UNIVERSITI PUTRA MALAYSIA

A NEW HYBRID APPROACH FOR CONCEPTUAL DESIGN OF SUGAR PALM FIBRE-REINFORCED POLYURETHANE COMPOSITES FOR AUTOMOTIVE ANTI-ROLL BAR

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By

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Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for the Degree of Doctor of Philosophy

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Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the Degree of Doctor of Philosophy

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Chairman : Professor Mohd Sapuan Salit, PhD, P.Eng
Faculty : Engineering

In this thesis, the development process relating to the conceptual design of an automotive anti-roll bar made of sugar palm fibre reinforced thermoplastic polyurethane composites is presented. The conceptual design is performed with the consideration of five mechanical design elements, which are material, function, force, failure mode and geometry. Each of the elements is considered at the beginning of design process, which is assisted by several design tools. Initially, after the customers and environment requirements are identified, selection of materials is carried out using an integrated Analytic Hierarchy Process (AHP) and three-phase Quality Function Deployment for Environment (QFDE). In the final stage of material selections, the ranked materials are evaluated based on their environmental impact using the Eco Audit tool from the Cambridge Engineering Selector 2013 software. This new approach to material selection using QFDE is applicable for selecting suitable natural fibre and thermoplastic matrix for the composite automotive anti-roll bar. Here, the results showed that sugar palm fibre is the suitable natural fibre and thermoplastic polyurethane is the suitable matrix for the composite automotive anti-roll bar. Next, function and failure modes for the automotive anti-roll bar are analysed using available tools in Theory of Inventive Problem Solving (TRIZ), which are Function Analysis Diagram (FAD) and Cause and Effect Chain Analysis (CECA) respectively. Improper function of each of the automotive anti-roll bars is identified through the implemented tool and the root cause of the problem is investigated through CECA, while force analysis is performed between the two analyses. Later, the problem is solved through geometry specification in generating the concept design by using the integrated tools TRIZ and Blue Ocean Strategy (BOS). Development of conceptual designs is performed through a Morphological Chart, where a combination of several design solutions has resulted in the development of 42 conceptual designs for a composite automotive anti-roll bar. The final concept design of a sugar palm fibre reinforced thermoplastic polyurethane

composites automotive anti-roll bar is selected through AHP and the results showed that a concept design that consists of tapered arms reinforced with ribs at both bent areas is the most suitable. Strategic Canvas from BOS is presented at the final stage and it showed that the sugar palm fibre reinforced thermoplastic polyurethane composites automotive anti-roll bar is the best one, compared with the steel and carbon fibre-based automotive anti-roll bar with respect to the customers' and environmental requirements. In a summary, design process of natural fibre composite-based automotive anti-roll bar should be incorporated with the principle of mechanical engineering design in order to properly obtain the design solution. The systematic and structured approach would prevent cost damage and save time and energy. In this study, the design process is limited at the conceptual design stage and further study need to be conducted for detail design where details simulation and experimental study should be carried out later.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk Ijazah Doktor Falsafah

PENDEKATAN HIBRID BARU UNTUK REKA BENTUK KONSEP KOMPOSIT TERMOPLASTIK POLIURETANA DIPERKUAT GENTIAN KABUNG UNTUK BAR ANTI-GELEK AUTOMOTIF

