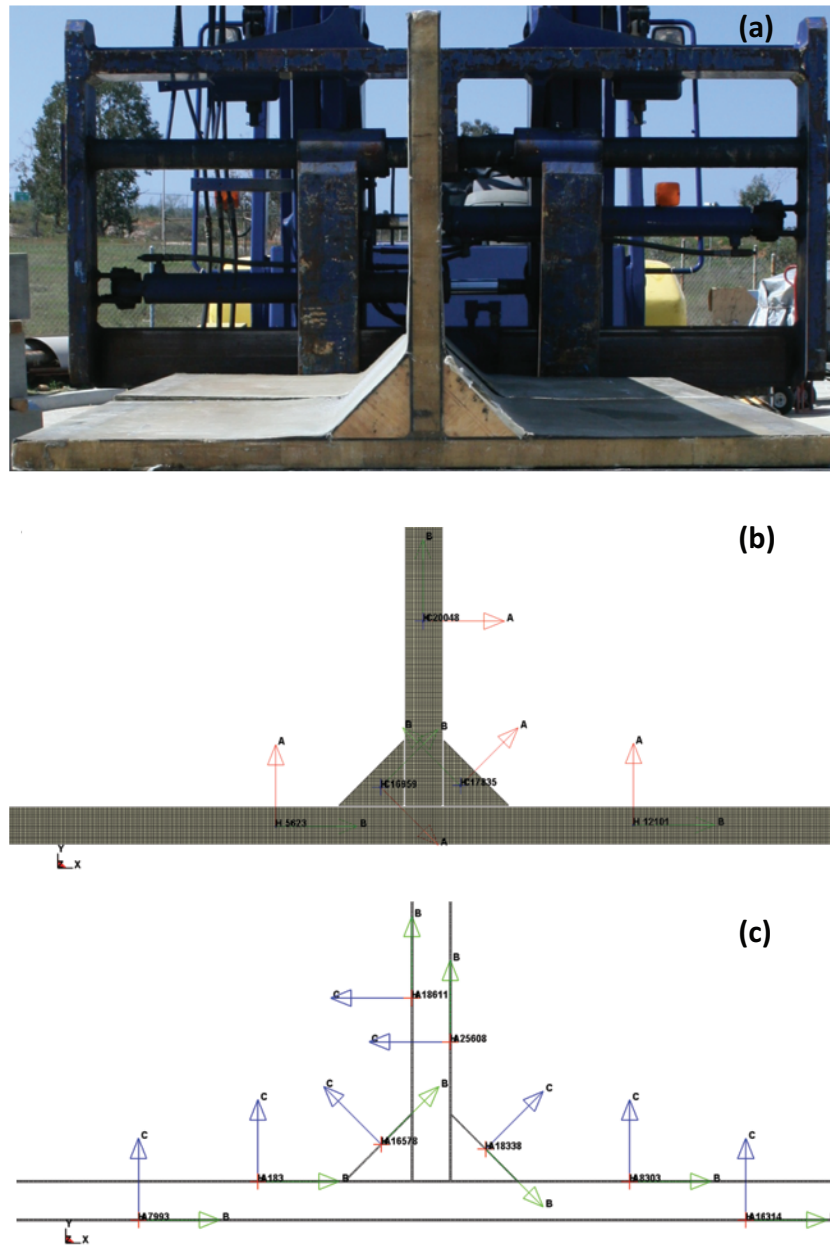


Figure 6.2: Material orientations for Composite Joint Test Simulations.

As described in Chapter 3, the gripping fixtures were composed of a thin steel t-web attached to the specimen via bolted grip plates on one end and sandwiched in between two steel Z assemblies mounted to the reaction blocks. Filling the gap between the end of the steel web and the inside faces of the Z assemblies was a structural foam, whose properties were obtained from [29]. Figure 6.3 depicts both the experimental and

numerical representation of the gripping fixtures, noting applied material models.

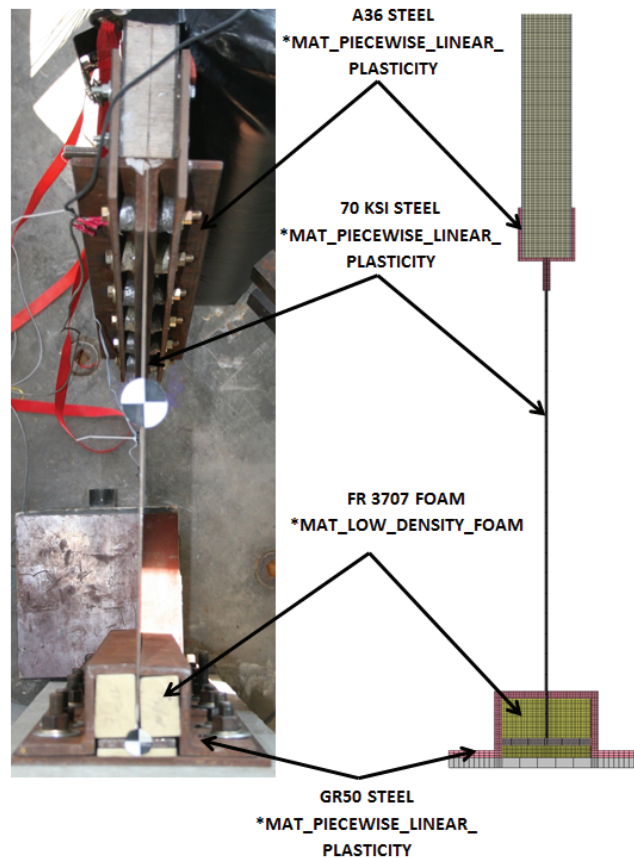


Figure 6.3: Gripping fixtures for Composite Joint Test simulations.

Boundary conditions and contact surfaces in the gripping areas are shown in Figure 6.4. Fixed boundary conditions were applied to the back side of the rigid block and the steel Z assemblies were merged in entirety to the specimen facing side of the block to represent the thread rod connection through the concrete reaction blocks. Surface to surface contacts were placed along the inside of the Z assembly/foam/steel web interface using LS-DYNA's SOFT=2 option to assist with numerical instabilities that occur when two materials with large stiffness differences are given contact definitions. The highly deformable foam was also prone to numerical instabilities resulting in negative volume errors and to remedy this, LS-DYNA's *CONTACT_INTERIOR was utilized. The code checks the user assigned part set during the simulation and applies a linear spring within the two surfaces of the element when it falls below the smallest thickness

dimension [21]. Surface to surface contacts were imposed between the Z assemblies and sides of the steel web, and the remaining parts were merged to simulate the bolted connection through the specimen.

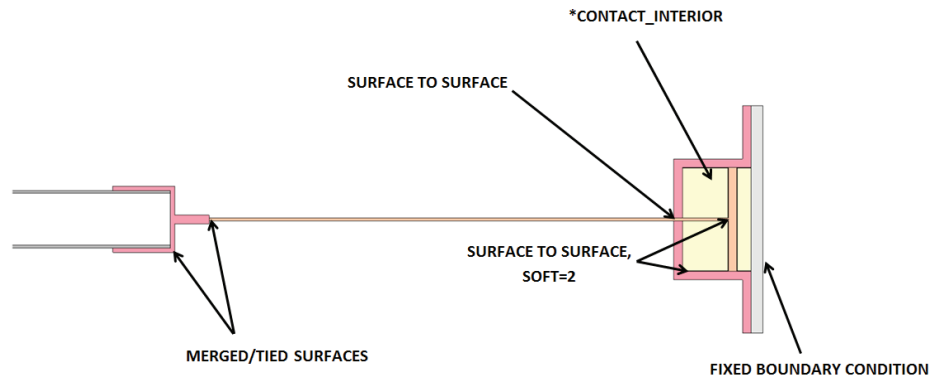


Figure 6.4: Contact surfaces assigned to gripping fixture assembly and boundary conditions for Composite Joint Test simulations.

Element sets were designated for strain output at the experimental strain gauge locations and are shown in Figure 6.5.

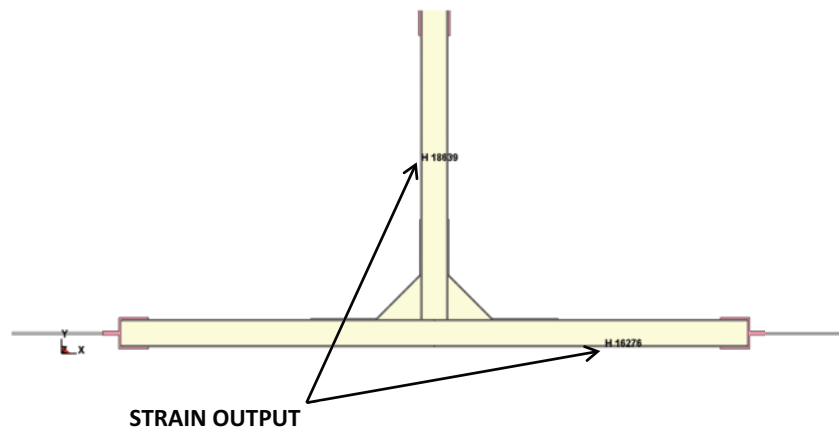


Figure 6.5: Strain output locations for Composite Joint Test simulations.

For each simulation, the pressures recorded from the embedded load cells were applied to facesets on each representative surface. Figure 6.6 illustrates the spatial distribution, which was approximated by the tributary area in between load cells.

