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 in-plane 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 three-point 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.

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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
c	-	Cell size
t	-	Paper thickness
θ	-	Core angle
L	-	Panel length
W	-	Panel width
H	-	Core height
$\rho*$	-	Density of the core
ρ_s	-	Cell wall material density
t	-	Cell wall thickness
E_{iso}	-	Young's modulus for Isotropic material
σ_{yield}	-	Yield strength for isotropic material
ν_{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
τ_{12}	-	Shear stress
ε_{11}	-	Strain in the fiber direction
ε_{22}	-	Strain in the transverse direction
γ_{12}	-	Shear strain
X	-	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
K	-	Stiffness
N	-	Mode I strength
δ_N^0	-	Relative displacement at the damage onset
δ_N^f	-	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
E_{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
v_{12}	-	In-plane Poisson’s ratio
v_{13}	-	In-plane Poisson’s ratio
v_{23}	-	Out-of-plane Poisson’s ratio in the thickness direction
σ_{33}	-	Stress in the out-of-plane loading
ε_{33}	-	Strain in the out-of-plane loading

ε_{11}	-	Strain in the longitudinal (fiber) direction
ε_{22}	-	Strain in the transverse (matrix) direction
τ_{13}	-	Shear strength in the ribbon direction
γ_{13}	-	Shear strain in the ribbon direction
τ_{23}	-	Shear strength in the transverse direction
γ_{23}	-	Shear strain in the transverse direction
E_s	-	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 $(\underline{x})$
$\underline{\underline{\epsilon}}(\underline{x})$	-	Strain at a material point $(\underline{x})$
$\underline{\underline{\Sigma}}$	-	Equivalent stress for macro-scale homogeneous material
$\underline{\underline{E}}$	-	Equivalent strain for macro-scale homogeneous material
F_z^{fcu}	-	Ultimate flatwise compressive strength (MPa)
P_{max}	-	Ultimate force before failure
A	-	Cross-sectional area
τ	-	Core shear stress
P	-	Applied load
γ	-	Core shear strain
u	-	Displacement between the loading plates
F_s^{ult}	-	Core ultimate shear strength
d	-	Sandwich thickness
b	-	Sandwich width
δ_{eq}^0	-	Equivalent displacement at the onset of damage
δ_{eq}	-	Equivalent displacement at any step
δ_{eq}^f	-	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
C	-	Constant
α_{avg}	-	Average of the exponent for cell aspect ratio
U_3	-	Displacement in out-of-plane direction

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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 tailor-made 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 fiber-reinforced polymer (CFRP) composite laminates [3, 16].

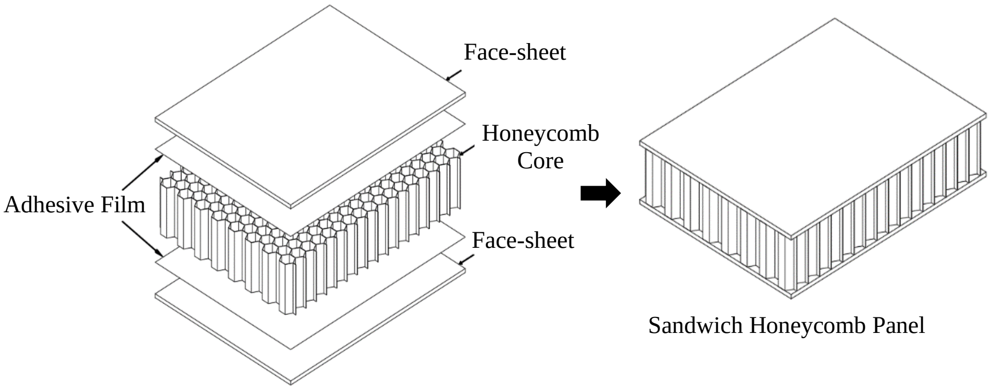
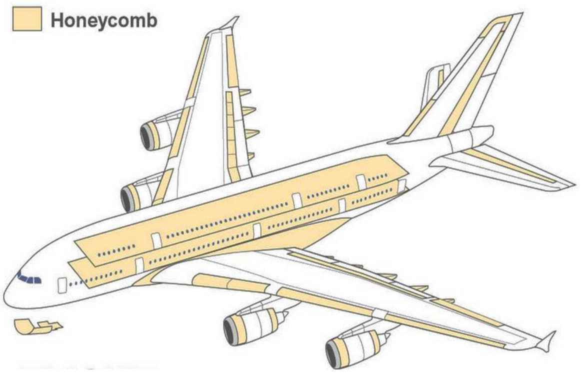


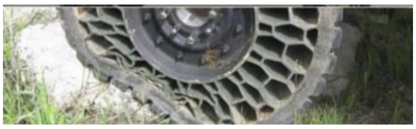
Figure 1.1 Honeycomb (HC) core application in sandwich panel

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].



(a)

(b)



(c)

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 meso-scale 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/m^3) 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/m^3, 64 kg/m^3, 128 kg/m^3) 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.

a. 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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