CRASHWORTHINESS CAPABILITY OF JUTE AND GLASS FIBRE REINFORCED EPOXY TUBES UNDER QUASI-STATIC LOADING CONDITION FOR AUTOMOTIVE APPLICATION

SABAH SALIM HAMZA

UNIVERSITI TUN HUSSEIN ONN MALAYSIA

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SABAH SALIM HAMZA

A thesis submitted in
fulfilment of the requirement for the award of the
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Universiti Tun Hussein Onn Malaysia

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I hereby declare that the work in this thesis is my own except for quotation and summaries which have been duly acknowledged

Student : ……………………………………………

Sabah Salim Hamza

Date : ……………………………………………

Supervisor : ……………………………………………

Prof. Madya Ir. Is. Dr. Al Emran bin Ismail

Co Supervisor : ……………………………………………

Co Supervisor : ……………………………………………

Dr. Kamarul- Azhar bin Kamarudin

For my beloved mother and father

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ABSTRACT

During last few years, the interest in using natural fibers as reinforcement in polymers has increased dramatically. Natural fibers are not only strong and lightweight but also relatively very cheap. This study examined the potential utilization of jute in the crash energy absorption. A combination of hand layup and vacuum bladder technique was kused to search the influence of utilizing jute fibre on crashworthiness parameters of composite materials. To improve the mechanical properties, jute fiber was hybridized with glass fiber. In this work, there are two main parts of study. Firstly, it is to investigate the effect of cross-sectional shapes, number of layers and temperature treatment on the progressive deformation of jute/epoxy composite tubes. Secondly, the suitable type of geometry was chosen to study the effect of hybrid (jute-glass/epoxy) onto the structural designs. All the tests were undergone quasi-static axial crushing of 10 mm/min. Their peak load (P_{max}), mean load (P_m), energy absorption (EA) and specific energy absorption (SEA) were discussed in detail. In the study of types of five geometrical shapes (corrugated, circular, hexagonal, octagonal and decagonal cross sectional) with different number of layers (two, three and four layers). It is found that the corrugated geometric shape with three layers (RHS) gives the best energy absorption (30.92 J/g) in specific energy absorption parameter compared to other geometries used in present study. For the temperature treatment, the results showed that the post-curing by gradual temperature treatment (TT) improved the peak load by decreased with 55% as compared to similar circular specimen without temperature treatment (No TT). From the test, it is found that the substitution of one layer of jute fibre with one layer of glass fibre resulted in an improvement in the crashworthiness parameters than layers jute. The best result was obtained when hybrid jute-glass was used, where the energy absorption and specific energy absorption was improved by about 43% and 31%, respectively.

ABSTRAK

Sejak beberapa tahun kebelakangan ini, minat dalam menggunakan gentian semula jadi sebagai pengukuhan dalam polimer telah meningkat secara mendadak. Gentian semula jadi bukan sahaja kuat dan ringan tetapi juga murah secara relatif. Kajian ini mengkaji potensi penggunaan rami dalam penyerapan tenaga semasa kemalangan. Kombinasi teknik peletakan tangan dan pundi vakum digunakan untuk mencari pengaruh penggunaan gentian rami pada parameter potensi pelanggaran bahan-bahan komposit. Untuk meningkatkan sifat-sifat mekanik, gentian rami dihibridisasi dengan gentian kaca. Dalam kajian ini, terdapat dua bahagian utama. Pertama, ia mengkaji kesan bentuk keratan rentas, jumlah lapisan dan perlakuan suhu terhadap ubah bentuk progresif tiub komposit rami/epoksi. Kedua, jenis geometri yang sesuai dipilih untuk mengkaji kesan hibridasi (kaca-rami / epoksi) pada reka bentuk struktur. Semua ujian menjalani penghancuran paksi kuasi statik 10 mm / min. Beban puncak mereka (P_{max}), beban purata (P_m), penyerapan tenaga (EA), dan penyerapan tenaga tertentu (SEA) dibincangkan secara terperinci. Dalam kajian ini, lima jenis bentuk geometri (keratan rentas bergelombang, bulat, heksagon, oktagon, dan dekagon) dengan bilangan lapisan yang berlainan (dua, tiga, dan empat lapisan) digunakan. Didapati bahawa parameter geometri bergelombang dengan tiga lapisan (RHS) memberikan penyerapan tenaga terbaik (30.92 J / g) dalam parameter penyerapan tenaga tertentu (SEA) berbanding dengan geometri lain yang digunakan dalam kajian ini. Untuk perlakuan suhu, dapatan kajian menunjukkan bahawa pasca pengawetan dengan perlakuan suhu bertahap (TT) meningkatkan beban puncak dengan penurunan sebanyak 55% berbanding spesimen bulat serupa tanpa perlakuan suhu (Tanpa TT). Dari ujian tersebut, didapati bahawa penggantian satu lapisan gentian rami dengan satu lapisan gentian kaca menghasilkan peningkatan parameter prestasi pelanggaran daripada lapisan rami. Hasil terbaik diperoleh ketika kaca rami hibrid digunakan, di mana penyerapan tenaga dan penyerapan tenaga spesifik masing-masing meningkat sekitar 43% dan 31%.