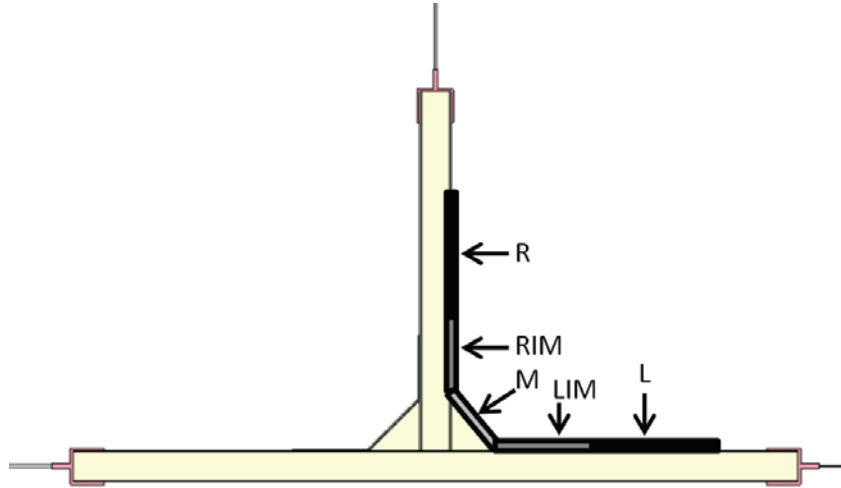


Figure 6.6: Spatial pressure distributions for Composite Joint Test simulations.

High frequency oscillations were observed in many of the pressure-time histories presented in Chapter 3. For simplification the pressure time histories were approximated in a linear stepwise fashion. This approximation is described graphically for each Composite Joint Test simulation.

The final parameter(s) necessary for the validation of the simulations was the strength of the overlamine. Reported tensile and shear strength values for the vinylester resin used in the fabrication of the joints of were used as initial estimates. As with the FRP/balsa interface, the FRP/FRP interface on the underside of the overlamine and top side facesheet of the panels were modeled using `*CONTACT_AUTOMATIC_ONE_WAY_SURFACE_TO_SURFACE_TIEBREAK`. Figure 6.7 illustrates the locations of the FRP to FRP tiebreak surface assignments.

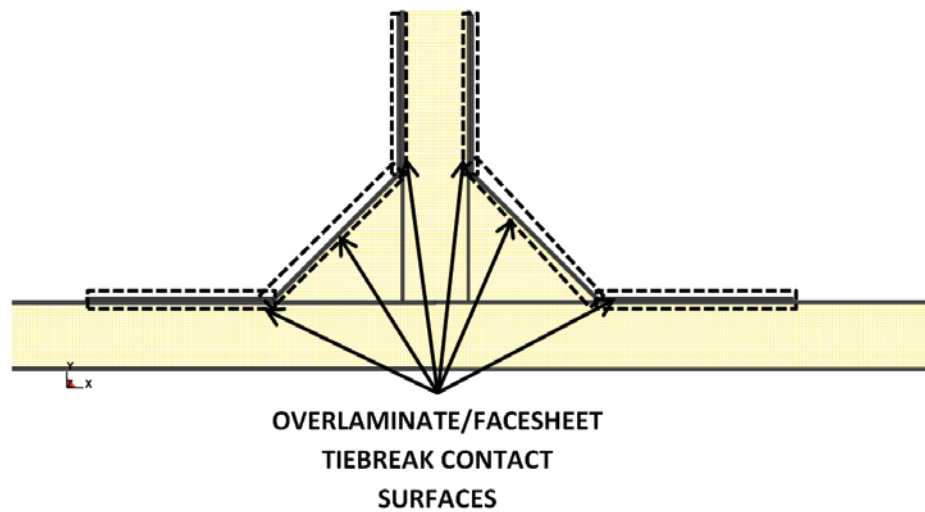


Figure 6.7: Overlamine tiebreak surface contact assignments for Composite Joint Test simulations.

As with the tiebreak study of the previous chapter, the Composite Joint Tests were used to calibrate the strength and damage parameters necessary to simulate the experimentally observed failure sequences during the Blast Simulator tests.

Next, the numerical simulation of each Composite Joint Test is presented, followed by a discussion of results. The simulations are presented in order of observed damage levels as this made calibration of the model the most efficient.

6.2 Simulation of Composite Joint Test 1

The experimentally measured pressure time histories from Composite Joint Test 1 are shown in Figure 6.8. To reduce the effects of the high frequency oscillations of the load cell readings on numerical outputs, the pressures were approximated step-wise linearly and are plotted over the experimental pressures.

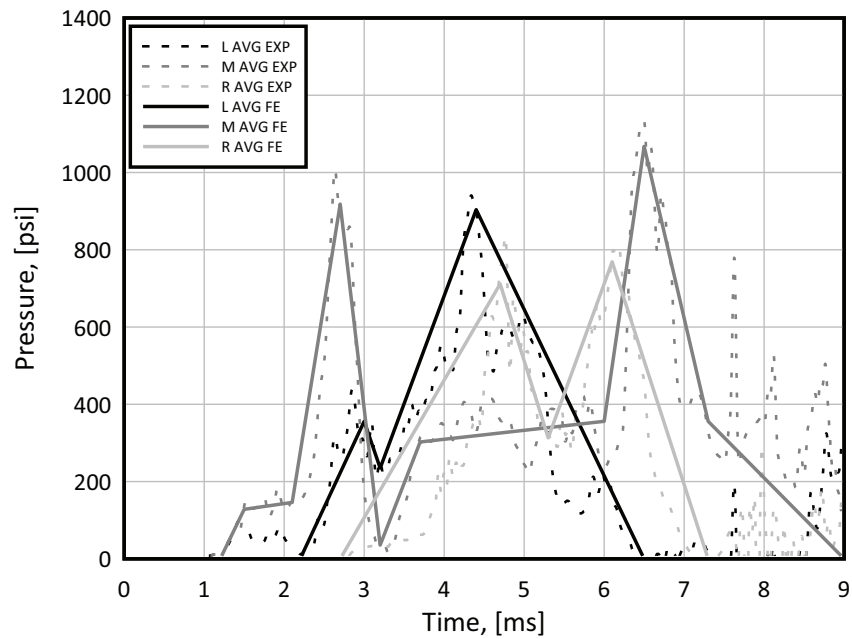


Figure 6.8: Experimental and approximated pressure-time histories for Composite Joint Test 1 simulation.

The result of the first simulation was catastrophic. An example of the initial runs using the full scale recorded pressures is shown in Figure 6.9.

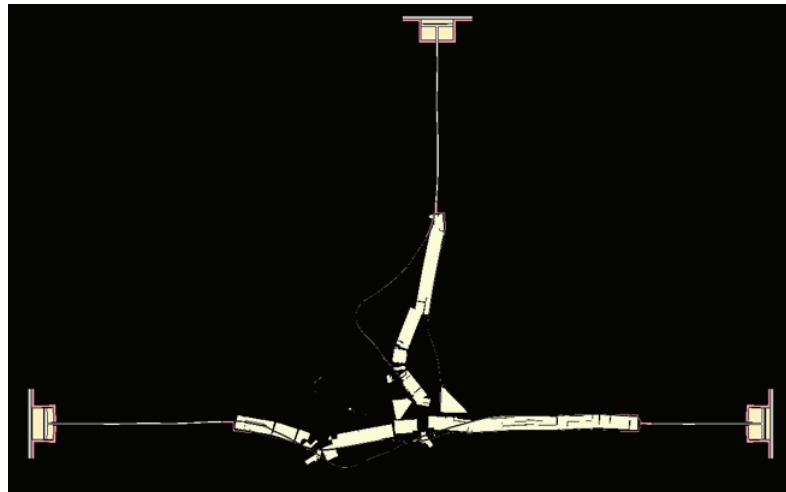


Figure 6.9: Illustration of excessive damage in simulation of Composite Joint Test 1 using full scale experimental pressures.

With the material properties calibrated to experiment in the previous section, the

magnitude of the pressures were investigated. As discussed in the 2D Impact and Load Cell Calibration Tests of Chapter 3, there was a common 28.1% difference between the forces read from the smaller embedded load cells and the large reaction load cells reacting the specimens. In the next simulation, the applied pressures were reduced by a factor of .281 and are plotted in Figure 6.10.

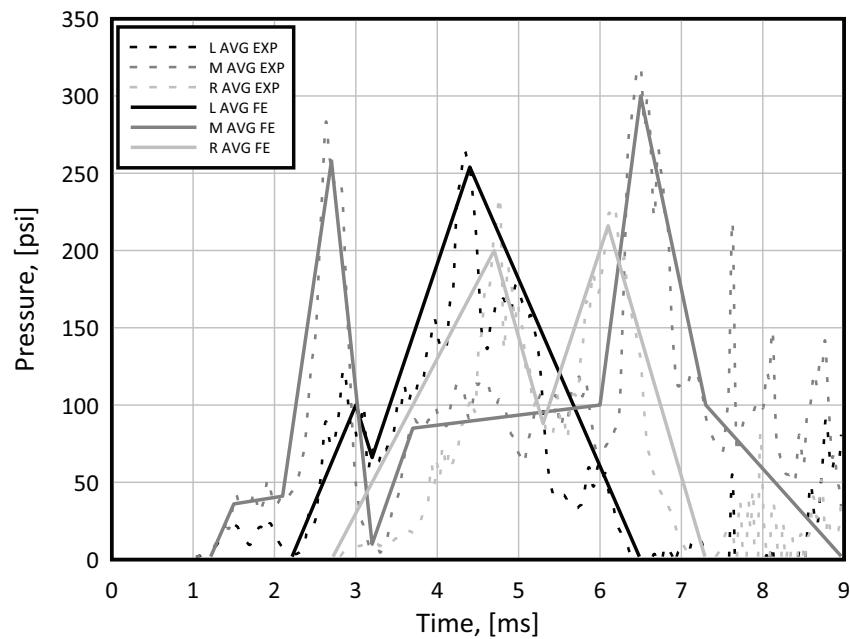


Figure 6.10: Experimental and approximated reduced pressure-time histories for Composite Joint Test 1 Simulation.

The simulation showed improved behavior with the reduced pressure-time histories. The sequence of events are compared to experiment in Figure 6.11 and the strains from the simulation are plotted against experimental measurements in Figure 6.12.

