DAMAGE MECHANICS-BASED MODEL FOR THE DEFORMATION RESPONSE AND FAILURE OF COMPOSITE HONEYCOMB CORE STRUCTURE

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ABSTRACT

The development of phenolic resin-based *Nomex* hexagonal Honeycomb (HC) structures is of great interest in recent years for low density, low in-plane, and high out-of-plane stiffness values achieving stable deformations over a wide range of structural geometries. Nonlinear elastic behavior covering the large geometric deformation is the critical issue in analyzing the mechanical response and failure of the cellular core structure. A useful approach for modeling such complex behavior is to replace the cellular structure with an equivalent homogenous material that represents identical mechanical behavior for the respective HC structure. This research aims to develop a Representative Cell (RC) model for the Nomex HC core and subsequently replace that with a homogenous orthotropic material of equivalent elastic properties utilizing the homogenization approach. A series of experimental testing was performed on the HC core to identify the nine elastic constants comprising both inplane and out-of-plane properties. The single unit cell structure is selected based on the parametric analysis through compression testing of the hexagonal HC cores with different cell geometries to compare the compression strength and energy absorption capacity. The selected cell geometry with 3.2 mm cell size, 12.7 mm height, and 0.05 mm paper thickness is used to develop a meso-scale solid element RC model to show the mechanical deformation under out-of-plane compression and shear loading. The constituent orthotropic material model along with Hashin damage parameters was used as input for phenolic resin-based *Nomex* paper in ABAQUS finite element analysis software. A direct homogenization method was employed to develop a homogenized equivalent homogenized honeycomb core (EHC) model. The model is examined to assess the predicted equivalent elastic properties against the stiffness matrix obtained by experimentation. The comparative analysis for the Nomex HC structural characterization showed that the geometric configurations, specifically the relative density and cell aspect ratio (height/cell size), greatly influence the mechanical properties. The optimum values obtained for the elastic moduli and compression strength were 126.5 MPa and 4.01 MPa, respectively, with a relative density of 0.056 and a cell aspect ratio of 3.96. Compared with the experimental testing results from compression loading, the developed damage mechanics-based RC model demonstrated less than a 2% difference in the collapse/compression strength and elastic moduli of the selected HC core. The EHC model was verified using a threepoint bend loading condition. The predicted flexural strength compared to the measured data had a minimal variation of only 4%. The developed EHC model can be effectively used to predict the mechanics of deformation and failure properties in the complex sandwich structures. The damage mechanics-based methodology presented in this research work could be implemented for complex structural parts in the aerospace and transport industry for reducing the need of extensive experimental testing eventually minimizing the developmental cost and time.

ABSTRAK

Pembangunan struktur indung madu heksagon Nomex berasaskan resin fenolik mula mendapat perhatian dalam beberapa tahun kebelakangan ini kerana nilai ketumpatannya yang rendah, sifat kekukuhan yang rendah di dalam satah dan tinggi di luar satah membolehkan deformasi yang stabil dalam pelbagai struktur geometri. Ciri-ciri elastik bukan lelurus yang merangkumi deformasi geometri besar adalah masalah penting dalam menganalisa tindak balas mekanikal dan kegagalan struktur teras selular. Pendekatan yang berguna bagi pemodelan ciri-ciri kompleks seperti itu adalah dengan mengganti struktur selular dengan bahan homogen yang setara yang mewakili ciri-ciri mekanikal yang sama untuk struktur HC masing-masing. Objektif penyelidikan ini adalah untuk membangunkan model Cell Perwakilan (RC) untuk teras Nomex HC dan seterusnya menggantinya dengan bahan ortotropik homogen yang mempunyai ciri-ciri elastik yang setara dengan menggunakan pendekatan homogenisasi. Siri ujian eksperimen dilakukan pada teras HC untuk mengenal pasti sembilan pemalar elastik yang terdiri daripada sifat dalam dan luar satah. Struktur sel unit tunggal dipilih berdasarkan analisis parametrik melalui ujian mampatan teras HC heksagon dengan geometri sel yang berbeza untuk membandingkan kekuatan mampatan dan kapasiti penyerapan tenaga. Geometri sel yang dipilih dengan ukuran sel 3.2 mm, tinggi 12.7 mm dan ketebalan kertas 0.05 mm telah digunakan untuk membangunkan model RC elemen pepejal berskala meso untuk menunjukkan deformasi mekanikal di bawah pemampatan luar satah dan beban ricih. Model bahan berunsur ortotropik bersama dengan parameter kerosakan Hashin digunakan sebagai input untuk kertas Nomex berasaskan resin fenolik dalam perisian ABAQUS. Kaedah homogenisasi langsung digunakan untuk membangunkan model teras HC yang homogen. Model tersebut diperiksa untuk menilai sifat elastik setara yang dijangkakan terhadap (EHC) matriks kekukuhan yang diperoleh melalui eksperimen. Analisa perbandingan untuk pencirian struktur Nomex HC menunjukkan bahawa konfigurasi geometri khususnya kepadatan relatif dan nisbah aspek sel (ketinggian/saiz sel) sangat mempengaruhi ciri-ciri mekanikalnya. Nilai optimum yang diperoleh untuk moduli elastik dan kekuatan mampatan masing-masing adalah 126.5 MPa dan 4.01 MPa, dengan ketumpatan relatif 0.056 dan nisbah aspek sel 3.96. Model RC berasaskan mekanik kerosakan yang telah dibangunkan tersebut, apabila dibandingkan dengan hasil ujian eksperimen dari beban mampatan menunjukkan perbezaan kurang dari 2% dalam kekuatan keruntuhan/mampatan dan moduli elastik teras HC yang dipilih. Model teras HC homogen yang setara telah disahkan menggunakan kaedah beban lentur tiga titik. Kekuatan lenturan yang dijangkakan berbanding dengan data yang diukur mempunyai variasi yang sangat kecil iaitu hanya 4%. Model teras EHC yang telah dibangunkan dapat digunakan dengan berkesan untuk meramalkan mekanisma sifat ubah bentuk dan kegagalan dalam struktur himpitan yang kompleks. Metodologi berasaskan mekanik kerosakan yang disajikan dalam karya penyelidikan semasa dapat dilaksanakan untuk komponen struktur yang kompleks di industri aeroangkasa dan pengangkutan untuk mengurangkan keperluan pengujian eksperimen yang luas akhirnya meminimumkan kos dan waktu pembangunan.

