COMPRESSION AND INDENTATION BEHAVIOR OF LIGHTWEIGHT FOAM-FILLED KRAFT PAPER HONEYCOMB STRUCTURE

BY

NURDINA BINTI ABD KADIR

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Kulliyyah of Engineering
International Islamic University Malaysia

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ABSTRACT

Honeycomb sandwich structure has been used extensively in engineering industries as an energy absorber to resist external loads due to its lightweight and high energy absorbing capability. However, the honeycomb core is the weakest part of the sandwich structure and they may fail or collapse through cell fracture or cell wall buckling depending on the loading regime and the core configuration. A foam-filled honeycomb structure has been proposed to provide an enhancement in the properties of the honeycomb core. The filler existence within honeycomb cells improves the honeycomb structure systems by strengthening the honeycomb cell wall and changes the structure's behavior. Therefore, statistical, experimental, and simulation works were carried out in this research work to investigate the effects of filling Kraft paper honeycomb with polyurethane foam. For the simulation, a three-dimensional finite element model for foam-filled Kraft paper honeycomb was developed. Statistical analysis was performed at the initial stage of this study to determine the optimum configuration of the Kraft paper honeycomb. Then, the optimized unfilled kraft paper honeycomb, polyurethane foam, and foam-filled Kraft paper honeycomb were subjected to quasi-static compression loading. The maximum force and energy absorption of foam-filled Kraft paper honeycomb were computed to study the improvements compared to the summation of unfilled kraft paper honeycomb and foam alone. The three-dimensional finite element analysis was performed using Ls-Dyna software to investigate the interaction between polyurethane foam and cell walls. Force-displacement behaviors obtained from numerical simulations were validated by experimental findings, and the distribution of energy absorption between cell walls and polyurethane foam in the foam-filled honeycomb was analyzed. In order to study the localized effect of foam-filled kraft paper honeycomb, experimental analyses and finite element analyses subjected to indentation loading were performed. As a result, the Kraft paper honeycomb with density 175gsm, 3 ply thickness of paper, and 10 mm cell size of honeycomb exhibit the optimum configuration with 724.80 J/kg of specific energy absorption (SEA) and 9.35 MPa/kg of specific compression strength (SCS). Moreover, the experimental results show that the peak force and energy absorption of the foam-filled honeycomb were increased up to 30% compared to the individual component. Meanwhile, the indentation at the vertical edge shows the higher peak force and energy absorbed which proves that the vertical edge of the cell wall behaves as a strong point to endure the indentation force. In conclusion, polyurethane foam filler has strengthened the honeycomb cell wall and improved the energy absorption capability of the Kraft paper honeycomb structure. The FEA results confirmed that the cell walls strengthened by the foam filler and the confinement of foam by cell walls increased the energy capability of the foam-filled honeycomb structure.

خُلاصة البحث

إن بنية خلية النحل قد استخدمت على نطاق واسع في مجال الهندسة، بوصفها امتصاص الطاقة لمقاومة حمولة خارجية بسبب وزنها الخفيف واستطاعتها في امتصاص الطاقة العالية. ولكن، إن قلب خلية النحل هو الجزء الأضعف لهذه البنية، ويستطيع القلب أن يفشل أو يسقط عبر انكسار الخلية أو تحنيب جدار الخلية، الذي يعتمد على نظام التحميل وتكوين القلب. إن بنية خلية النحل معبأ بالرغوة مقترحة لتجهيز التحسين على قلب خلية النحل. إن وجود التعبئة داخل خلية النحل يتحسن نظام هيكل خلية النحل بتقوية جدار الخلية وتغيير سلوك الهيكل. لذلك، قد نفّذت عملية الإحصاء والتجريب والمحاكاة في هذا البحث ليستكشف تأثير تعبئة ورقة خلية النحل Kraft برغوة بوليوريتان. إن للمحاكاة، فتقدم نظام نموذج عنصر محدود بثلاثية الأبعاد لورقة خلية النحل Kraft معبأ بالرغوة. وقد أقيم التحليل الإحصائي في المرحلة الأولى بهذا البحث لتعيين التكوين الأمثل لورقة خلية النحل Kraft. ثم، تعتمد الورقة الفارغة الأنسب ورغوة بوليوريتان والورقة معبأ بالرغوة على حمل الضغط شبه ساكن. إن القوة العظمى وامتصاص الطاقة للورقة معبأ بالرغوة محسوبان للبحث عن التحسينات مقارنة بمجموع الورقة الفارغة والرغوة وحدها. وقد قيّم نظام نموذج عنصر محدود بثلاثية الأبعاد باستخدام برمجية Ls-Dyna لاكتشاف عن التفاعلات بين رغوة بوليوريتان وجدار الخلية. إن سلوكيات النزوح القسري المحصول من المحاكاة العددية قد اعتمدت بالاستنتاجات الاختبارية، كما قد تم تحليل توزيع امتصاص الطاقة بين جدار الخلية ورغوة بوليوريتان في خلية النحل معبأ بالرغوة. وللبحث عن التأثير الموضعي للورقة معبأ بالرغوة، قد أقيمت التحليلات الاختبارية والتحليلات المحدودة مُعَرّضٌ لِتحميل الفجوة. والنتيجة هي إن ورقة خلية النحل Kraft مع الكثافة 175غرام وسُمك ثلاث طيات وحجم خلية النحل 10 ميلي متر تشير أن التشكيل الأمثل هو مع معدل امتصاص الطاقة المحدد 724.80 J/kg ومُقَاوَمة الضغط النوعية 9.35 MPa/kg. إضافة إلى ذلك، إن النتيجة التجريبية أشارت أن ذروة امتصاص القوّة والطاقة للورقة معبأ بالرغوة قد ارتفعت إلى% 30 مقارنة بالمكونات الفردية. أما من جهة أخرى، الفجوة في الحافة العمودية أشارت إلى أعلى امتصاص الطاقة والضغط الذي يبرهن بأن الحافة العمودية للخلية تصرّفت كنقطة حصينة لتتحمل قوة الفجوة. وختاما، إن رغوة بوليوريتان قد تقوي جدار خلية النحل وتحسن مستوى امتصاص الطاقة لهيكل ورقة خلية النحل Kraft. إن نتيجة تحليل العناصر المنتهية أشارت إلى أن تقوية جدار الخلية بالرغوة، وتطويق الرغوة لجدار الخلية، قد ارتفعتا استطاعة الطاقة في خلية النحل.