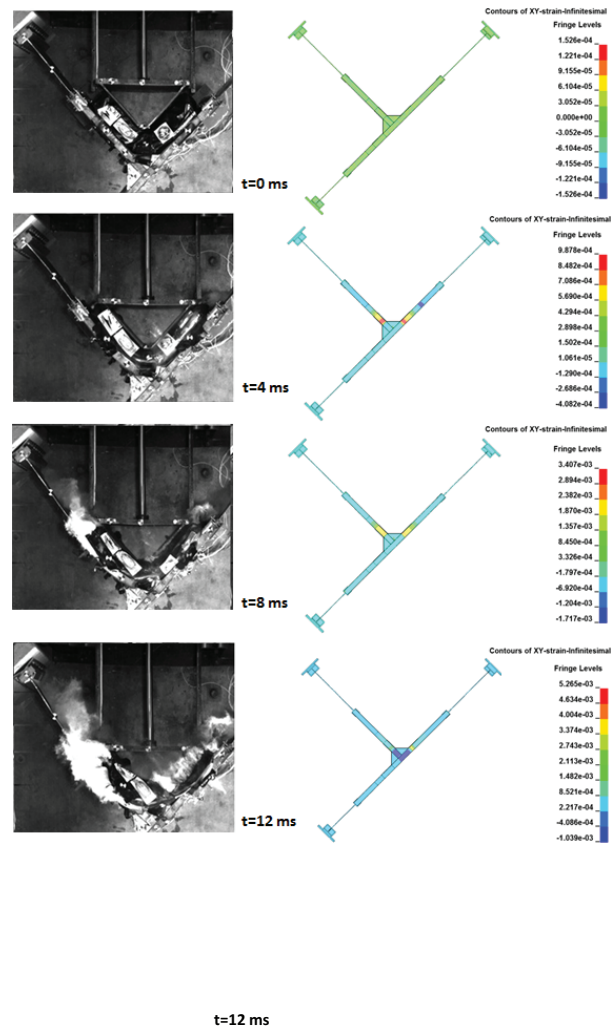


Figure 6.11: Shear strain development in simulation of Composite Joint Test 1 compared to experimental sequence of events.

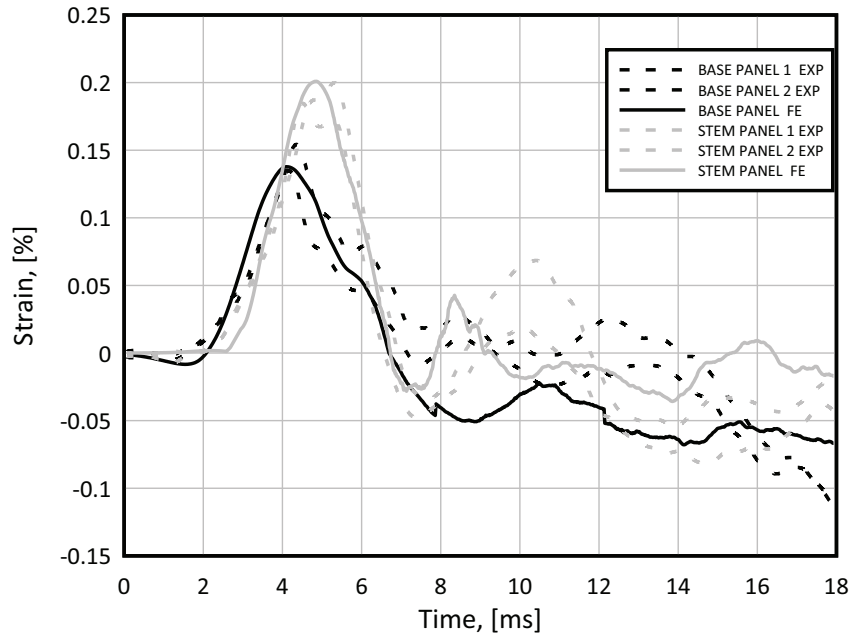


Figure 6.12: Comparison of Composite Joint Test 1 experimental and numerically calculated strain time histories.

Although the displaced water hinders full visual comparison, the strain-time histories from the simulation show good correspondence to the experiment, both in terms of rise times and magnitude. Although the secondary rebound in the NE panel was not captured fully by the model, but the result of the simulation was found acceptable for the elastic case.

6.3 Simulation of Composite Joint Test 4

The experimentally measured pressure time histories from Composite Joint Test 4 are shown in Figure 6.13. Per the results of the previous simulation, the pressure time histories were reduced by the same factor as the previous simulation and overlayed in the plot.

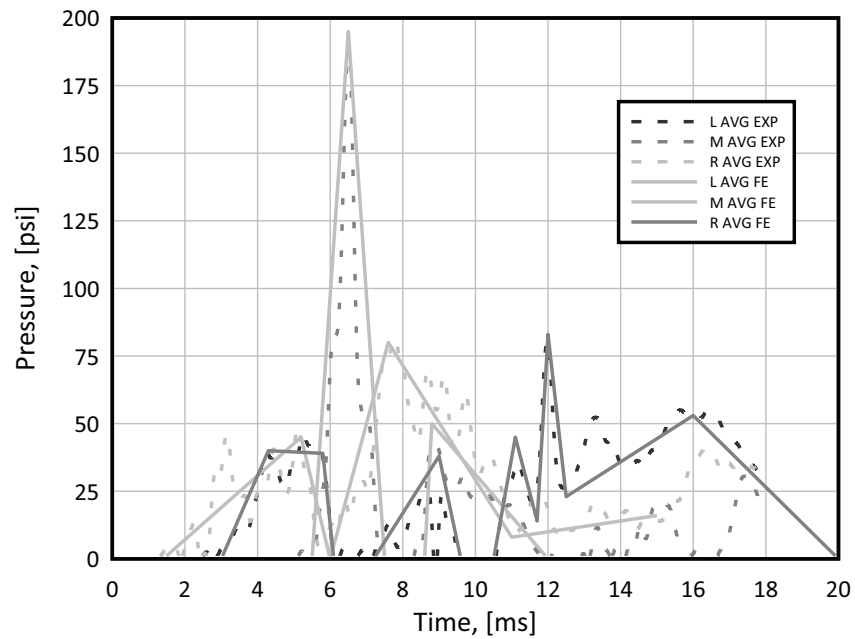
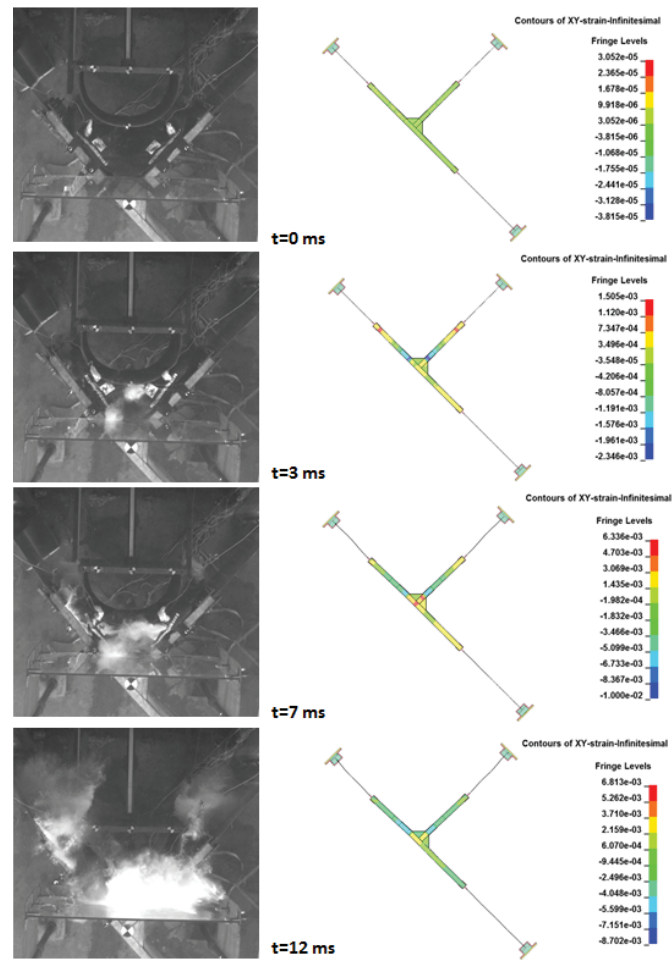


Figure 6.13: Experimental and approximated reduced pressure-time histories for simulation of Composite Joint Test 4.

The qualitative comparison between experiment and simulation of Test 2 is depicted in Figure 6.14 and strain-time histories are plotted for quantitative comparison in 6.15.



$t=12$ ms

Figure 6.14: Shear strain development in simulation of Composite Joint Test 4 compared to experimental sequence of events.

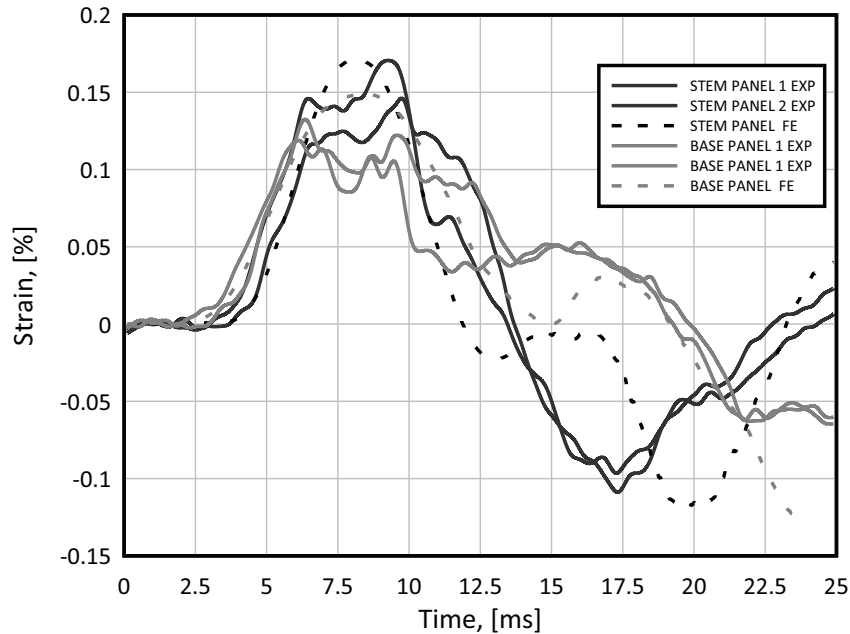


Figure 6.15: Comparison of Composite Joint Test 4 experimental and numerically calculated strain time histories in the base and panel facesheets.