TABLE OF CONTENTS

TITLE

DECLARATION	iii
DEDICATION	iv
ACKNOWLEDGEMENT	v
ABSTRACT	vi
ABSTRAK	vii
TABLE OF CONTENTS	viii
LIST OF TABLES	xiii
LIST OF FIGURES	xiv
LIST OF ABBREVIATIONS	xxi
LIST OF SYMBOLS	xxii
LIST OF APPENDICES	xxvi

CHAPTER 1	INTRODUCTION	1
1.1	Honeycomb Core Structure	1
1.2	Research Background	3
1.3	Statement of Research Problem	6
1.4	Research Objectives	7
1.5	Scope of the study	7
1.6	Significance of the Study	10
1.7	Thesis Layout	10
CHAPTER 2	LITERATURE REVIEW	15
2.1	Introduction	15
2.2	HC Core as Part of the Sandwich Structure	15
2.3	Geometry of Cellular HC Cores	17
2.4	Materials Used for HC Cores	19
	2.4.1 Aluminum	20
	2.4.2 <i>Nomex</i> Paper	21

2.5	Mecha	anical Beha	vior and Structure Properties of HC Core	23
	2.5.1	Deformat	ion Response and Failure Mechanisms	23
	2.5.2	Effects of	Geometric Parameters	28
2.6	Finite	Element M	Iodeling for HC Core Structure	30
	2.6.1	Represent	ative Cell Models	32
	2.6.2	Constituti	ve Material Models	34
		2.6.2.1	Single Layer Isotropic	34
		2.6.2.2	Single Layer Orthotropic	35
		2.6.2.3	Multi-Layer Resin Coating	37
2.7	Dama	ge Mechan	ics-Based Analysis of HC Core Structure	41
	2.7.1	Failure C	riteria for Composite Materials	43
		2.7.1.1	Hashin Damage Model Criteria	46
2.8	Homo	genization	Concepts for HC Core Structure	49
	2.8.1	Out-of-Pl	ane Elastic Constants	53
	2.8.2	In-Plane I	Elastic Constants	55
	2.8.3	Strain En	ergy-based Homogenization Approach	57
2.9	Summ	nary		58
CHAPTER 3	RESI	EARCH M	ETHODOLOGY	61
3.1	Introd	uction		61
3.2	Resear	rch Framev	vork	61
3.3	Extrac	ction of <i>No</i>	mex Paper Material Properties	64
3.4	HC Co	ore Cellula	r Configuration and Geometric Parameters	66
3.5	Mecha	anical Test	Procedures for HC Core	67
	3.5.1	Flatwise 7	Tension Test	68
	3.5.2	Flatwise (Compression Test	69
	3.5.3	Shear Tes	t	70
	3.5.4	Edgewise	Tension Test	73
	3.5.5	Three-Poi	nt Bend Test of Sandwich HC Panel	74
3.6	Dama	ge-Based R	Representative Cell Model for HC Core	76
	3.6.1	Represent	ative Unit Cell Models	77
	3.6.2	Boundary	Conditions and Load Cases	78

		3.6.3	Material	Properties and Damage Model Parameters	79
		3.6.4	Mesh Co	nvergence Analysis	81
		3.6.5	Element	Type Selection	82
		3.6.6	Represen	tative Cell FE Model Validation	84
	3.7	Devel	opment of	Equivalent Homogenized HC Core Model	84
		3.7.1	Represen	tative Structures	85
		3.7.2	Element for EHC	Type, Mesh Size and Boundary Conditions Models	87
		3.7.3	Extractio	n of Structural Properties	89
			3.7.3.1	Elastic Constants for Stiffness Matrix	90
			3.7.3.2	Structural Damage Model Parameters	90
		3.7.4	EHC Mo	del Verification	91
	3.8	Summ	nary		93
СНАРТЕ	CR 4	MEC HON	CHANICA EYCOMI	L PROPERTIES AND BEHAVIOR OF 3 CORE STRUCTURE	95
	4.1	Introd	uction		95
	4.2	Tensil	e Propertie	es of Phenolic Resin-Based Nomex Paper	95
		4.2.1	Elastic C	onstants	96
		4.2.2	Damage	Model Parameters	97
	4.3	Defor Struct	mation Res ures	sponses and Failure Mechanism of HC Core	98
		4.3.1	Out-of-P	ane Tension	99
		4.3.2	Out-of-P	ane Compression	101
		4.3.3	Out-of-P	ane Shear	104
		4.3.4	In-Plane	Tension	106
		4.3.5	In-Plane	Shear	108
	4.4	Flexu Bendi	re Respons ng	e of HC Sandwich Panel Under Three-Point	110
	4.5	Summ	nary		111
СНАРТЕ	CR 5	EFFI DEN FAII	ECTS OF SITY ON JIRE OF	CELL ASPECT RATIO AND RELATIVE THE DEFORMATION RESPONSE AND HONEYCOMB CORE	113
	5.1	Introd	uction		113

5.2	Effects of Design Parameters on the Structural Properties	113
	5.2.1 Relative Density	115
	5.2.2 Cell Height	116
	5.2.3 Hexagonal Cell Size	118
5.3	Comparative Analysis of Mechanical Properties	120
	5.3.1 Effects on the Elastic Modulus	120
	5.3.2 Dissipated Energy Density Comparison	121
	5.3.3 Phenomenological Model for the Compressive Strength of HC Core	122
5.4	Summary	130
CHAPTER 6	REPRESENTATIVE CELL ANALYSIS FOR DAMAG BASED FAILURE MODEL OF HONEYCOMB CORE UNDER OUT-OF-PLANE LOADINGS	E- 133
6.1	Introduction	133
6.2	Failure under the Out-of-Plane Tension	133
6.3	Out-of-Plane Compression Responses	139
6.4	Out-of-Plane Shear Failure	146
	6.4.1 In Transverse Orientation	147
	6.4.2 In Ribbon Orientation	153
6.5	Comparative Analysis of Out-of-Plane Mechanical Propertie	s 158
6.6	Summary	160
CHAPTER 7	DEVELOPMENT OF EQUIVALENT HOMOGENIZEI HONEYCOMB CORE MODEL) 163
7.1	Introduction	163
7.2	Equivalent Homogenized HC Core (EHC) Model	163
	7.2.1 Structural Properties for EHC Model	164
	7.2.2 Elastic Constants and its Comparison with Theoretical Models	165
	7.2.3 Damage Model Parameters	166
7.3	Damage Mechanics-Based Equivalent HC Core Model Results	167
	7.3.1 Multi-Cell Equivalent Model	168
	7.3.2 Single-Cell Equivalent Model	172

7.4	Verification of EHC Model	178
	7.4.1 Sandwich HC Panel FE Model Failure Analysis	180
7.5	Summary	184
CHAPTER 8	CONCLUSIONS AND RECOMMENDATIONS	185
8.1	Conclusions	185
8.2	Contribution of the Work	187
8.3	Recommendations for Future Work	188
REFERENCES		189
LIST OF PUBLI	CATIONS	208