APPROVAL PAGE

The thesis of Nurdina Binti Abd Kadir has been approved by the following:

Mohd Sultan Ibrahim
Supervisor

Hanan Mokhtar
Co-Supervisor

Yulfian Aminanda
Co-Supervisor

Jaffar Syed Mohamed Ali
Internal Examiner

Jamaluddin Mahmud
External Examiner

Kamal Ariffin Mohd Ihsan
External Examiner

DECLARATION

I hereby declare that this thesis is the result of my own investigations, except where otherwise stated. I also declare that it has not been previously or concurrently submitted as a whole for any other degrees at IIUM or other institutions.

Nurdina Binti Abd Kadir

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LIST OF SYMBOLS

E	Young's modulus
A	density of paper
B	thickness of cell wall
C	the cell size of honeycomb
E_s	young's modulus of solid cell wall materials,
$ETAN$	tangent modulus
E_z	flatwise compression
ε	strain
F	Applied unidirectional force
F_D	dynamic coefficient friction
F_s	static coefficient of friction
Gsm	Grams per square meter.
G_{xz}	Shear modulus of the sandwich panel along x-direction
G_{yz}	Shear modulus along the y-direction
h	width
K	End constant factor,
l	length
m	mass of specimen
PR	Poisson's ratio
RO	Mass density
s	Cell size of Honeycomb
$SIGY$	Yield stress
SW	sense switch control
t	thickness
t	time
$Tan\ \delta$	tangent modulus
U_i	Energy absorbed by specimen
X	x-axis
$X1$	initial length of specimen
$X2$	final length of specimen
Y	y axis
Z	z-axis
ρ	Density of Paper,
σ_{max}	maximum compressive stress
σ_y	yield strength
υ_s	Poisson's ratio of the solid cell wall materials,
σ	normal / compression stress

LIST OF ABBREVIATIONS

ANOVA	analysis of variance
CAI	compressive loading after indentation
DOE	design of experiment
DW	Double Wall
FEA	Finite Element Analysis
FEM	Finite Element Model
FFKP	Foam-Filled Kraft Paper
FFKPH	Foam-filled Kraft Paper Honeycomb
KPH	Kraft Paper Honeycomb
LCID	The load curve ID
PU	Polyurethane foam
SCS	Specific compressive strength
SEA	Specific energy absorption
SW	Single Wall
TTX	Korean Tilting Train Express
VE	Vertical Edge

CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND OF THE STUDY

Sandwich structures are known for having a high strength-to-weight ratio as well as high specific bending stiffness and strength under uniform load. A typical structural sandwich panel comprises two thin face sheets on both sides and a core in the centre. Honeycomb, foam, balsa wood, corrugated, and textile cores are the most common types of core materials. Core materials' primary functions are to absorb energy and provide resistance to face sheets to avoid local buckling (Xiong et al., 2018). The use of honeycomb core is continuously increasing due to its superior properties. Previous research shows that the honeycomb core structure provides an impressive crush resistance and high energy absorption capability in the out-of-plane direction (Alia et al. 2019; Miller, Smith, and Evans 2011; bin Pokaad et al. 2015). Kraft paper honeycomb core was first introduced in industry in the early 1900s. However, due to the comparatively low cost of wood components and widespread consumer preference for solid panels, Kraft paper honeycomb did not attain considerable market traction for many decades. However, with the rising cost of wood materials in recent years, the use of Kraft paper honeycomb has increased, particularly in the furniture business (Chen et al., 2014).