As with Test 1, the results from the simulation of Test 4 show acceptable correspondence with the experimentally measured strains of 0.17% in the base panel in both the experiment and simulation. The stem panel reaches a maximum bending strain of 0.13% in the stem panel in experiment, while the simulation shows a maximum of 0.14%. Figure 6.14 plots fringes of shear strains which reached a maximum value of 0.6% at 8 ms, which is approaching the strain necessary to shear the panel, but no shear failures were observed.

6.4 Simulation of Composite Joint Test 3

The experimentally measured and approximated reduced pressure-time histories from Composite Joint Test 3 are shown in Figure 6.13.

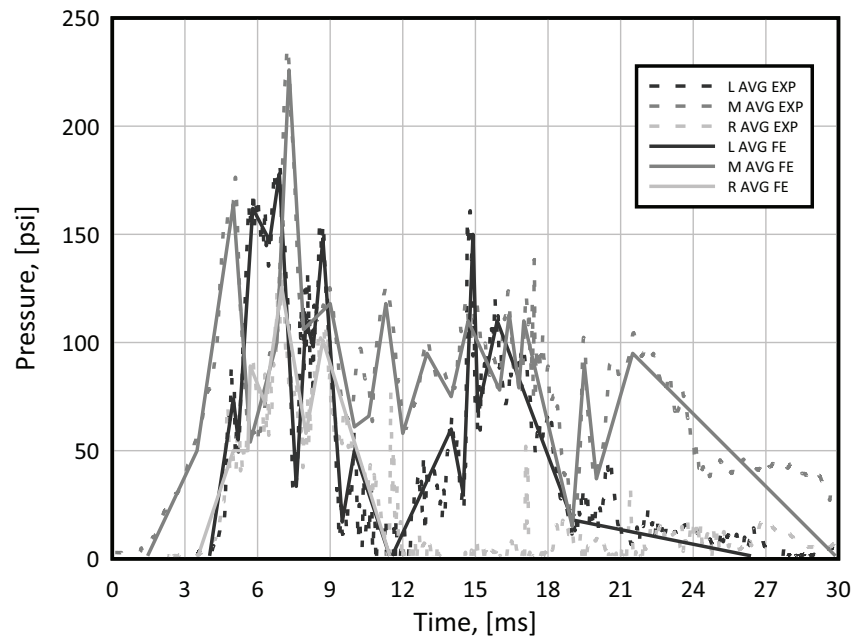


Figure 6.16: Experimental and approximated reduced pressure-time histories for Composite Joint Test 3 simulation.

The sequence of events leading to failure in the simulation is shown next to frames taken from the high speed cameras in Figure 6.17, however visibility of the damage sequence was blocked by the water dispersion. Verification of simulated behavior was accomplished via post test inspection, shown in Figure 6.18 (a) and (b), and the strain-time history comparisons plotted in Figure 6.19.

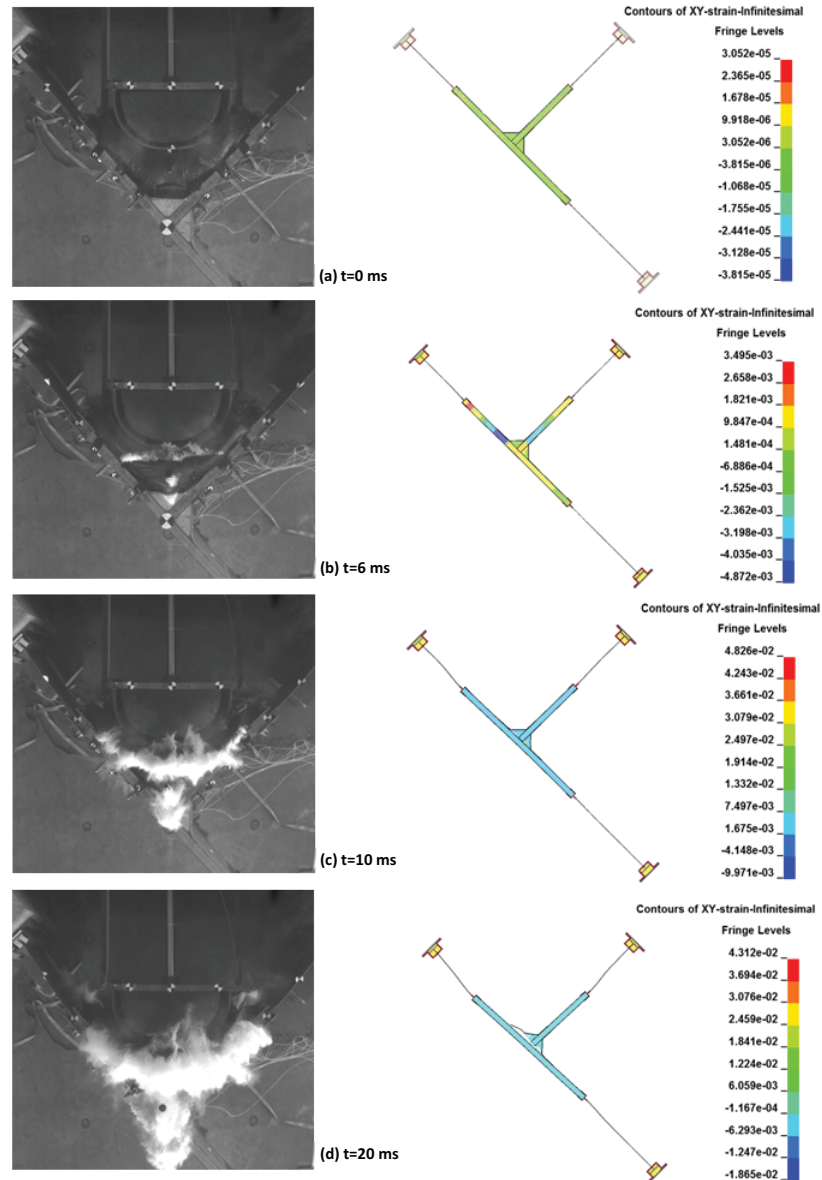


Figure 6.17: Simulated shear strains from Composite Joint Test 3 and frames of experiment taken from high speed video.

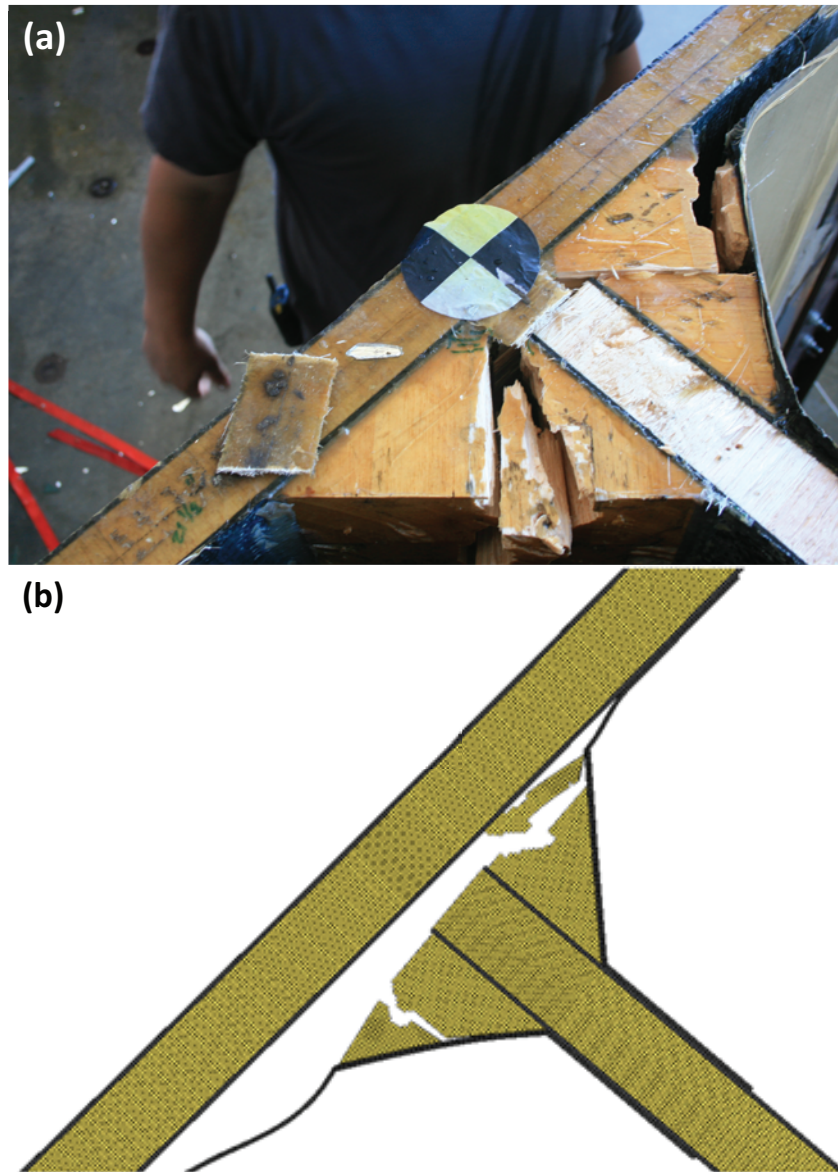


Figure 6.18: Comparison of (a) post test damage and (b) simulated damage propagation to balsa stiffeners.