LIST OF TABLES

TABLE NO.	TITLE	PAGE
Table 2.1	Hexagonal HC core geometric parameters [67-69]	19
Table 2.2	Review summary of material models used for FE analysis of <i>Nomex</i> HC core structure	39
Table 3.1	HC cell configuration	67
Table 3.2	Strength properties of phenolic resin impregnated Nomex paper	80
Table 3.3	Comparison of the computational parameters used for the FE Single-Cell model under tension with conventional and continuum shell elements.	84
Table 3.4	EHC FE model parameters	89
Table 3.5	Extraction of damage initiation parameters from measured data and numerical analysis of real HC core structure	91
Table 3.6	Element types and distribution for the three-point bend numerical model	93
Table 4.1	Properties of phenolic resin impregnated Nomex paper	97
Table 4.2	Constitutive damage model parameters of polymeric <i>Nomex</i> paper	98
Table 4.3	Mechanical properties of <i>Nomex</i> HC* core structure in different load orientations	112
Table 5.1	Specifications of the HC core specimens	114
Table 6.1	Comparison in mechanical properties (compression loading)	141
Table 6.2	Mechanical properties for all FE models compared to the measured data	159
Table 7.1	Comparison of out of plane elastic constants for <i>Nomex</i> HC core	166
Table 7.2	Structural properties for EHC model	167
Table 7.3	Comparison of EHC model mechanical properties with measured data	180

LIST OF FIGURES

FIGURE NO	TITLE	PAGE
Figure 1.1	Honeycomb (HC) core application in sandwich panel	2
Figure 1.2	(a) HC application in airframe structure (Airbus A380), (b) wooden surfboard and (c) Non-pneumatic tire with HC spokes [21]	2
Figure 2.1	HC core cellular configurations [1]	18
Figure 2.2	Hexagonal HC core cellular configuration [69]	18
Figure 2.3	Paper-based hexagonal HC core manufacturing process [1, 29]	23
Figure 2.4	Failure modes of HC core sandwich panel under flexure load [109]	25
Figure 2.5	Tensile and compressive load-displacement curves of the resin-impregnated fiber-reinforced paper HC core [24-25, 29].	26
Figure 2.6	Out-of-plane compression load-displacement responses with different cell size for HC cores (a) aluminum, (b) <i>Nomex</i> [27]	27
Figure 2.7	Classification of multiscale methods for numerical modeling of HC core structure.	31
Figure 2.8	Representative cell (RC) models for hexagonal HC core [29].	33
Figure 2.9	Material modeling approaches for phenolic resin-based <i>Nomex</i> HC core structure [27, 29, 36, 50]	34
Figure 2.10	Stress-strain relationship for different material models; (a) Linear elastic isotropic material [25] and (b) Liner elastic orthotropic material [29]	35
Figure 2.11	Phenolic resin impregnation in the <i>Nomex</i> HC core specimen [94]	37
Figure 2.12	Mechanics of materials and analysis classification (based on [134, 135])	42
Figure 2.13	Longitudinal and transverse orientation in a composite lamina [40]	44
Figure 2.14	Bi-linear softening laws for composite lamina [40]	48

Figure 2.15	Bi-linear traction-separation curve for Mode I loading of a composite lamina [135].	49
Figure 2.16	Hexagonal HC core; (a) RVE single-cell and (b) Equivalent homogenized volume [147]	51
Figure 2.17	Illustration of the out-of-plane elastic constants for the HC core [70]	53
Figure 3.1	Flowchart of the research activities	62
Figure 3.2	Phenolic resin-based <i>Nomex</i> paper (a) tension test setup, (b) geometry of the specimen.	65
Figure 3.3	Hexagonal HC core	66
Figure 3.4	(a) The assembly of the HC sandwich specimen in the flatwise tensile test jig, and (b) the HC sandwich specimen with the loading blocks.	68
Figure 3.5	HC core flatwise compression test setup	70
Figure 3.6	(a) HC core out-of-plane shear loading jig, (b) ribbon orientation (G_{13}) and (c) transverse orientation (G_{23}).	71
Figure 3.7	HC core in-plane shear test setup	72
Figure 3.8	Fabricated jigs for hexagonal HC core in-plane tension loading	73
Figure 3.9	HC core test setup for in-plane tension loading, (a) Ribbon orientation (X_1) and (b) Transverse orientation (X_2).	74
Figure 3.10	Schematic diagram and sandwich specimen dimensions,	76
Figure 3.11	Sandwich HC panel three-point bend test (3PBT) setup.	76
Figure 3.12	(a) Single-Cell and (b), (c) Multi-cell models for the out- of-plane tension and compression, and (d), (e) 6-cell model for the out-of-plane shear in the transverse and ribbon direction, respectively.	78
Figure 3.13	(a) Cell wall thickness of the HC core at different magnification and (b) distribution of the wall thickness of the HC cell.	80
Figure 3.14	Mesh convergence analysis outcomes based on the out-of- plane compressive load case with the Single-Cell model.	82
Figure 3.15	Conventional and continuum shell element description	83
Figure 3.16	Comparison of the FE-calculated responses of the Single- Cell model with the measured curve for the tensile load	0.2
F ' 2.17		83
Figure 3.17	Multi-Cell EHC model	86

Figure 3.18	Single-Cell (RC-1) replaced by Single-Cell EHC model with same geometric dimensions.	87
Figure 3.19	EHC models with boundary conditions (a) Single-Cell (mesh size: 0.2) and (b) Multi-Cell (mesh size: 1)	88
Figure 3.20	Mesh convergence for Multi-Cell EHC model	88
Figure 3.21	Three-point bend FE model geometry and boundary conditions	92
Figure 4.1	Phenolic resin-based Nomex paper tension test graphs	97
Figure 4.2	Tensile load-displacement curves of the HC core with CFRP face sheets.	100
Figure 4.3	HC Sandwich Specimen (a) before the flatwise tension test and (b) at the end of the test.	101
Figure 4.4	Load-displacement curves of the HC core under flatwise compressive loading	102
Figure 4.5	The geometry (side view) of the HC core specimen at the various stages of the flatwise compression test. Refer to Figure 4.4 for the corresponding load and displacement values.	103
Figure 4.6	(a) The as-received hexagonal HC core, and (b) after the flatwise compression test.	103
Figure 4.7	Out-of-plane shear load-displacement curves of the HC core with the transverse and ribbon orientation.	104
Figure 4.8	Deformed and fracture features of the HC core with transverse orientation (a, b and c) and ribbon orientation (d, e and f) under the out-of-plane shear loading. The corresponding loading stage is as indicated in Figure 4.7.	105
Figure 4.9	In-plane tension load-displacement curves of the HC core. (a) Transverse orientation, X_2 , (b) Ribbon orientation, X_1	107
Figure 4.10	Fracture features of the in-plane tensile test specimens of the HC core with (a) Transverse orientation, X_2 , (b) Ribbon orientation, X_1	108
Figure 4.11	In-plane shear load-displacement curves of the HC core.	109
Figure 4.12	Fracture of cell walls during in-plane shear loading of HC core	110
Figure 4.13	(a) Flexure load-displacement response and (b) sandwich HC core panel testing	111
Figure 5.1	Stress-strain curves of the HC cores with different relative densities (Cell aspect ratio, $H/c = 3.96$).	115