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LIST OF SYMBOLS AND ABBREVIATIONS

ACL	-	Average crushing load
ASTM	-	American society for testing materials
C	-	Carbon
CC	-	Conical circular
CCT	-	Conical circular section tube
CC-X	-	Conical circular Type-X
CC-Y	-	Conical circular Type-Y
CFRP	-	Carbon fibre reinforced polyester
CGG	-	Carbon-glass-glass
CHS	-	Circular hollow specimen
CT	-	Cotton fibre
d	-	Internal diameter
D	-	External diameter
DHS	-	Decagonal hollow specimen
E	-	Young's modulus, MPa
EA	-	Energy absorbed, kJ
ENS	-	Normalized specific energy absorption, kJ/kg
Etotal	-	Total energy absorbed, kJ
ε	-	Strain, %
FRP	-	Fibre reinforced plastic
GCG	-	Glass-carbon-glass
GGC	-	Glass -glass-carbon
GT	-	Glass fibre
HG	-	Hour glass shape
HG-A	-	Hour glass Type-A
HG-B	-	Hour glass Type-B
HG-X	-	Hour glass Type-X

HG-Y	-	Hour glass Type-Y
HHS	-	Hexagonal hollow specimen
ICL	-	Initial crushing load
JFRE	-	Jute fibre reinforced epoxy
KFRE	-	Kenaf fibre reinforced epoxy
L	-	Length
L/w	-	Length/inner width
m	-	Mass, kg
Ø	-	Diameter, mm
OHS	-	Octagonal hollow specimen
P	-	Force, kN
Pi	-	Initial peak force, N
P_{max}	-	Maximum force, kN
PP	-	Polypropylene
RCCT	-	Radial corrugated cross section tube
RCSCT	-	Combination of the circular and corrugated circular cross section
RHS	-	Corrugated hollow specimen
R-KFRE	-	Random oriented kenaf fibre reinforced epoxy
s	-	Displacement, mm
SEA	-	Specific energy absorption, kJ/kg
SHS	-	Square hollow section
t	-	Thickness, mm
t/d	-	Thickness / diameter
t/w	-	Thickness / width
U-KFRE	-	Unidirectional oriented kenaf fibre reinforced epoxy
v	-	Volume, m^3
VARTM	-	Vacuum assisted resin transfer moulding
VR	-	Volume reduction
WT	-	Total energy absorbed, kJ
Wt %	-	Fibre content in weight percentage
ρ	-	Density, kg/m^3
σb	-	Flexural strength, MPa

σ_{max} - Maximum tensile strength, MPa

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CHAPTER 1

INTRODUCTION

1.1 Background

Nowadays, synthetic fibre, such as glass and carbon fibre reinforced plastics (FRP) composites, have been widely used in industry as well as in transportation due to their low weight and good mechanical properties (Shibata *et al.,* 2006; Elanchezhian *et al.,* 2018; Mahdi and Eltai, 2018; Lau *et al.,* 2020). However, the synthetic composite gives rise to environmental pollution due to its non-degradability (Mahdi *et al.,* 2019). On the other hand, with an increasing environmental consciousness and awareness of the need for sustainable development, natural fiber-based bio-composite materials are now emerging as viable alternatives to glass fibers either alone or in a hybrid form in composite materials for various applications (Mache, Deb, and Gupta, 2020). Natural fibers' advantages over synthetic fibers such as carbon, boron, glass, etc., are low cost, low density, competitive-specific mechanical properties, sustainability, recyclability, and biodegradability (Dastan, Safian and Sheikhzadeh, 2020; Karthika, Deb and Venkatesh, 2020). Extensive researches have been carried out on the energy absorption attributes of synthetic fiber-based composite materials. However, relatively limited studies have been reported on the energy absorption capabilities of natural fiber-based bio-composite materials.

In the axial composite collapsing review, the carbon and glass FRP have been greatly investigated (Lau, Said, and Yaakob, 2012). Various shapes, structure geometries, and type of fracture modes, which contributed to better energy absorption, have been reviewed. (Abosbaia *et al.,* 2003) reported that behaved axial collapsed on cotton fabrics. In the test, filament-winding manufacturing was utilized, adopting the stacking concept. From the study, cotton has deformed progressively.