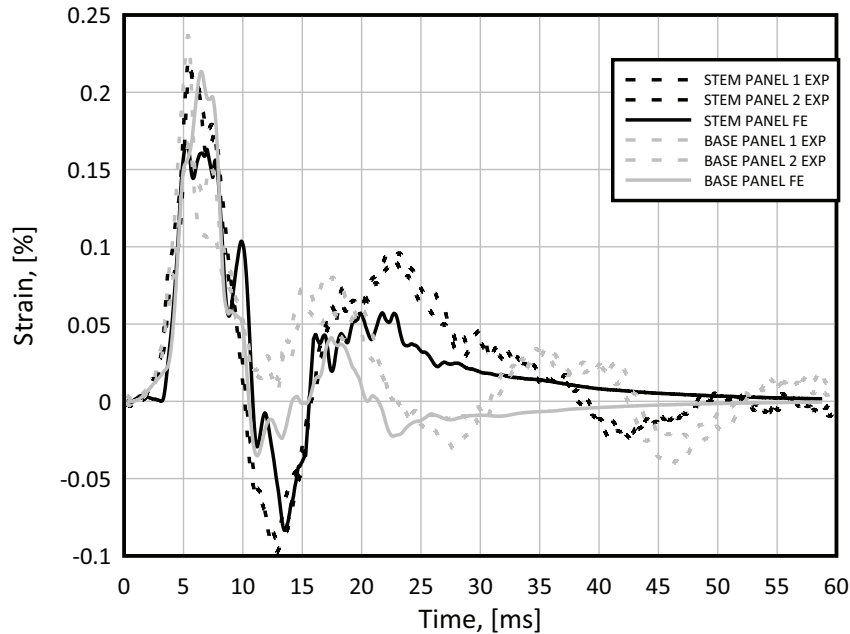


Figure 6.19: Comparison of Composite Joint Test 3 experimental and numerically calculated strain time histories in the base and stem panel facesheets.

The simulation demonstrates similar damage characteristics as the experiment. The calibrated wood model accurately predicts shear failures through both of the triangular stiffeners as well as delamination of the overlaminates. The recorded strains from the back of the base and panel facesheets also coincide, rising to peak strain of 0.23% at very similar rates and maintaining the elongation for close to 5 ms. The simulation denotes a drop into compression in the base panel at 13 ms, whereas the in the experiment the base panel stayed in a relatively small amount of tension 20 ms.

The overlaminate to facesheet tiebreak contact parameter used in Composite Joint Test 3 were knocked down to nearly half of the estimated resin strength to obtain the presented results. Additional calibration of the tiebreak parameters used for the interface contact were needed in order to capture the failure propagation in Tests 2 and 5, which are presented next.

6.5 Simulation of Composite Joint Test 2

The experimentally measured and approximated reduced pressure-time histories used in Composite Joint Test 2 are shown in Figure 6.20.

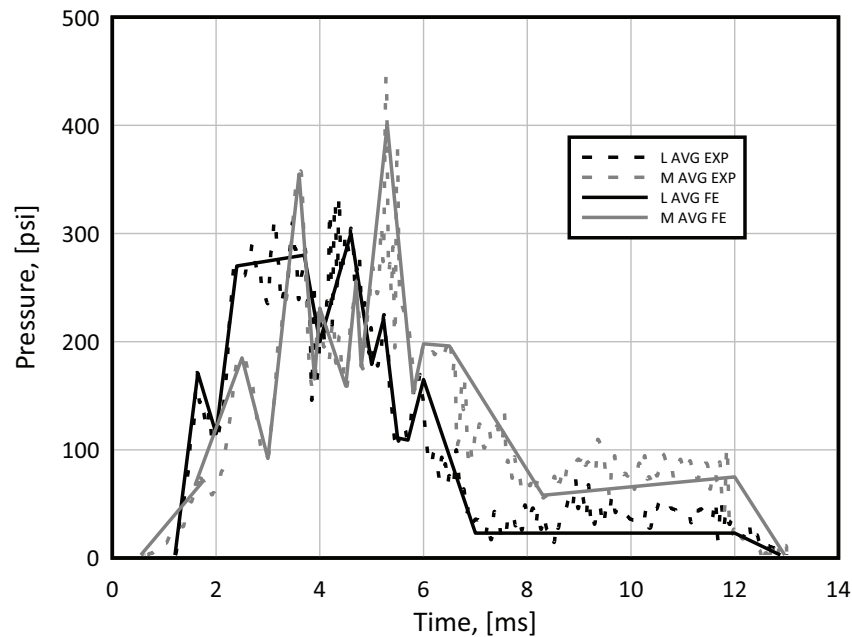


Figure 6.20: Composite Joint Test 2 experimental and approximated reduced pressure-time histories.

The sequence of events leading to failure in the simulation is compared to experiment in Figure 6.21, and close ups of the failure progressions are highlighted in Figure 6.22 and Figure 6.23.

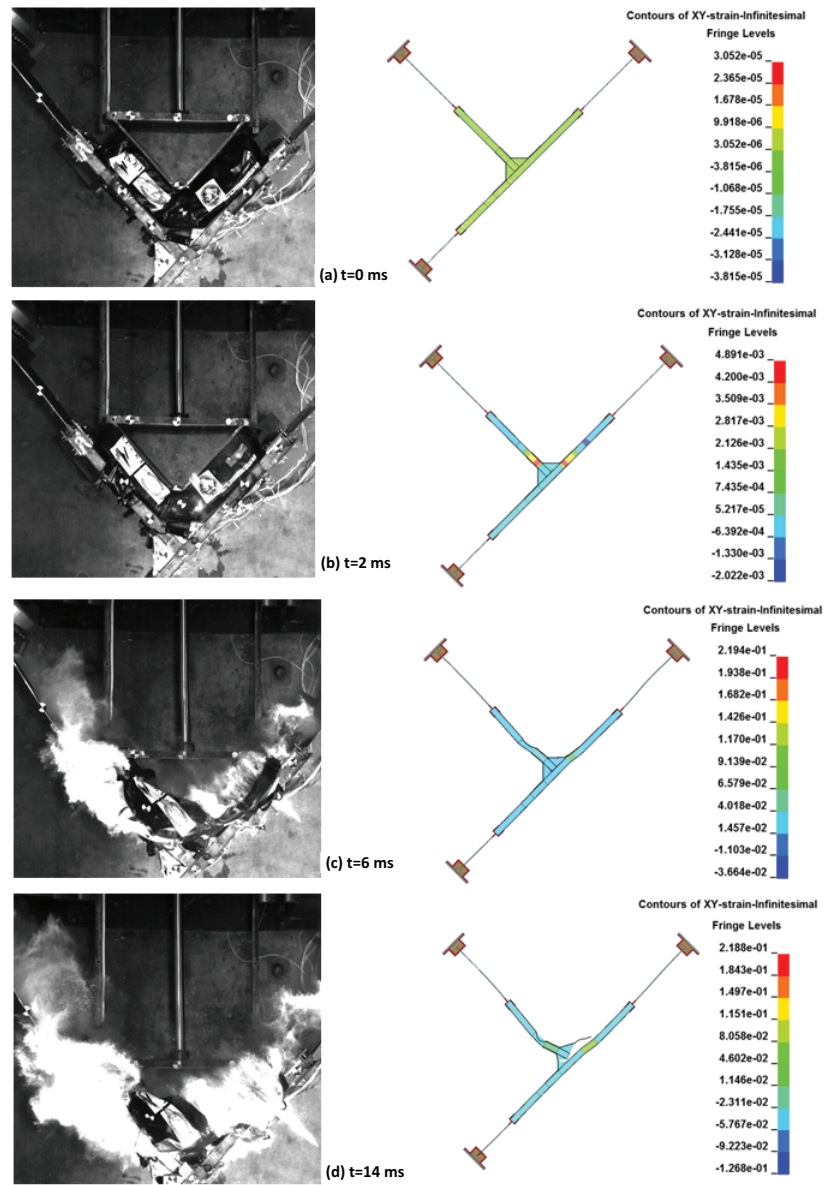


Figure 6.21: Simulated shear strain development in Composite Joint Test 2 compared to experimental sequence of events.

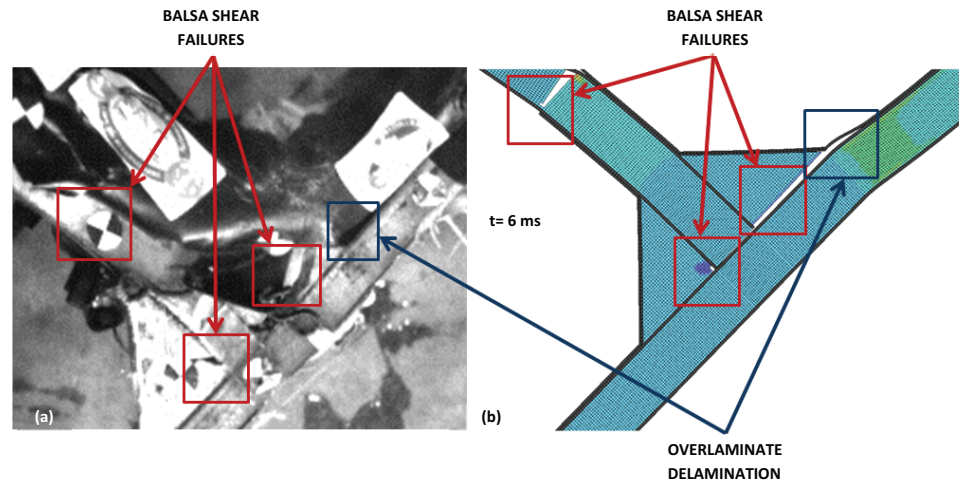


Figure 6.22: Overlaminate delamination and balsa shear failures in (a) Composite Joint Test 2 compared to (b) finite element results @ $t = 6$ ms.