Kraft paper honeycomb core with pre-impregnated resin or no resin at all is widely used in furniture, doors, partitions, mobile homes, signs, and similar construction. Meanwhile, a special grade Kraft paper honeycomb core that has been expanded and then dipped in a phenolic resin to increase its water resistance and strength are used in portable military shelters, aerospace, and naval industries (Bitzer, 2012). Some main advantages of these sandwich panels include lightweight, high specific stiffness, stable energy-absorbing property and recyclability (Samad, Warsame, & Khan, 2018; D. Wang, Liang, & Guo, 2019; Z Wang, Xuebao, 2012). Although honeycomb sandwich panels have been widely used in engineering industries for many decades, there is limited information about the properties and behavior of the lightweight Kraft paper honeycomb panel. Meanwhile, Extensive work has been carried out on the structural optimization and failure behavior of honeycomb sandwich structures from different materials such as Nomex, Aluminum and composite materials.

Zhou et al. (2018), Rodrguez-Ramrez, Castanié, and Bouvet (2018), and Liu et al. (2018) investigated the mechanical behavior and energy absorption properties of the Nomex honeycomb structure. He et al. (2019) also investigated the effects of flexural strength on the Aluminum honeycomb sandwich panel (2019). Moreover, Aziz et al. (2018) investigated the energy absorption of honeycomb structures made of carbon fiber reinforced plastics.

Metallic and polymeric foams have recently been extensively investigated as a filler for the hollow core (Cheng et al. 2018; M. Li et al. 2018; Zhejian Li, Chen, and Hao 2019; Niknejad et al. 2011; Yi et al. 2019; G. Zhang et al. 2014). The results show that these low-density foams have a positive effect on strengthening the cell walls of panels and are also credited with improving the honeycombs' energy absorption capability and damping properties (Niknejad et al., 2011; G. Zhang et al. 2014). Zhang et al. (2014) investigated the energy absorption and low-velocity impact response of pyramidal lattice core sandwich panels filled with polyurethane foam. They discovered that the foam-filled sandwich panels have a more significant load carrying capacity than the summation of unfilled specimens and the polyurethane block due to a synergistic effect. Furthermore, Niknejad and Rahmani's (Niknejad and Rahmani 2014) experimental and theoretical study of the lateral compression process on an empty and foam-filled hexagonal column revealed that as the plateau stress of polyurethane foam filler increases, the lateral load and absorbed energy by the structure increases as well. Numerous researchers have conducted research on foam-filled honeycombs used in high-tech applications such as aerospace and naval industry, such as Nomex and metallic honeycomb. Unfortunately, few studies in the literature deal with honeycomb sandwich panels used for low-tech applications such as furniture and load-bearing applications. Due to the lower cost and material usage of paper honeycomb compared to solid wood-based panels, some manufacturers are aiming to use paper honeycomb panel or structure for load-bearing applications such as floor, decks, transportation pallet, load-bearing wall, and partition in recent years (D. Wang 2009a; D. Wang et al 2019). Thus, this study combines experimental and simulation studies of Kraft paper honeycomb filling with polymer foam, which is expected to be used for load-bearing applications.

1.2 STATEMENT OF THE PROBLEM AND ITS SIGNIFICANCE

Over the last two decades, numerous experimental and analytical studies have been conducted to determine how honeycomb cells fail under various loading conditions. Basically, depending on the nature of the cell wall material, honeycomb cells collapse via elastic buckling, plastic yielding, creep, or brittle fracture. As a result, a number of experimental and numerical approaches for strengthening honeycomb cell walls and increasing the energy absorption capacity of honeycomb core structures have been proposed. However, recent research indicates that filling the honeycomb core with foam filler improves the honeycomb core's properties. This method is economical and does not significantly increase the weight of a sandwich structure. Furthermore, the presence of filler within honeycomb cells not only increases the structure's resistance to damage, but also changes its behavior. Although foam-filled honeycomb structures under various loading conditions have received significant attention in recent years, there is a lack of information on the properties and behavior of foam-filled Kraft paper honeycomb structures. Due to the significant difference in material properties between sandwich panels containing Kraft paper core and aerospace structural sandwich panels such as Nomex honeycomb, comprehensive studies of the structure-property relationships of sandwich panels containing Kraft paper core are required. Thus, the purpose of this research is to examine the behavior of foam-filled Kraft paper honeycomb and to develop a finite element model for foam-filled Kraft paper honeycomb. Furthermore, it can contribute to the advancement of knowledge in the field of foam-filled structures.