Figure 5.2	Failure features of the HC core specimens at a different relative density of (a) 0.056 (B2) and (b) 0.112 (C2). The cell height, $H = 12.7$ mm.	116
Figure 5.3	Stress-strain curves of the HC cores with different cell aspect ratio, H/c ($c = 3.2$ mm, $\rho^*/\rho_s = 0.056$)	117
Figure 5.4	Failure features of the HC core specimens with different cell heights of (a) 8 mm (specimen B1) and (b) 18 mm (specimen B3).	118
Figure 5.5	Comparison of the stress-strain curves for different cell size; Specimen A2 ($c = 4.8 \text{ mm}$, $\rho^*/\rho_s = 0.028$) and specimen B2 ($c = 3.2 \text{ mm}$, $\rho^*/\rho_s = 0.056$).	119
Figure 5.6	Before and after compression fractographs of specimen A2 ($c = 4.8 \text{ mm}, \rho^* / \rho_s = 0.028$)	119
Figure 5.7	Variations of elastic modulus with the cell aspect ratio and relative density of the HC core.	121
Figure 5.8	Variation of the dissipation energy density with the cell aspect ratio of the <i>Nomex</i> HC cores	122
Figure 5.9	The variation of compressive strengths with the relative density of the <i>Nomex</i> HC cores. The filled symbols represent data from the current study	123
Figure 5.10	Variations of compressive strengths with cell aspect ratio and relative density of HC core.	124
Figure 5.11	$\ln \sigma c$ versus $1H/c$, where $(H/c \le 3.96)$. $(H/c = 3.96)$ is considered as starting point).	125
Figure 5.12	Compressive Strength, σc vs $1H/c$	127
Figure 5.13	$\ln \sigma c$ versus $1H/c$, where $(H/c > 3.96)$	127
Figure 5.14	Illustration of the phenomenological model in Eqn. (5.15) and (5.16).	129
Figure 5.15	Graphical illustration of the effects of relative density and cell aspect ratio on the compressive strength of HC core: (a) $H/c > 3.96$, $r^2 = 0.9768$ and (b) $H/c \le 3.96$, $r^2 = 0.9752$.	130
Figure 6.1	Comparison of FE-calculated and measured tensile responses of the HC core	134
Figure 6.2	(a) Damage initiation and evolution to separation, and (b) the corresponding stresses at the critical material point in the cell wall of the HC core.	135

Figure 6.3	(a) Damage evolution at $dpmt = 1$ and (b) max principal stress contours of Single-cell FE model with increasing displacement.	136
Figure 6.4	(a) Location of the fractured plane along the cell height and(b) fractured surface of the polymer hexagonal HC core specimen following the out-of-plane tensile loading.	137
Figure 6.5	(a) Damage evolution $(dpmt = 1)$ and (b) Maximum principal stress contours of 4-Cell FE model with increasing displacement.	138
Figure 6.6	The measured compressive load-displacement responses of the HC core panel with different sizes (core thickness, $H = 12.7$ mm).	139
Figure 6.7	Comparison of the measured and the FE-calculated compressive load-displacement responses for the different FE models of the HC core.	140
Figure 6.8	(a) Evolution of the matrix damage variable to the onset of damage and subsequent damage evolution, (b) contour of the damage at the start of the global buckling of the HC cell.	142
Figure 6.9	Contours of the minimum principal stress in the single-cell and 4-cell HC core model. Values plotted correspond to the onset of localized buckling of the critical material points in the cell wall	143
Figure 6.10	Distribution of minimum principal stress in the cell wall material (Top) and deformation (Bottom) during the out-of- plane compression test of the one-cell specimen. (a) matrix damage, $dpmc = 0$, following damage initiation, (b) $dpmc = 0.75$, showing wrinkling of the unconstrained cell walls, and (c) $dpmc = 1.0$, with the occurrence of the first fold.	145
Figure 6.11	Total displacement fields following the densification of the single-cell FE model.	146
Figure 6.12	Comparison of the measured and FE-calculated out-of- plane shear stress-strain responses of the HC core	147
Figure 6.13	(a) Failed HC core specimen under the out-of-plane shear in the transverse direction, illustrating the critical shear plane, and (b) the corresponding FE-calculated shear stress in the HC core model.	148
Figure 6.14	Similar variation of the shear stress τ_{23} and the maximum principal stress along the shearing plane (Path 2), indicating the pure shear test condition.	148

Figure 6.15	(a) Minimum principal stress, and (b) the matrix compressive damage contour, corresponding to the applied shear displacement of 0.33 mm.	149
Figure 6.16	(a) Shear load-displacement response in the transverse direction, (b) Evolution of damage initiation and subsequent damage for the material point marked C in Figure 6.15 (b), and (c) Evolution of stresses of the HC core	150
Figure 6.17	(a) Evolution of damage and stresses for the material point marked as Node D, (b) Matrix tension damage contour and (c) Maximum principal stress distribution, corresponding to the applied shear displacement of 0.33 mm in Figure 6.16(a).	152
Figure 6.18	Damage evolution contours at 0.59mm displacement (see Figure 6.16 and Figure 6.17 (a)) in transverse orientation shear load for (a) Matrix compression and (b) Matrix tension.	153
Figure 6.19	(a) Failed HC core specimen under the out-of-plane shear in ribbon direction, illustrating the critical shear plane, and (b) the corresponding FE-calculated shear stress in the HC core model.	154
Figure 6.20	Variation of the shear stress, τ_{13} and the maximum principal stress along (a) Path 3 (shearing plane), and (b) Path 4 of the HC core model.	154
Figure 6.21	(a) Maximum principal stress, and (b) the matrix tension damage initiation contour, corresponding to the applied shear displacement of 0.33 mm.	155
Figure 6.22	(a) Shear load-displacement response in Ribbon direction,(b) Evolution of damage initiation and subsequent damage for the material point marked E in Figure 6.21 (b), and (c) Evolution of stresses during the shear test	156
Figure 6.23	(a) Evolution of damage and stresses for the material point marked as Node F, (b) Matrix compression damage contour and (c) Minimum principal stress distribution at the applied shear displacement of 0.45 mm in Figure 6.22 (a).	157
Figure 6.24	(a) Matrix tension damage evolution at $dpmt = 1$ and (b) Maximum principal stress corresponding to the displacement of 0.6 mm (see Figure 6.22 (a)) in Shear Load (Ribbon Orientation).	158
Figure 6.25	Comparison of relative wall-clock time taken by the different cell models for the out-of-plane load cases.	160