Oleh

MASTURA BINTI MOHAMMAD TAHA

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Di dalam tesis ini, proses pembangunan reka bentuk konsep bar anti-gelek automotif yang diperbuat daripada komposit termoplastik poliuretana diperkuat gentian kabung ditunjukkan. Kaedah keseluruhan proses merangkumi prinsip kejuruteraan serentak di mana reka bentuk konsep dan pemilihan proses pembuatan dijalankan serentak untuk memenuhi keperluan berdasarkan suara pelanggan dan suara alam sekitar yang diperoleh di awal proses. Reka bentuk konsep dijalankan dengan mengambil kira lima elemen reka bentuk mekanikal iaitu bahan, fungsi, daya, mod kegagalan dan geometri. Setiap elemen tersebut diambil kira di awal proses reka bentuk dengan dibantu oleh beberapa alatan reka bentuk. Pada permulaan, selepas keperluan pelanggan dan alam sekitar dikenal pasti, pemilihan bahan dijalankan dengan menggunakan penggabungan Proses Hirarki Beranalisis (AHP) dan 3-fasa Penggunaan Fungsi Kualiti untuk Alam Sekitar (QFDE). Pada langkah yang terakhir dalam proses pemilihan bahan, bahan-bahan dinilai berdasarkan impak terhadap alam sekitar dengan menggunakan Eco Audit daripada perisian Cambridge Engineering Selector 2013. Pendekatan baru dalam pemilihan bahan yang menggunakan QFDE ini boleh digunakan untuk memilih gentian semulajadi dan matrik termoplastik yang sesuai untuk komposit bar anti-gelek automotif. Di sini, keputusan menunjukkan bahawa gentian kabung adalah gentian semulajadi yang terbaik dan termoplastik poliuretana adalah matrik yang terbaik untuk komposit bar anti-gelek automotif. Seterusnya, fungsi dan mod kegagalan untuk bar anti-gelek automotif dianalisa dengan menggunakan alatan yang sedia ada dalam Teori Penyelesaian Masalah secara Inventif (TRIZ) iaitu Gambar Rajah Analisa Fungsi (FAD) dan Analisa Rantaian Punca dan Kesan (CECA). Setiap fungsi bar anti-gelek automotif yang tidak wajar dikenalpasti melalui alatan yang dilaksanakan dan punca permasalahan disiasat melalui CECA. Dalam masa yang sama, analisa daya dijalankan. Kemudian, masalah diselesaikan melalui spesifikasi geometri dalam menjana rekabentuk konsep dengan menggunakan penggabungan kaedah TRIZ dan

Strategi Lautan Biru (BOS). Pembangunan reka bentuk konsep dijalankan melalui Carta Morfologi di mana beberapa penyelesaian reka bentuk digabungkan dan ia menghasilkan 42 reka bentuk konsep untuk komposit bar anti-gelek automatif. Reka bentuk konsep komposit termoplastik poliuretana diperkuat gentian kabung yang terakhir dipilih melalui AHP dan keputusannya menunjukkan bahawa rekabentuk konsep yang terdiri daripada bar berlengan tirus dan diperkuat dengan rusuk di bahagian bengkok di kedua-dua bahagian dipilih. Kanvas Strategik daripada BOS ditunjukkan di langkah yang terakhir dan ia menunjukkan bahawa bar anti-gelek automotif yang diperbuat daripada komposit termoplastik poliuretana diperkuat gentian kabung adalah yang terbaik berbanding dengan bar anti-gelek automotif yang diperbuat daripada keluli dan gentian karbon dengan mengambil kira keperluan pelanggan dan alam sekitar. Kesimpulannya, proses reka bentuk komponen automotif berasaskan komposit gentian semulajadi perlu digabungkan bersama prinsip reka bentuk kejuruteraan mekanikal supaya penyelesaian reka bentuk dapat diperoleh dengan betul. Pendekatan sistematik dan berstruktur akan mengelakkan kerosakan dari segi kos, dan menjimatkan masa dan tenaga. Dalam kajian ini, proses reka bentuk terhad kepada peringkat reka bentuk konsep dan sambungan kajian perlu dijalankan untuk reka bentuk terperinci di mana ianya melibatkan kajian simulasi dan eksperimen yang terperinci.

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I certify that a Thesis Examination Committee has met on 2 May 2017 to conduct the final examination of Mastura binti Mohammad Taha on her thesis entitled "A New Hybrid Approach for Conceptual Design of Sugar Palm Fibre-Reinforced Polyurethane Composites for Automotive Anti-Roll Bar" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

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LIST OF ABBREVIATIONS

AHP	Analytic Hierarchy Process
ARB	Anti-Roll Bar
BIW	Body-In-White
BMC	Bulk Moulding Compound
BOS	Blue Ocean Strategy
CAD	Computer-Aided Diagram
CECA	Cause and Effect Chain Analysis
CI	Consistency Index
CO_2	Carbon Dioxide
CR	Consistency Ratio
DI	Direction of Improvement
EC	Engineering Contradiction
ECQFD	Environmentally Conscious Quality Function Deployment
FAD	Function Analysis Diagram
FAHP	Fuzzy Analytic Hierarchy Process
FANP	Fuzzy Analytic Network Process
FBD	Free-Body Diagram
GQFD	Green Quality Function Deployment
HDPE	High Density Polyethylene
HOQ	House of Quality
ISO	International Organization for Standardisation
IQFDE	Intelligent Quality Function Deployment
LCA	Life Cycle Assessment