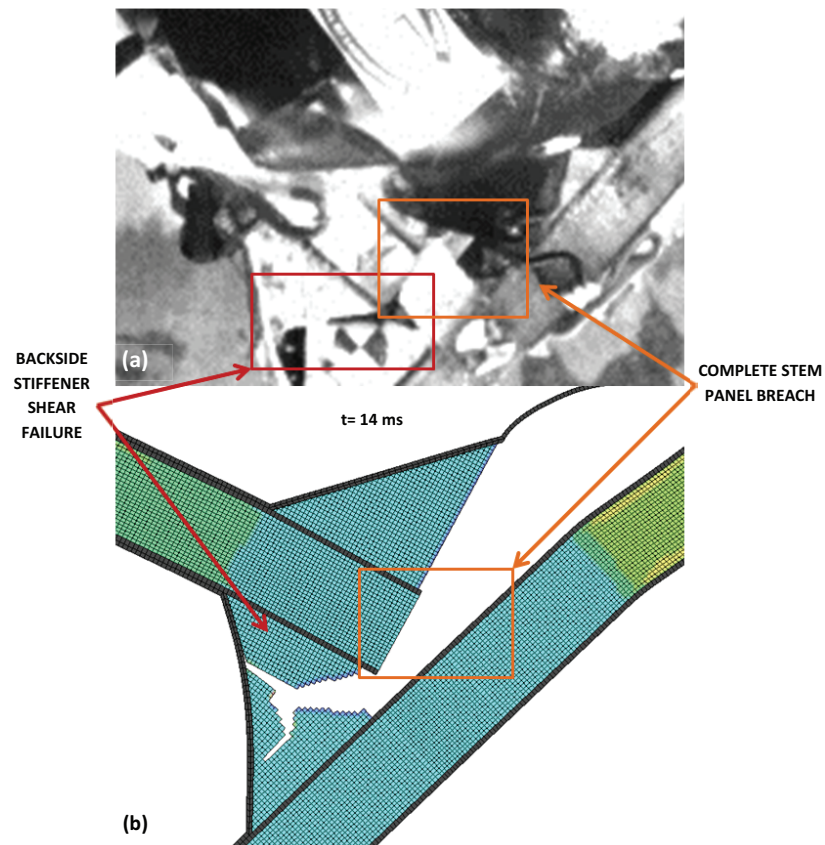


Figure 6.23: (a) Experimental balsa shear propagation and stem panel detachment compared to (b) simulated results @ $t = 14$ ms.

As seen from the figures, the model correlates well with the sequence of failures seen in experiment. The shear failure in the stem causes delamination of the overlamine along the base panel almost instantaneously, triggering shear failure of the triangular stiffener along the base panel through to the bottom of the stem panel, depicted in 6.22. The damage path continues through the backside stiffener in both experiment and simulation, shown in Figure 6.23, leaving little to no resistance in the joint and ultimately leading to full joint breach.

The strain histories recorded from the strain gauges placed on the backside facesheets of the stem and base panel are compared to the simulation results in Figure 6.24.

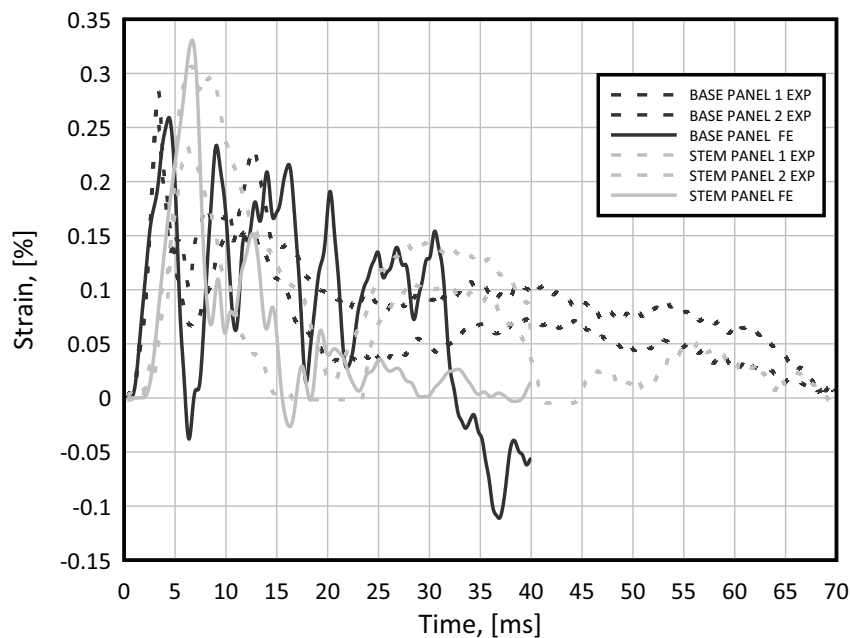


Figure 6.24: Experimental and simulated strain-time histories in Composite Joint Test 2.

The strains in the simulation show good correlation with the experiment in terms of rise times and peaks strains of approximately 0.3% in the stem panel and 0.25% in the base panel, however the experiment shows longer durations in strains approaching 5 ms at peak elongation while the simulation decays more rapidly. Both histories on the stem denote rapid decays to zero strain at 14 ms, immediately following breach.

The value of PARAM was increased for the tiebreak contact used in the simu-

lation of Composite Joint Test 2, as the initial simulations demonstrated delamination propagation more quickly than seen in the experiment. The discrepancy between the tiebreak damage value used between Composite Joint Tests 2 and 3 was evaluated in the simulation of Composite Joint Test 5.

6.6 Simulation of Composite Joint Test 5

The experimentally measured and approximated reduced pressure time histories used in Composite Joint Test 5 are shown in Figure 6.25.

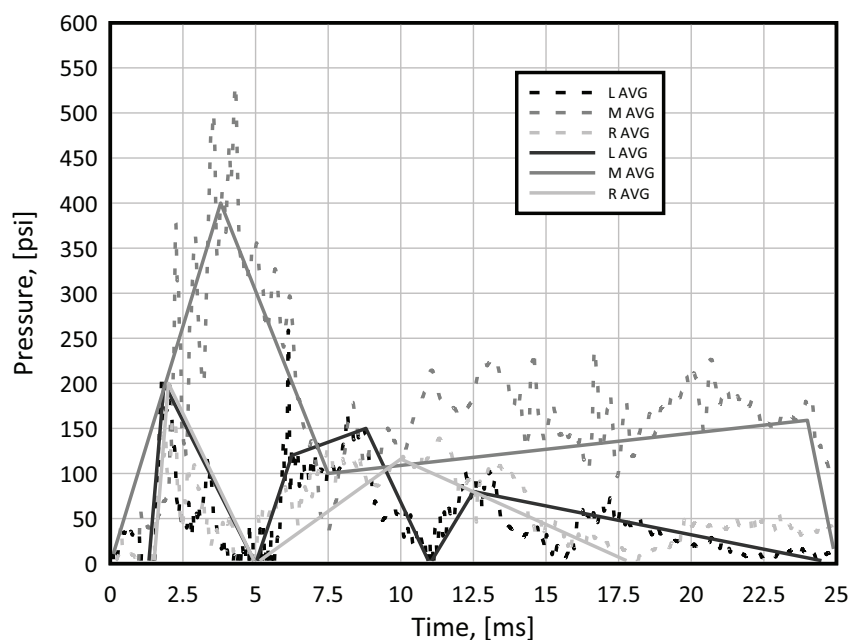


Figure 6.25: Composite Joint Test 5 experimental and approximated reduced pressure-time histories.

The sequence of events leading to failure in the simulation is compared to experiment in Figure 6.26, and close ups of the observed failure modes are highlighted in Figure 6.27. The deformation in the loaded arm of the base panel was unable to be seen in the high speed video due to the water, therefore post test photos are added for clarity.

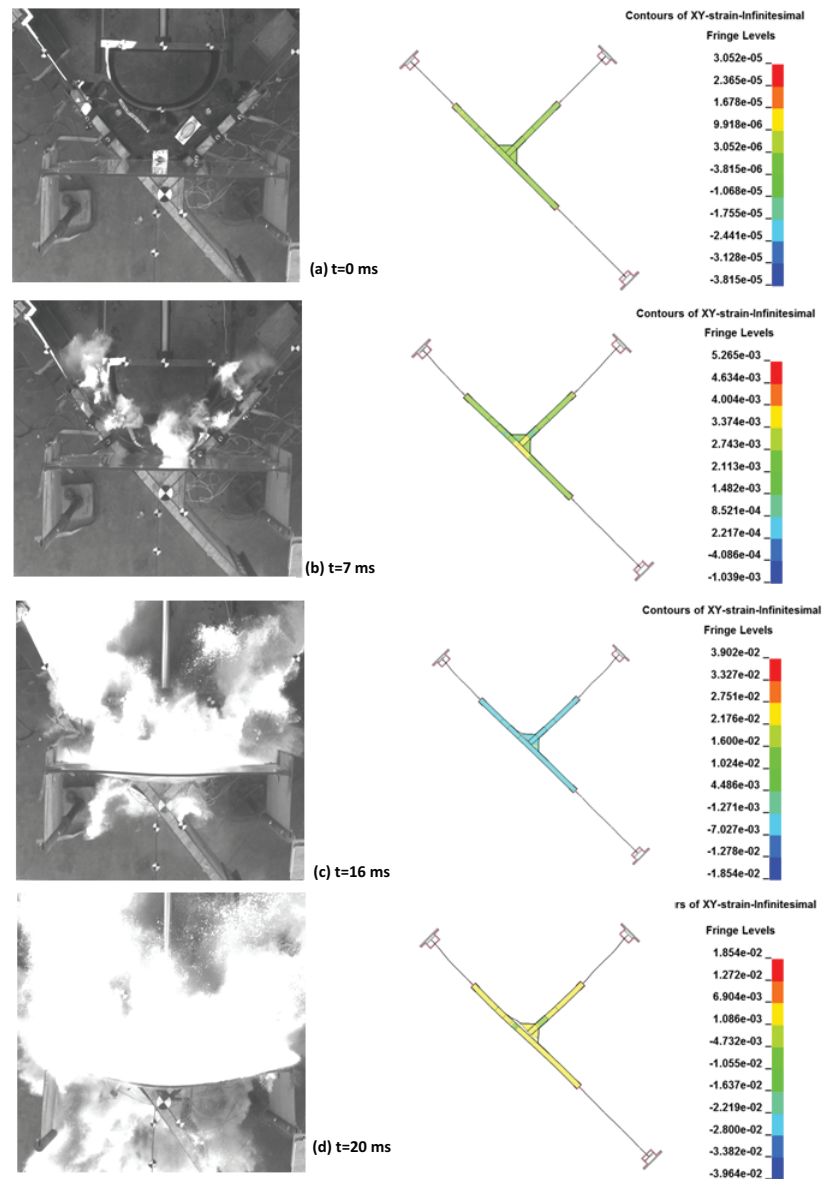


Figure 6.26: Comparison of sequences in Composite Joint Test 5 and simulation, plotting shear strains.