Figure 7.1	Out-of-Plane Compression load-displacement plots for the Multi-Cell HC Core FE models and measured data	169
Figure 7.2	Multi-Cell EHC model damage initiation and Stress plots. Contours are shown in (b) and (c) for peak load at 0.37 mm displacement.	170
Figure 7.3	Contours at 1 mm displacement for (a) Minimum principal stress and (b) Matrix compression damage evolution, $dpmc = 0.95$	171
Figure 7.4	Total displacement in Multi-Cell EHC model following the crushing due to compression loading.	171
Figure 7.5	Out-of-Plane compression load-displacement plots for the Single-Cell HC Core FE models and measured response.	173
Figure 7.6	Single-Cell EHC model response under out-of-plane compression (a) Damage and stresses plots at Node K. Contours at 0.33 mm displacement for (b) Damage initiation and (c) Minimum principal stress.	174
Figure 7.7	Matrix compression damage evolution (<i>dpmc</i> =1) at 0.5 mm displacement, (a) Single-cell EHC Model, (b) Single-Cell (RC-1) Model	175
Figure 7.8	Deformed and undeformed geometry of the Single-Cell EHC model	176
Figure 7.9	Comparison of compression load-displacement graphs of EHC FE models and the measured data, including the crushing zone (plateau stress).	177
Figure 7.10	EHC models responses with the increase in the number of cells. (The dashed lines represent the measured value)	178
Figure 7.11	Three-point bend loading response of sandwich HC structure	179
Figure 7.12	Sandwich HC panel in three-point bend loading; (a) Maximum principal stress in face-sheets, (b) Minimum principal stress in EHC and (c) Deformed specimen after experimentation	181
Figure 7.13	Damage initiation graphs and stress plots for matrix region in the equivalent HC core of the sandwich panel. The nodes are identified in Figure 7.14.	182
Figure 7.14	Damage initiation contours in EHC model; (a) Matrix compression and (b) Matrix tension.	183
Figure 7.15	EHC model deformation in matrix tension region (a) Damage evolution ($dpmt = 1$), (b) Shear stress field.	183

LIST OF ABBREVIATIONS

HC	-	Honeycomb
GFRP	-	Glass fiber reinforced polymer
CFRP	-	Carbon fiber reinforced polymer
FE	-	Finite element
RVE	-	Representative volume element
RC	-	Representative cell
3D	-	Three-Dimensional
ABS	-	Acrylonitrile butadiene styrene
PLA	-	Polylactic acid
Al-Li	-	Aluminum Lithium
HOBE	-	Honeycomb before expansion
S4R	-	4 node shell element with reduced integration
C3D8R	-	Continuum 3 D Solid element with reduced integration
LTC	-	Lee and Tsotsis criteria
SVS	-	Shell-volume-shell
3PBT	-	Three-point bend test
ASTM	-	American Standard for Testing of Materials
SC8R	-	Continuum 8 node shell element
DOF	-	Degree of freedom
CPU	-	Central processing unit
EH	-	Equivalent homogenous
DED	-	Dissipation energy density
EHC	-	Equivalent homogeneous honeycomb core
MT	-	Matrix Tension
MC	-	Matrix Compression

LIST OF SYMBOLS

l	-	Cell wall length
С	-	Cell size
t	-	Paper thickness
θ	-	Core angle
L	-	Panel length
W	-	Panel width
Н	-	Core height
ho*	-	Density of the core
$ ho_s$	-	Cell wall material density
t	-	Cell wall thickness
E _{iso}	-	Young's modulus for Isotropic material
σ_{yield}	-	Yield strength for isotropic material
v_{iso}	-	Poisson's ratio for isotropic material
E ₁	-	Elastic Modulus in the longitudinal direction
E ₂	-	Elastic Modulus in the transverse direction
E ₃	-	Elastic Modulus in out-of-plane orientation
$\sigma_{1,T}$	-	Tensile strength in the longitudinal direction
$\sigma_{2,T}$	-	Tensile strength in the transverse direction
$\sigma_{1,C}$	-	Compression strength in the longitudinal direction
$\sigma_{2,C}$	-	Compression strength in the transverse direction
σ_{11}	-	Stress in the fiber direction
σ_{22}	-	Stress in the transverse direction
$ au_{12}$	-	Shear stress
E11	-	Strain in the fiber direction
E22	-	Strain in the transverse direction
γ12	-	Shear strain
Χ	-	Longitudinal strength
Y	-	Transverse strength
S	-	Shear strength
X_E	-	Maximum allowable strain in the longitudinal direction

Y_E	-	Maximum allowable strain in the transverse direction
S_E	-	Maximum allowable shear strain
X^T	-	Longitudinal tensile strength
Y^T	-	Transverse tensile strength
S^T	-	Longitudinal shear strength
X^C	-	Longitudinal compressive strength
Y^C	-	Transverse compressive strength
S^C	-	Transverse shear strength
d_f^t	-	Damage initiation variable for fiber tension
d_f^c	-	Damage initiation variable for fiber compression
d_m^t	-	Damage initiation variable for matrix tension
d_m^c	-	Damage initiation variable for matrix compression
d_p^{mt}	-	Damage evolution variable for matrix tension
d_p^{mc}	-	Damage evolution variable for matrix compression
d_p^{ft}	-	Damage evolution variable for fiber tension
d_p^{fc}	-	Damage evolution variable for fiber compression
Κ	-	Stiffness
Ν	-	Mode I strength
δ^0_N	-	Relative displacement at the damage onset
δ^f_N	-	relative displacement at the fracture
G_{1C}	-	Mode I fracture energy
E_{11}	-	Elastic modulus in the ribbon direction
E_{22}	-	Elastic modulus in the transverse direction
<i>E</i> 33	-	Elastic modulus in the thickness direction
G_{12}	-	In-plane shear modulus
G_{13}	-	Out-of-plane shear modulus
G_{23}	-	Out-of-plane shear modulus in the thickness direction
<i>V</i> 12	-	In-plane Poisson's ratio
V13	-	In-plane Poisson's ratio
<i>V</i> 23	-	Out-of-plane Poisson's ratio in the thickness direction
σ_{33}	-	Stress in the out-of-plane loading
E33	-	Strain in the out-of-plane loading

ε_{11}	-	Strain in the longitudinal (fiber) direction
E ₂₂	-	Strain in the transverse (matrix) direction
T 13	-	Shear strength in the ribbon direction
<i>γ13</i>	-	Shear strain in the ribbon direction
$ au_{23}$	-	Shear strength in the transverse direction
<i>Y23</i>	-	Shear strain in the transverse direction
Es	-	Elastic modulus of the material
G_s	-	Shear modulus of the material
ν_s	-	Poisson's ratio of material
V	-	Volume of the representative volume element
$\underline{\underline{\sigma}}(\underline{x})$	-	Stress at a material point (\underline{x})
$\underline{\epsilon}(\underline{x})$	-	Strain at a material point (\underline{x})
Σ	-	Equivalent stress for macro-scale homogeneous material
<u>E</u>	-	Equivalent strain for macro-scale homogeneous material
F_z^{fcu}	-	Ultimate flatwise compressive strength (MPa)
P_{max}	-	Ultimate force before failure
Α	-	Cross-sectional area
τ	-	Core shear stress
Р	-	Applied load
γ	-	Core shear strain
и	-	Displacement between the loading plates
F_s^{ult}	-	Core ultimate shear strength
d	-	Sandwich thickness
b	-	Sandwich width
δ^{0}_{eq}	-	Equivalent displacement at the onset of damage
δ_{eq}	-	Equivalent displacement at any step
δ^{f}_{eq}	-	Equivalent displacement at the fracture
G_{XT}	-	Longitudinal tensile fracture energy
G_{XC}	-	Longitudinal compressive fracture energy
G_{YT}	-	Transverse tensile fracture energy
G_{YC}	-	Transverse compressive fracture energy