LDPE	Low Density Polyethylene
MC	Morphological Chart
MCDM	Multi-Criteria Decision Making
NFC	Natural Fibre Composites
NFRC	Natural Fibre Reinforced Composites
NFRPC	Natural Fibre Reinforced Polymer Composites
NRS	Normalized Raw Score
PDS	Product Design Specifications
PE	Polyethylene
PP	Polypropylene
PS	Polystyrene
QFD	Quality Function Deployment
QFDE	Quality Function Deployment for Environment
RI	Random Consistency Index
RS	Raw Score
RW	Relative Weight
ROM	Rule Of Mixtures
SAE	Society of Automotive Engineering
TFN	Triangular Fuzzy Number
TOPSIS	Technique For Order Preference By Similarity To Ideal Solution
TPU	Thermoplastic Polyurethane
TRC	Textile Reinforced Concrete
TRIZ	Theory Of Inventive Problem Solving
TRT	Technical Requirement Target

TUSL	Technical Upper Specification Limit
VIKOR	Vise Kriterijumska Optimizacija Kompromisno Resenje
VOC	Voice of Customers
VOE	Voice of Environment
W	Weight

CHAPTER 1

INTRODUCTION

1.1 Background

Environmentally friendly products can be easily found in any product market nowadays. In product design and development, ISO standard 14062 defines environmentally friendly design as a design with the integration of environmental aspects (ISO, 2002). The integration includes the reduction of the need for virgin raw materials, selection of the right eco-friendly sources of energy, recyclability and bio-degradability, and maximising the product's end-of-life value (Mayyas, Qattawi, Omar & Shan, 2012). In the automotive industry, due to legal and consumer demands, environmentally friendly automotive components have undergone extensive research on their ability to achieve the performance target. This could be a challenge for automotive manufacturers to comply with the environmental concerns while maintaining or improving the performance over the long run. Generally, the initiatives to produce environmentally friendly automotive components include eco-innovation, eco-production and eco-supply chain management (Kushwaha & Sharma, 2016). Among these initiatives, eco-innovation is very important since it requires a systematic strategy from the beginning of the process and more costs will be saved if the process is done well.

Innovation includes a process of product design and development where a set of activities are performed to turn the product idea into a marketable and profitable product. One of these activities is concept design development, which is introduced initially in a process to combine the whole product idea into several alternatives for design solutions before the complete, detailed specifications are determined (Ulrich & Eppinger, 2004). In concept design development, the product design specifications that are set up are only used as a guide to ensure the product's ability to achieve the performance target. Regarding this, several decisions have to be made using good decision-making skills that will guarantee the product's future success. The right decision will reduce all the costs involved in the product design and development process (Albiñana & Vila, 2012). The decision-making process is required in the selection of materials and selection of final conceptual design. However, these activities are interrelated and preferably carried out concurrently to save more time and reduce the cost. The selected material will influence the performance and future development of the product. There are other basic design elements that are essential in a product's design and development, especially for mechanical products, which are function, force and failure mode. These elements require clarification with regard to the product's operation as they will influence the decision when selecting the most suitable material and final concept design. Hence, it is necessary to consider all these basic design elements in the product design and development of a marketable and profitable product.

Conceptual design approaches that comply with the environmentally friendly aspect have been proposed by many researchers. These include the selection of environmentally friendly material, which is known as 'green' material or bio-material or natural material. Materials that have a low negative impact on the environment during their production are highly desired for environmentally friendly product design and development. Therefore, 'green' materials such as natural fibre composite are widely found in many product markets. Natural fibre composites, which are known to be recyclable, reusable, highly available and highly corrosion-resistant materials, are a popular choice as alternative materials to steel. Although glass and carbon fibre composites are commonly utilised for their lightweight and high-strength characteristics, the positive environmental impact of the production of natural fibre composites is always the winning point when choosing between these types of composite. Other than fewer emissions during the production of natural fibre composites, the other positive environmental impact is that the incineration of the composites leads to positive carbon credits and energy recovery and has a lower global warming effect. In addition, natural fibre composites contain a higher fibre volume, enabling them to give an equivalent performance to the synthetic fibre composites, which therefore would reduce the amount of polluting base polymer (Joshi, Drzal, Mohanty & Arora, 2004). However, both types of fibre used in the composite have been hybridised to achieve better properties than a single fibre composite can achieve. Therefore, to enhance the strength of the natural fibre and add a positive environmental impact on the application of the glass fibre composite, a natural fibre/glass hybrid composite is applied in many products, especially in the automotive and construction industries (Sanjay, Arpitha, & Yogesha, 2015).