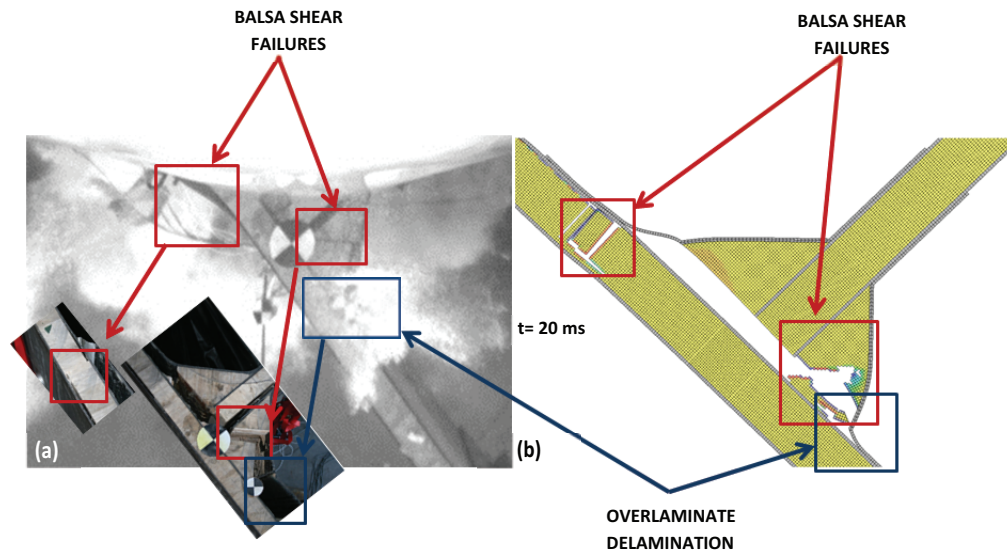


Figure 6.27: (a) Experimentally observed joint failure in Composite Joint Test 5 compared to (b) simulated results @ $t=20$ ms.

Figure 6.27 demonstrates that the model was able to capture the key elements of failure observed in Composite Joint Test 5. The shear failure in the base panel triggered delamination of the adjacent overlamine, followed by damage propagation through the backside triangular stiffener and ultimately leading to full joint breach. The strain time histories between the simulation and experiment are plotted in Figure 6.28.

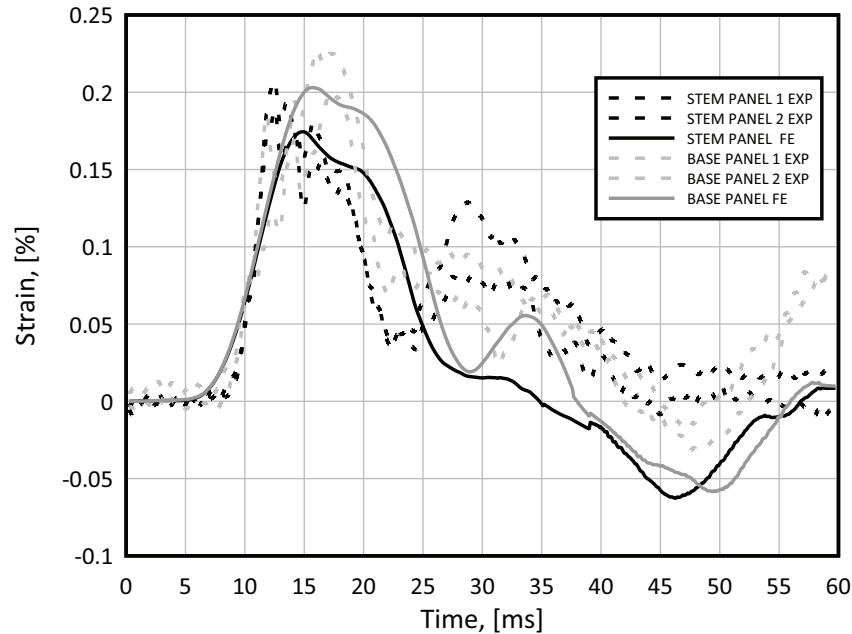


Figure 6.28: Experimental and simulated strain-time histories in Composite Joint Test 5.

The simulation demonstrated similar rises to peak strains in the panel facesheet near 0.2% at 15 ms. The base panel reached slightly higher strains than the stem, and both experimentally stay in tension until 45 ms, whereas the simulation drops into compression near 40 ms.

The same tiebreak parameters used in the simulations of Test 2 and 3 for the normal and shear stress inputs were again used in Composite Joint Test 5. This proved to correlate well with all three experiments that demonstrated joint breach. The damage parameter that gave the presented results fell in between the values used in Composite Joint Tests 2 and 3. The contact surfaces within the joint are numerous, and depending on manufacturer, the attempt to model such joints could end with dozens of necessary tiebreaks calibrations. Therefore, the small range of discrepancy between post delamination progression was deemed acceptable from a general standpoint.

6.7 Summary

This chapter presented five finite element simulations of the Composite Joint Tests.

Tests 1 and 4 were presented first, as both tests remained undamaged under the simulated blast loadings. With no observed delamination of the overlaminates, these simulations allowed for refinement and debugging of the numerical setup. This included the validation of elastic bending properties of the composite sandwich panels when placed in the T-joint configuration as well as demonstrated the necessity to reduce the magnitudes of the embedded load cell outputs.

Test 3 demonstrated shear failures through the triangular balsa stiffeners and full overlaminate removal, but denoted no shearing of the core in either of the panels. The lack of individual panel failures isolated the tiebreak calibration in the joint region and the mimicked shear failure through the stiffener cores was the first validation of the balsa material property resultants of the IS and Dynamic Shear Test Simulations presented in Chapter 4.

The simulations of Composite Joint Tests 2 and 5 followed, both of which demonstrated shear failure through the core of the stem panels as well as full delamination of the composite overlaminates which resulted in joint breach. These phenomena were strongly coupled, as the input of weak tiebreak strengths caused premature delamination of the overlaminates, which resulted in losses of strain energy necessary to shear the panels. If the strength and damage inputs of the overlaminate tiebreak parameters were too strong, then shear failures and delamination dominated in the panels sections. The simulations were able to capture all of the experimentally exhibited modes of deformation that led to the numerical studies of Chapter 4: bending of the stem and base panels, shear failures through the core, and delaminations. The final two tests validated the overall performance of the connection models ability to capture the complex sequence of experimentally observed phenomena.

The next and final Chapter will summarize the experimental and numerical methods developed through the course of this dissertation.

Chapter 7

Conclusions and Recommendations

7.1 Summary and Conclusions

This dissertation presented research conducted at the UCSD Blast Simulator and structural testing facilities pertaining to the high rate behavior of dynamically loaded composite sandwich joints. Through a vast series of experimental and numerical structural assessments, methodologies were developed to simulate internal blast loadings on structures complex in geometry and material composition. The loading protocols involved the use of momentum transfer through high strength fluid filled media impacted with the Blast Simulator, which produced pressure-time histories similar to those observed in confined or internal blast scenarios. For the first time in the history of the UCSD Blast Simulator facility, a reaction structure and tailorable gripping fixture assembly was designed that enabled the simulated blast loading of structures consisting of non flat geometries, in specific, composite joint connections. The results of the Simulator tests revealed the critical modes of joint failure propagations that lead to breach, a vital understanding in the design of resistant composite structural assemblies. In an effort to characterize the failure modes numerically, a set of novel material test setups were designed to excite dynamic shear and moment failures in the sandwich material as well as the development of a test method that isolates delamination phenomena. The generated data sets enabled the calibration of a high fidelity finite element material model for balsa wood as well as numerical techniques to capture delamination. Finally, the culmination of the research resulted in a validated composite joint model that can ade-

quately predict failure modes of composite sandwich joints used in aerospace, marine and a range of emerging structural applications. Summaries for each of the presented chapters are included below, along with recommendations for future research utilizing the developed technologies.

Chapter 2 provided background information and a literature review of related reference material. This included the fundamentals of external and internal blast loads, an overview of current composite joint design technology, a summary of the UCSD Blast Simulator facility and its uses as well as a synopsis of relevant finite element material models and numerical modeling techniques.

Chapter 3 presented a series of experiments that led to the development of protocols for simulating confined blast loads on CFRP/balsa wood composite sandwich joints. Custom high strength water bladders were engineered that demonstrated the ability to generate pressure-time histories seen in internal blast scenarios, both temporally and spatially. Also incorporated in the experimental setup was the design of adjustable gripping fixtures that can be used to tailor specimen reaction forces and simulate larger scale structural environments. A set of five Blast Simulator experiments revealed the failure modes and damage progressions of the composite sandwich connection under simulated internal blast loadings.