$\sigma_{min.p}$	-	Minimum principal stress
∞	-	Infinity
G_C	-	Equivalent dissipation energy
E_T	-	Tensile strength of the HC core
E _c	-	Compression strength of the HC core
σ_T	-	Tensile strength of HC core
σ_{C}	-	Compression strength of HC core
X_1	-	Ribbon direction
X_2	-	Transverse direction
n	-	Exponent for relative density
α	-	Exponent for cell aspect ratio
С	-	Constant
α_{avg}	-	Average of the exponent for cell aspect ratio
U_3	-	Displacement in out-of-plane direction

LIST OF APPENDICES

APPENDIX	TITLE	PAGE
Appendix A	Hexagonal Jig Designs for In-Plane Tensile Test	203
Appendix B	Damage at Different Paths in Single-Cell EHC Model	206
Appendix C	Compression Load/Displacement Plots of EHC Models	207

CHAPTER 1

INTRODUCTION

1.1 Honeycomb Core Structure

Honeycomb (HC) sandwich panels have found numerous engineering applications in the aerospace and transportation industry. This is primarily due to their high strength-to-weight ratio, high structural stiffness, and improved resistance to the harsh operating environment [1]. Also, these lightweight structures offer an excellent capability to withstand through-thickness compression. The HC sandwich panel is constructed by laminating a HC cellular core structure's outer surfaces with thin and stiff face sheets. The face sheets are glued together with the thick core using adhesive films, resulting in a three-layered sandwich panel, as shown in Figure 1.1. It is designed such that the HC core not only maintains the distance between the face sheets and improves the flexural stiffness but also carries the normal compression and shear loads [2, 3]. The selection of face sheet material and its thickness, along with the material and geometry of the core, offers several choices for designers allowing tailormade structural properties, including not only mechanical but also acoustic and thermodynamic aspects. The common HC cores with square or hexagonal cells [4] are fabricated from metallic alloys such as aluminum [5-7], and polymers including Kevlar or Aramid resin-impregnated papers [8-11]. The face sheets are typically made of aluminum [12, 13], glass fiber-reinforced polymer (GFRP) [14, 15], or carbon fiberreinforced polymer (CFRP) composite laminates [3, 16].



Figure 1.1 Honeycomb (HC) core application in sandwich panel

The extensive application of polymeric composite sandwich panels in the aerospace industry has continuously increased over the last decades. Modern aircraft design like the Airbus A380 was among the first commercial airplane using 25 % of the composite structures, including the sandwich panels in the aircraft secondary parts such as the spoilers, flaps, wings, engine cowls, nacelles, and ailerons [17], as presented in Figure 1.2. Recently, the automotive industry used composite panels in the floor pans and front bulkheads of the body structure [18]. Moreover, many hexagonal-shaped core structure applications are employed in sports equipment like surfboards and snowboards [4, 19]. Recent advanced lightweight composite sandwich panels are introduced for the wind turbine blades and the helicopter blades [18]. Most of these structural applications, specifically the aerospace industry, utilizes the HC core made of phenolic resin impregnated *Nomex* paper [20].



Figure 1.2 (a) HC application in airframe structure (Airbus A380), (b) wooden surfboard and (c) Non-pneumatic tire with HC spokes [21]

1.2 Research Background

The design of HC sandwich panels could be optimized with respect to the strength, stiffness, and stability requirements. The challenge is to consider the design trade-offs in the combination of lightweight materials that meet the product's strength requirements while maintaining cost-effectiveness. Thus, the industries need to evaluate the structure resistance under different loading conditions like quasi-static, fatigue and impact loading, and the failure propagation during service life. The mechanical behavior of the HC core under various loading conditions such as compression, tension, shear, and flexural loading is beneficial to measure the intrinsic properties of the core [22]. Depending on the geometric specifications, the HC core exhibits an anisotropic response under the quasi-static and low impact loading conditions [23]. Under the lateral forces, the compressive failure mode of the HC structure in the through-thickness direction and the associated localized buckling of the HC core are of primary concern. [24, 25]. In addition, the HC sandwich panel's reliability should also be considered in the presence of the fatigue loading. However, the weakest point of the core is the small adhesive area of HC cells with face sheets such that a manufacturing defect or in-service load-induced damage could easily cause debonding, leading to catastrophic failure of the HC sandwich structure [26-28]. Also, the structural properties of the HC core are relatively weaker than the high-strength face sheets in the majority of cases [11, 29]. Core deformation and failure are, therefore, decisive factors for the energy absorption capability of sandwich panels. A thorough understanding of the mechanical responses of the HC core is thus inevitable in quantifying the performance and reliability of these HC structures.

In this respect, finite element (FE) analysis is commonly employed to establish the internal states of strains and stresses during the deformation and failure process of the structure [30-33]. With the available FE tools, the need to find efficient analysis methods relies mainly on the level of understanding of the core behavior and the impact of core design on the overall behavior of the sandwich panel. The numerical modeling of the HC core structural behavior under general loading conditions has been performed at both macro-and meso/micro-length scales. The macro-mechanical approach employs an equivalent homogeneous solid. This approach does not account for the localized buckling of the core [34-36]. The meso/micro-mechanical model utilizes the representative unit cell of the HC core [32, 37]. The models account for the details of the geometric features of the cellular structure and the cell wall material. The model takes the cell wall material properties and predicts the structural properties and behavior of the HC core panel with multiple cells. The success of the abovementioned models relies, to a great extent, on the availability of the experimentally-determined structural and material properties of the HC cores. Owing to that, the accuracy of the FE-calculated results depends, among others, on the accuracy of the geometrical model of the HC cells, prescribed boundary conditions and loading, the precision of the measured material properties, suitable constitutive laws for the face sheet and cell wall materials.

While the mechanics of the CFRP laminates for the face sheet have rigorously been studied [38-42], limited research work is available on the deformation and failure of the HC core, particularly those fabricated from the resin-impregnated papers [10, 43]. The observed localized failure leading to the final fracture of the sandwich structure necessitates the simulation of the complete deformation process to capture the observed failure mechanisms. This calls for the constitutive model of the cell wall materials with appropriate failure criteria. In this respect, several failure criteria, including Hashin [44], Tsai-Wu [45], and Tsai-Hill [46] are of particular interest for HC core made of unidirectional fiber-reinforced polymer papers. Many researchers analyzed the out-of-plane compression response of the HC core using meso-scale multi-cell representative models [47, 48], but the mechanics of deformation through damage mechanics are yet to be elaborated. The implementation of the damage mechanics approach covers the strength characteristics and the complete failure response through localized damage initiation and propagation, as already done in CFRP laminates [40, 42]. Surprisingly, this approach is not being utilized till now for the polymeric composite HC core structures. Therefore, an efficient and validated FE model of the HC core behavior is invaluable in view of the ever-increasing computational power available for design and simulation. A validated representative cell model could then be effectively used to generate the response of the HC core structure under the general loading scenarios. This limits the costly testing on the HC core samples for identifying the primary structural properties.