Application of natural fibre composites has been widely found in the automotive industry. The advanced research on this type of material has convinced manufacturers to use natural fibre composites in automotive components. Toyota, Honda, Ford, BMW and Audi are among the automotive manufacturers using natural fibre composites in their automobile models (Faruk, Bledzki, Fink & Sain, 2014). The most common natural fibres used for this purpose are hemp, kenaf, sugar cane, sisal and flax (Ahmed Ali, Sapuan, Zainudin & Othman, 2013). These natural fibres have undergone extensive research and experiments on their capability to be part of the design of automotive components that are subjected to mechanical loading. Currently, natural fibre composites are applied to the door panel, headliner panel, wheel box, roof cover, floor mats, dashboard and bumper. These automotive components are subjected to moderate mechanical loading, and the application of natural fibre composites could reduce the weight of the vehicle in general. In producing a lightweight vehicle, automotive manufacturers have applied carbon or glass fibre composites in a component that is subjected to extreme mechanical loading, such as drive shaft and anti-roll bar. These automotive components are familiar in their traditional material, which is steel alloy, which has great mechanical properties such as being high strength. However, in producing environmentally friendly automotive components, the application of natural fibre in the composite could be considered, as the strength of the fibre could be enhanced by a hybridisation process with glass fibre to produce a hybrid composite, as mentioned previously. Therefore, the production of an automotive component such as a natural fibre hybrid

composite anti-roll bar would not only significantly reduce the weight of vehicle but also reduce the negative impact on the environment.

In this research, an environmentally friendly conceptual design for an automotive anti-roll bar is created with consideration of the application of a natural fibre reinforced thermoplastic composite in a concurrent environment. The design approach includes design elements – which are materials, function, forces, failure mode and geometry – that are interrelated and considered concurrently with assistance from several decision-making and design tools. The main research is focused on the material selection of natural fibres and thermoplastic polymer matrix, development of conceptual design of the natural fibre composite automotive anti-roll bar. Decision-making tools such as the Analytic Hierarchy Process (AHP) integrated with the Quality Function Deployment for Environment (QFDE) are used to select the materials for the natural fibre reinforced polymer composite and the conceptual design is developed by integrating the Theory of Inventive Problem Solving (TRIZ), Blue Ocean Strategy (BOS) and Morphological Chart (MC). AHP is applied in the development of a conceptual design to select the final conceptual design. At the end of this research, a new conceptual design of a natural fibre reinforced thermoplastic composite automotive anti-roll bar is developed that considers customer and environment requirements and satisfies the product design specification.

1.2 Problem Statements

The design of a natural fibre composite-based product is quite challenging, especially in automotive component design. One of the challenges is the difficulty in achieving performance targets in terms of strength and durability. The anti-roll bar is one of the automotive components that have to bear extreme mechanical loads, which are bending and torsion. For this reason, alloy steel is traditionally used as the main material for this application. However, anti-roll bars made of alloy steel are considered heavy. Manufacturers solved this issue by constructing a tubular anti-roll bar, but it is susceptible to breakage. Consequently, a carbon fibre composite anti-roll bar was invented to overcome the weight and stiffness issues in the traditional automotive anti-roll bar design. However, new problems keep arising for the automotive industry due to the introduction of stringent regulations in terms of environmental health and safety policies. Therefore, the application of green materials such as natural fibre in the design of the automotive anti-roll bar could be the next solution to the problems relating to its traditional design.

In order to address the issues concerning the technical requirements of the design of an anti-roll bar and material properties of natural fibre composites, a systematic and structured design approach is required that considers all the basic design elements of mechanical engineering design. Many approaches have been proposed by many researchers but most of them only focus on particular requirements. For example, Awad, Aravinthan, Zhuge & Gonzalez (2012) proposed optimisation techniques that offer a solution for the geometry and materials at the same stage, which is included in the design process when designing composite-based products. Moreover, Mansor,

Sapuan, Zainudin, Nuraini & Hambali (2014b) proposed a conceptual design strategy for composite-based products that includes an inventive solution from the Theory of Inventive Problem Solving (TRIZ). Davoodi Sapuan & Yunus (2008) used geometric optimisation for composite-based component design by changing the volume and size. A systematic design strategy is required where the anti-roll bar's suitable material characteristics, functions, forces to which it is subjected, mechanical failure modes that can occur in its design and geometry specification are all considered together to compute the best design for the composite-based automotive anti-roll bar.