The fourth chapter of the dissertation presented the results from a series of composite sandwich material tests conducted at UCSD's structural testing facilities. This included the development of methodologies to excite the sandwich material's dynamic failure properties both in shear and in bending, as well as a test setup that isolated the material's interlaminar strength and damage characteristics that govern initiation and progression of delamination.

In Chapter 5, the experimentally generated data was used for an in depth investigation on how to accurately simulate the dynamic failure modes of the highly non isotropic materials numerically. A complex finite element material model typically used to simulate failure and damage in wood under perpendicular-to-the-grain loadings was calibrated for use in predicting damage due to loading parallel-to-the-grain direction *via* the manipulation of fracture energy inputs. The numerical studies were also used to simulate both the initial and progression of delamination along the sandwich material's

facesheet/core interface.

The culmination of the experimental and numerical research conducted over the course of the preceding chapters was a high fidelity finite element model of the composite sandwich joint connection. The simulations of the Composite Joint Tests demonstrated the model's ability to capture the key phenomena that govern the composite joints resistance to high rate deformations and failures. It was found that the overall performance of the joint is highly dependant on the strength of the overlamine to facesheet interfacial bonds, which, when coupled with individual panel and stiffener to overlamine adhesion quality, created a very complex progression of structural damage. The validated numerical tools are currently being extrapolated into the prediction of composite joint connection behavior in larger scale structural environments, including the development of simplified numerical joint representations that can be used to predict damage propagation of full scale, high performance composite structures under severe blast loading conditions.

7.2 Recommendations for Future Work

This section provides recommendations for future work relevant to the simulation of blast loadings as well as structural testing methodologies that can be conducted from extrapolation of the research methods presented in this dissertation.

The use of fluid filled media to load structures has a range of experimental potentials in the realm of blast engineering. Some of the most challenging blast load cases to simulate that could be accomplished experimentally with this technology would be the extended pressure-time durations involved in vapor cloud explosions (VCE) and the development of quasi-static gas pressures due to un-vented internal explosions. The parameters varied in the presented research represent only a small fraction of possible bladder/impacting mass configurations and experimental setups that could be designed to simulate loads from explosions occupying any type of structural geometry. In the mechanical sense, the air compressed by a blast wave *is* a fluid, so any number of non-volatile materials with fluid like properties could be used in place of the water depending on the scenario of interest. The fluid-structure dynamics involved in these experiments

would also be of interest to computational fluid-structure interaction engineers and theorists.

The gripping fixture and reaction structure design could be used for the assessment of various types of structural connections and configurations. The west side of the Blast Simulator facility has the capability of utilizing up to four BGs mounted vertically, and therefore the methodology could be extended to joints with longer base and stem panels in an effort to simulate full scale rooms or compartments.

From a numerical standpoint, LS-DYNA's wood model proved to very versatile in modeling the transversely orthotropic properties of the balsa wood. The 29 available user inputs include methods for simulating plasticity and hardening, rate effects as well as the post peak softening investigated in Chapter 5. Further studies could be done to extract estimates on material properties difficult to measure experimentally.

Finally, the composite joint of interest in these studies was in a 90° configuration, and the experimental protocols could easily be extended to joints of other angles and as well as the variation of facesheets material such as glass-laminates or core materials such as foam and/or honeycombs which are very common in composite applications. The strength of the overlamine plays a tremendously critical role in the connection's resistance to failure and no failure was seen in any of outer skins of the panels. The results support the design criteria emphasized by Krauthammer and the guidelines set forth in the US Department of Defense's technical manuals: Connections should be designed so that individual structural members are able to reach full force and moment capacities prior to failure. It is recommended that engineers, manufacturers and end consumers of composite structures utilizing these types of connections allocate the time and resources to ensure that the quality and strength of the connection points are focused on in the early stages of design.

References

- [1] BAKER, W., COX, P., WESTINE, P., KULESZ, J., AND STREHLOW, R. *Explosion Hazards and Evaluation*. Elsevier, 1983.
- [2] BALA, D. *Tie-break Contacts in LS-DYNA*, 2007.
- [3] BALTEK. Baltek sb select grade structural balsa data sheet., 2012.
- [4] BANEJA, M., AND DASILVA, L. Adhesively bonded joints in composite materials: an overview. *J. Materials: Design and Applications* (2009).
- [5] BOLICK, R. Composite fabrication via the vartm process. Tech. rep., North Carolina A&T State University, 2004.
- [6] BRODE, H. Numerical solution of spherical blast waves. *J. of Applied Physics* (1955).
- [7] CHEN, A. Non-explosive simulated blast loading of composite sandwich beams. Master's thesis, University of California, San Diego, 2010.
- [8] CIOPOLLA, D. J., 2011. Personal communication.
- [9] CRANE, R. Intelligent processing and inspection of naval composites. *AMPTIAC Quarterly* (2003).
- [10] DANIEL, I., AND ISHAI, O. *Engineering Mechanics of Composite Materials*. Oxford University Press, 2006.
- [11] GALANIS, K. Hull construction with composite material for ships over 100 m in length. Master's thesis, Massachusetts Instituted of Technology, 2002.
- [12] GOUGEON BROTHERS INC. Vacuum bagging techniques. Tech. rep., West System, 2010.
- [13] GREGORY, F. Analysis of the loading and response of a suppressive shield when subjected to an internal explosion. In *Minutes of the 17th Explosives Safety Seminar* (1976).

- [14] GROVES, A., LYSTRUP, A., MCGEORGE, D., AND AANHOLD, H. Dynamic and static performance of composite t-joints. In *Symposium on Combat Survivability of Air, Space, Sea and Land Vehicles* (2002).
- [15] HAMITOUCHE, L., TARFAOIU, M., AND VAUTRIN, A. Design and test of a sandwich t-joint for naval ships. *J. Damage and Fracture Mechanics* (2009).
- [16] HEGEMIER, G., SIEBLE, F., ARNETT, K., RODRIGUEZ, T., OESTERLE, M., WOLFSON, J., GRAM, M., AND CLARK, A. The UCSD Blast Simulator. In *The 77th Shock and Vibration Symposium* (Monterey, 2006).
- [17] HEIDER, D., DEFFOR, H., GILLESPIE, J., MOHAMED, M., A., B., AND CRANE, R. Improved large-scale joint performance using 3-d woven non-crimp fabrics. Tech. rep., International Commotee on Composite Materials, 2009.
- [18] KRAUTHAMMER, T. Blast-resistant Structural Concrete and Steel Connections. *International J. of Impact Engineering* (1999).
- [19] LI, H., DHARMAWAN, F., HERZBERG, I., AND JOHN, S. Fracture behavior of composite maritime t-joints. *J. of Composite Structures* (2006).
- [20] LIVERMORE SOFTWARE TECHNOLOGY CORPORATION. *LS-DYNA Theory Manual*, 2006.
- [21] LIVERMORE SOFTWARE TECHNOLOGY CORPORATION. *LS-DYNA Keyword User's Manual*, 2007.
- [22] MAYS, G., AND SMITH, P. *Blast Effects on Buildings: Design of Buildings to Optimize Resistance to Blast Loading*. Thomas Telford, 1995.
- [23] MCGEORGE, D., VERITAS, D., LILLEBORGE, J., HOYNING, B., AND ELIASSEN, G. Survivable composite sandwich superstructures for naval applications. In *Proceedings of the International Conference of Sandwich Structures*. (2003).
- [24] MURRAY, Y. *Manual for LS-DYNA Wood Material Model 143*, 2007.
- [25] MURRAY, Y., REID, J., FALLER, R., AND BIELENBERG, B. *Evaluation of LS-DYNA Wood Material Model 143*, 2005.
- [26] NORTHROP GRUMMAN SHIPBUILDING. Resin infusion process, 2010. Online Image, www.compositesworld.com.
- [27] OESTERLE. *Blast Simulator Wall Tests: Experimental Methods and Mitigation Strategies for Reinforced Concrete and Concrete Masonry*. PhD thesis, University of California, San Diego, 2009.

- [28] PILIPCHUK, V., AND IBRAHIM, R. Analysis of crack formation in t-joint structures under dynamic loading. *J. of Vibration and Control* (2010).
- [29] PLASTICS, G. General plastics fr-3707 technical data sheet., 2012.
- [30] PROCTOR, J. Internal blast damage mechanisms computer program. Tech. Rep. AD-759 002, Naval Ordnance Laboratory, 1972.
- [31] RANKINE, W. Phil. trans. *Roy. Soc.* 160 (1870).
- [32] RODRIGUEZ, T. *Experimental Simulations of Explosive Loading on Structural Components: Reinforced Concrete Columns with Advanced Composite Jackets*. PhD thesis, University of California, San Diego, 2006.
- [33] SMITH, P., AND HERRINGTON, J. *Blast and Ballistic Loading of Structures*. Butterworth-Heinemann, 1994.
- [34] STEWART, L. *Testing and Analysis of Structural Steel Columns Subjected to Blast Loads*. PhD thesis, University of California, San Diego, 2010.
- [35] THEOTOKOGLU, E., AND MOAN, T. Experiment and numerical study of composite t-joints. *J. of Composite Materials* (1996).
- [36] TOFTEGAARD, H., AND LYSTRUP, A. Design and test of lightweight composite sandwich t-joint for naval ships. *J. of Composites* (2004).
- [37] UNITED STATES DEPARTMENT OF DEFENSE. *United Facilities Criteria TM 3-340-02: Structures to Resist the Effects of Accidental Explosions*, 2002.
- [38] VAIDYA, U., AND DEK, L. Single and multisite impact response of s2-glass/epoxy balsa wood core sandwich composites. *Major Accomplishments in Composite Materials and Sandwich Structures* (2009).
- [39] WHISLER, D., CHEN, A., KIM, H., HUSON, P., AND ASARO, R. Methodology for exciting dynamic shear and moment failure in composite sandwich beams. *J. of Sandwich Structures and Materials* (2012).
- [40] WU, E. Application of fracture mechanics to anisotropic plates. *J. Applied Mechanics* (1967).