The numerical analysis capability of the structural products employing the HC sandwich panels requires the proper design verification prior to experimental tests and certification for deployment. Even with the revolutionary computation power, the structural analysis of the products made of tens or thousands of sandwich panels (like fairings, flappers, and spoilers in the wing of aircraft) can become very complicated. In addition, the cost and time constraints necessitate efficient virtual methods to confirm that the structural product is capable of handling the different loading conditions during its service life. Thus, the macro-mechanical modeling approach comes into consideration, termed as the homogenization of the cellular core [17, 36, 37, 49]. Instead of the detailed cellular core model, an equivalent homogenous material replaces the cellular core having the same mechanical behavior as that of the actual HC core. This approach simplifies the numerical modeling of the complex structural parts and results in reducing computational cost and time. Developing an equivalent HC core is difficult due to the complexity of the cellular core and its mechanical characteristics based on the core geometry variation. The issue becomes more complex as new composite materials are made to be used as cell wall material for the cellular HC core. Currently, some research works are conducted to establish the equivalent HC core model, and computational tools are devised to calculate the structural properties to be used for the homogenous material in the complex sandwich panel products [50]. But this field is still open for research as the challenge is concerned with the accuracy of the assumptions being used for creating the homogenous material equivalent to the actual HC core.

The present research work establishes the damage mechanics-based mesoscale representative cell model to predict structural properties and failure processes in the HC core structure under quasi-static loading conditions. Contrary to the previously developed multi-cell models consisting of a large number of cells, the smallest possible representative cell models are created with periodic boundary conditions that drastically reduce the computational time. The predicted mechanical responses and damage behavior provide the internal states of displacement, strain, and stress, referring to the explicit material phases. The in-plane and out-of-plane mechanical properties are quantified for general loading conditions like tension, compression, and shear using experimental tests and numerical analysis. Furthermore, the FE validated out-of-plane and the in-plane mechanical properties from the experimental tests are implemented to develop a damage-based equivalent homogenous HC core model. The validation of the equivalent model is claimed by comparing measured data and FE-predicted flexure load-displacement plots of the sandwich HC panel under three-point bend load. The FE-calculated behavior acknowledges the damage initiation event and the subsequent evolution of damage to fracture of the core structure in the representative cell model and equivalent homogenous HC core (EHC) model.

1.3 Statement of Research Problem

Multiple Representative volume element (RVE) models are used in the analytical formulations by the researchers individually for the derivation of orthotropic elastic constants to generate the equivalent model for HC core [51-54]. These theoretical equations result in different calculated values for the elastic constants for the equivalent model. Also, various finite element models are created using the meso/micro-scale representative structure of the HC core [55, 56]. FE tools are devised to replace the real HC core with the equivalent material model using the single-cell representative structure of hexagonal HC core, but that provides the initial approximation of the elastic constants for stiffness matrix [50]. Most of the open literature focused on characterizing the mechanical behavior under static or impact loading using different geometric parameters of the hexagonal honeycomb core [57-60]. But the combined effects of certain geometric parameters like cell size and cell height are yet to be quantified. To the author's knowledge, far too little attention has been given to the damage-based mechanics of deformation in paper-made honeycomb cores. These attributes can be very interesting in analyzing the failure of the honeycomb core under different loading conditions. In addition to these primary data, systematic studies are still needed for the mechanical behavior of a single honeycomb core geometry under all in-plane and out-of-plane quasi-static loading conditions. This could provide a complete set of effective elastic properties to develop an equivalent HC core model. This research aims to provide a methodology to develop a predictive model for the failure in Nomex HC core using a damage mechanics-based representative cell model. The structural properties from this damage mechanics-based predictive model are used as input to create an equivalent model for replacing the

cellular HC core in the sandwich panel that duplicates the real HC core behavior under any loading condition. Therefore, the research gap could be summarized to answer the following research problem. "*How effectively the HC core in the sandwich panel could be replaced with a homogenous material using a damage mechanics approach resulting in the same mechanical behavior of the real composite sandwich panel*?"

1.4 Research Objectives

The research aims to develop a verified damage mechanics-based model for deformation and failure prediction of honeycomb structures. The specific objectives of the research are :

- i. To establish relevant material properties and behavior of Honeycomb (HC) core used in the sandwich panels.
- ii. To determine the effects of geometric parameters for the structural characterization of hexagonal *Nomex* HC core under the out-of-plane compression loading.
- iii. To develop the damage mechanics-based model using meso-scale Representative Cell (RC) structure for the HC core.
- iv. To verify the damage mechanics-based FE model for the equivalent homogenized honeycomb (EHC) core structure.

1.5 Scope of the study

The present study focuses on developing a damage mechanics-based representative cell model of *Nomex* HC core that could efficiently predict the mechanical response of the real structure under different loading conditions. The research is limited to the following scope of work:

- i. Conduct the mechanical testing for material and structural characterization of the hexagonal HC core.
 - a. Phenolic resin impregnated *Nomex* paper (type 410) specimens are used for the tension test to obtain the material properties. The overall dimension of the specimen was 350 mm (length) x 50 mm (width) with a paper thickness of 0.05 mm. The tension load was applied in the paper roll (0°) and transverse (90°) direction.
 - b. Bare Nomex HC core (HRH-10) specimen (cell size = 3.2 mm, height = 12.7 mm and density 64 kg/m³) with square (30 mm x 30 mm to 70 mm x 70 mm) and rectangular (150 mm x 50 mm) cross-section are cut from the HC core panels of real aerospace structural parts. The square specimen is used for quasi-static out-of-plane compression, while the rectangular specimen is employed in the in-plane tension, shear, and out-of-plane shear loading.
 - c. Sandwich HC panel specimen comprised of CFRP 2-ply [0]₂ and 8-ply [0]₈ face sheets and *Nomex* HC core with same cell size and height as above. These sandwich panels were cut into a square (50 mm x 50 mm) and rectangular (200 mm x 75 mm) cross-section. The square sandwich specimen (with 8-ply CFRP face sheets) is used for quasi-static out-of-plane tension, while the rectangular sandwich panel (with 2-ply CFRP face sheets) for the quasi-static three-point bend experiment.
- ii. Parametric analysis of bare HC core structures is conducted using different cellular configurations for out-of-plane compression. Specimen with cell size (3.2 mm, 4.8 mm), core height (8 mm, 12.7 mm, 18 mm) and density (32 kg/m³, 64 kg/m³, 128 kg/m³) are used for the compression testing.
- iii. Damage-based finite element representative cell models are developed by using ABAQUS 6.14. Hashin damage criteria with energy-based damage

evolution is implemented to simulate the following quasi-static out-of-plane loading cases:

- a. Tension and compression load cases are simulated using hexagonal cell configurations of single-cell, 4-cell, and 24-cell models.
- b. A shear load case model was created using a 6-cell configuration of hexagonal HC core. The shear load case is comprised of the ribbon and transverse direction.
- iv. A Hybrid experimental-computational approach is adapted to obtain the effective structural properties of hexagonal *Nomex* HC core. The in-plane structural properties are taken directly from mechanical testing, while the out-of-plane structural responses are validated through representative cell models. These both are used as input to create the following damage mechanics-based equivalent homogenized HC core models.
 - Multi-cell equivalent model with geometric dimensions of 50 mm x 50 mm
 x 12.7 mm is simulated using the said structural properties for quasi-static compression load.
 - b. Single-cell equivalent model with a geometric configuration of 5.54 mm x
 3.36 mm x 12.7 mm is created, and numerical analysis is performed to assess the deformation and failure process, respectively.
 - c. Verification of the newly developed damage-based equivalent HC core model is done by simulating the quasi-static three-point bend loading of sandwich HC panel. The localized structural deformation and damage evolution to fracture of the HC core is analyzed in detail for the respective loading condition.