Composite material has unique characteristics where its material properties depend on its constituents, which are the fibres and matrix. Carbon and glass fibre composites are favoured in many industries because they are readily available and can be tailored to the desired material properties. In contrast, natural fibre's properties vary and are influenced mainly by their chemical composition. The percentage of cellulose, hemicellulose, lignin, pectin and water-soluble compounds varies for different types of natural fibre (Furtado, Araujo, Silva, Alves, & Ribeiro, 2014). Ishak, Sapuan, Leman, Rahman, & Anwar (2011) in their experimental study found a significant relationship between cellulose and fibre strength. Moreover, the properties of the natural fibres are also influenced by their origin. The plant's location, quality of the soil, age of the plant and from which part of the plant the fibres (bast, stem or leaf) are extracted will also influence the fibres' properties (Mohanty, Misra, & Hinrichsen, 2000). Therefore, due to this variation, designers have to make the right decision about the most suitable natural fibres to use in a composite automotive anti-roll bar. In product design development, design requirements are highly important to ensure the designed product can achieve the desired performance quality within the desired time and at the right cost. Based on the total design method, market investigation is initially carried out in order to gain a broader view of the design requirements. Design requirements are collected through Voice of Customer, which includes the opinions from stakeholders, end users and manufacturers. In addition, environmental requirements should be included as part of the design requirements to produce an environmentally conscious design. Therefore, it is necessary for the designers to perform the material selection process according to the design requirements from customers and environmental requirements. A material selection process performed under consideration of material constraints also should consider both requirements, so that the selected materials support the design target. Here, a suitable decision-making tool that could connect both requirements and material constraints should be applied to select the right natural fibre and matrix material for the composite automotive anti-roll bar. Prior to this, the customers and environmental requirements should be prioritized using appropriate decision-making method.

1.3 Research Objectives

The research objectives are as follows:

i) To compute priority value for Voice of Customer and Voice of Environment of design automotive anti-roll bar using appropriate decision-making tools
ii) To synthesize the natural fibre to use for a new natural fibre reinforced thermoplastic composite automotive anti-roll bar based on Voice of Customer and Voice of Environment
iii) To synthesize the thermoplastic polymer matrix for the new natural fibre reinforced thermoplastic composite automotive anti-roll bar based on Voice of Customer and Voice of Environment
iv) To synthesize a conceptual design for the new automotive anti-roll bar using the natural fibre reinforced thermoplastic composite and to determine the final design concept based on the anti-roll bar's product design specification.

1.4 Significance of the Study

It is expected that the findings of this study may broaden the application of local natural fibre in the automotive industry, especially for highly technical automotive components such as the anti-roll bar. The environmentally conscious design of the automotive anti-roll bar could be enhanced by considering the environmental requirements in the material selection process. Furthermore, application of Quality Function Deployment for Environment is a new approach in selecting materials for composites while evaluating the quality in terms of environmental aspects in product quality requirements. Moreover, the natural fibre composite automotive anti-roll bar has to compete with the alloy steel anti-roll bar in the market because of the public's lack of knowledge about the performance of natural fibre composites. Therefore, the natural fibre composite anti-roll bar has to have its own market space in order to survive the market competition. Blue Ocean Strategy is applied to increase the value to buyers while creating value innovation and reducing the costs for the natural fibre composite automotive anti-roll bar. Considering the value of innovation is a new approach in natural fibre composite design. Additionally, consideration of potential failure mode analysis of the product with the other mechanical design elements (materials, function, forces, geometry) in developing the conceptual design for the natural fibre composite may improve the public's acceptance and also a better design solution will be generated.

1.5 Scope and Limitation of the Study

The scope of the present research is to perform the conceptual design of a natural fibre composite automotive anti-roll bar that begins with problem definition. In between, several design activities are included, such as market investigation, prioritising design requirements from Voice of Customers and Voice of Environment, developing product design specifications, and material selection for the natural fibre and thermoplastic matrix. In addition, understanding of function, forces and failure mode of the automotive anti-roll bar takes place concurrently in

order to generate ideas for the new natural fibre composite automotive anti-roll bar. The research framework will be developed using a concurrent engineering strategy with employment of the Analytic Hierarchy Process (AHP), Quality Function Deployment for Environment (QFDE), Theory of Inventive Problem Solving (TRIZ), Morphological Chart (MC) and Blue Ocean Strategy (BOS).

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