1.6 Significance of the Study

This research work presents a methodology for replacing the cellular HC with the equivalent homogenous structure that effectively predicts the mechanical behavior of the real HC core. The developed equivalent homogenized honeycomb core (EHC) model significantly reduced the model size, which lowers the computational time and cost for the whole composite sandwich panel. The validated model acknowledges the gradual accumulation of material damage leading to crack initiation of material points in the equivalent model. In addition, the methodology can be adapted for other polymer-based materials with available experimental data. Moreover, the research also provides an in-depth understanding of failure mechanics by using damage-based representative cell models. The representative cell models are formed using the smallest possible unit-cell structure that efficiently predicted the material point damage under different loading conditions. The verified methodology for the representative cell and the EHC models will be significant for all the industries associated with lightweight structures, specifically the aerospace companies such as Composite Technology Research Malaysia (CTRM) and transport industries as well. The representative cell model methodology could be useful for these companies in conducting the computational analysis instead of experimental testing that could save high product development cost and time for different aircraft parts. The damage mechanics-based approach implemented in these models helps in quantifying the real HC core mechanical response. This is of immense significance in the computational analysis of large complex structures where the computational time and cost are of utmost importance.

1.7 Thesis Layout

This thesis consists of eight chapters. All the chapters are arranged to establish an equivalent homogenized HC core model for predicting the deformation response under different loading conditions. The validated damage mechanics-based finite element methodology is described for representing actual HC core behavior through a homogenous model using structural properties. Each chapter's content is specified here to link them with the specific objectives and scope of the research.

In Chapter 1, the research background and challenges in numerical analysis relate to the complexity of the anisotropic *Nomex* honeycomb core structures used in sandwich panels for automotive and aerospace industries. The problem statement, specific objectives, and significance are clarified. The limits of this research are defined in the scope of the study.

Chapter 2 summarizes the literature on honeycomb core structures, mechanical properties, and behavior under quasi-static loading. Exiting numerical tools and FE procedures to predict the failure response are covered. Various representative cell models are identified from literature used in previous studies to predict the deformation and failure. Different homogenization models are discussed that were created to replace cellular honeycomb core structure as an equivalent material. Previous research based on theoretical models to find elastic constants for stiffness matrix are described. All this literature review is given in detail to have an insight on the current topic and provide the basis for further research needed in this specific area.

Chapter 3 provides the detailed research methodology of the current study. A hybrid experimental-computational approach is established to find the structural properties of hexagonal *Nomex* HC core. Firstly, validated damage mechanics-based representative cell model formation is elaborated for the out-of-plane loading conditions. The representative cell model consists of the real hexagonal HC core geometry. Then, the creation of damage mechanics-based equivalent homogenized HC core model methodology is explained in which the HC core is replaced by equivalent homogenous material that will duplicate the real HC structure behavior. The detailed information of validating the equivalent model through three-point bend loading on the sandwich HC panels is described.

Chapter 4 consists of all the experimental test results that relate to HC core structures. First, the phenolic resin-based *Nomex* paper tensile properties are described. The orthotropic elastic constants along-with the damage parameters are extracted that are to be used as input for the damage mechanics-based representative cell model of the HC core. Secondly, the out-of-plane tension, compression, and shear deformation are presented for the respective HC core, while the global load-displacement responses are plotted to quantify the mechanical properties. Then, the in-plane tension and shear deformation results are described for the same geometry of HC core structure. The catastrophic damage to different loading conditions is explained through the mechanics of deformation and failure for each loading case. In the last section, the three-point bend experimental test results of sandwich HC panel are given that will be used for validation of equivalent homogenized HC core model.

In Chapter 5, the parametric analysis of the HC core structure is provided for the out-of-plane compression behavior. The influence of HC geometry, particularly the cell size, the height of core, and relative density, are analyzed and discussed individually. Then, the effects of cell aspect ratio (height/cell size) and relative density on the compression modulus, strength, and dissipation energy are established. A phenomenological model is presented that could effectively predict the compressive strength of the *Nomex* HC core using the combined effects of relative density and cell aspect ratio.

Chapter 6 describes the developed representative cell model numerical results for the HC core out-of-plane loading conditions. The mechanical responses of the damage mechanics-based models consisting of single-cell and multiple hexagonal cells of the HC core are presented in detail. The FE-calculated behavior acknowledges the damage initiation followed by the damage evolution to fracture of the HC core. The representative cell models are validated experimentally for each respective load case and cover both mechanics of materials and the deformation mechanism. It is clarified that the mechanical deformation responses could be efficiently predicted by the smallest possible representative cell model of hexagonal HC core using the damage mechanics approach.

Chapter 7 elaborates the numerical analysis of damage-based homogenous equivalent homogenized honeycomb core (EHC) models. The computational results of equivalent multi-cell and single-cell models are assessed to examine the developed homogenization technique through structural properties. The load-displacement plots and the progressive damage in the EHC models are described for each case. A numerical model of the three-point bend loading condition for sandwich HC panel is done in the last section. The sandwich panel is modeled to have stiff CFRP face sheets bonded to equivalent HC core surfaces, and a three-point load is applied. The EHC model results are compared with the measured response. The computational results are shown to be in accordance with the measured data, and the EHC model replicated the exact mechanical behavior of the real HC core.

Chapter 8 summarizes the main conclusion related to the methodology adopted for the representative cell model. Furthermore, the verified EHC model responses are concluded. The main contributions that are addressed in the form of research objectives are concluded in this chapter. Further research recommendations are listed to increase the knowledge base in the field of HC structures.

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189

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LIST OF PUBLICATIONS

- <u>MS Khan</u>, SSR Koloor, MN Tamin. Effects of cell aspect ratio and relative density on deformation response and failure of honeycomb core structure. Materials Research Express. 2020 Jan 20;7(1):015332. DOI: 10.1088/2053-1591/ab6926 (ISI Indexed Q3, IF = 1.929)
- <u>MS Khan</u>, A Abdul-Latif, SSR Koloor, M Petrů, MN Tamin. Representative cell analysis for damage-based failure model of polymer hexagonal honeycomb structure under the out-of-plane loadings. Polymers. 2021 Jan;13(1):52.

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