Furthermore, the folding formation was observed after peak load at 5.43 kN. Apart from that, (Mahdi, Hamouda and Sen, 2004) examined solid cones fabricated of oil palm fibers and coir fibers reinforced polyester composite structures. In their work, it was found that cone vertex angles affected the peak loads. However, the types of fibers utilized in the tests affect the crashworthy parameters. Despite all the structures deformed progressively, specific absorbed energy (SEA) of NFRP composites were relatively low compared to glass and carbon fibers reinforced plastic, which for coir, cotton, and oil palm reinforced plastic composite at 2.501 kJ/kg, 0.633 kJ/kg, and 0.577 kJ/kg, respectively.

Therefore, a hybridization with natural fibers using a single reinforcement is a proposed solution to a potential method to solve this matter. Besides, the combination of natural and glass fibers contributes to the production of hybrid composite structures with desirable mechanical properties as well as being less expensive and facile to use (Ramesh, Palanikumar and Reddy, 2013a). The usage of two types of fibers in an appropriate composition leads to synergistic performance, thus producing a hybrid compound with better performance characteristics than the singular fiber performance. Many researchers have reported that hybridizing using high strain to failure fiber will be an efficient way to improve the impact strength of low strain to fiber composites (Kalaprasad *et al.,* 1996; Samal, Mohanty and Nayak, 2007; Tonoli *et al.,* 2011).

In work compiled by (Ramakrishna, 1997), fiber materials and their constituent, fiber architecture, and fiber content affect the SEA. Due to this, crashworthy composite materials can be customized by mixing the fiber lay-up effect. Moreover, (Hadavinia and Ghasemnejad, 2009) reported investigating the influence of various layers of fiber architecture. The study revealed that composites with layers $[0/45]_2$ have greater SEA than composites with layers $[0]_4$. However, deform load efficiency for composites with layers $[0]_4$ is the greatest due to the composite's initial maximum crush load. In another investigation by (Solaimurugan and Velmurugan, 2007), two types of tubes with four and six combinations of fiber lay-up have been studied. From the study, FRPc with a combination of the most unidirectional fibers (along the composite specimen) close to internal diameter led to the best energy absorbing characteristics because of the resistance of bending and smaller radius of curvatures.

A few studies on using natural jute mat and hybrid compound reinforced glass fibers/polymer for quasi-static loading from the literature. Despite that, jute is the second most natural and biodegradable fiber. Jute fiber is an excellent alternative when strength, thermal conductivity, and cost are major concerns (Wang *et al.,* 2019). Besides, jute fibers are also eco-friendly. Nowadays, jute fiber-reinforced polymer composites have become an important research area (Ahmadi and Dastan, 2017; Sinha, Narang, and Bhattacharya, 2017; Selver, Ucar, and Gulmez, 2017; Ilman and Hestiawan, 2018). Typically, jute fiber is used for basic and low-end textile products. If the jute properties could be modified in favor of high-value and technical textiles, the cost and the environment would benefit a great deal (Wang *et al.,* 2019).

The advantages of these composites include: (a) being conducive to occupational health and safety during fabrication of parts as well as handling as compared to GFRCs, (b) low cost, especially when compared to carbon fibre reinforced composites, (c) renewability and biodegradability of fibers and (d) aesthetic appeal. Jute fibers are specifically relevant in this context as jute fabric has a consistent supply base, particularly in South Asian countries, and has reliable mechanical properties (Karthika, Deb, and Venkatesh, 2020). Furthermore, the addition of jute fibres in glass fibres shows an effective and value-added application of the composite application (Gopinath, Kumar and Elayaperumal, 2014). In addition, relatively limited studies have been reported on jute fiber-based bio-composite materials on energy absorption capabilities. Therefore, in the current study, a study on natural fiber/polymer and hybrid jute-glass/polymer under quasi-static loading was proposed to be carried out. This study assesses the (SEA) and the corresponding failure modes by implementing various tests based on several parameters.

1.2 Problem statement

In recent decades, the trend has been made by researchers and manufacturers to produce lighter vehicles instead of metallic structures used nowadays. In the near future, vehicles must be lighter to meet the requirements for reducing fuel consumption and carbon dioxide emissions but provide higher occupant safety (Borazjani, 2017). One way to reduce fuel consumption is to use a lightweight structure, but this should not cause any change in occupant safety. Therefore, natural fibers have been proposed as an alternative to traditional materials due to their combined properties of high stiffness and strength to weight ratio, creep resistance, resilience, good damping property, corrosion resistance, abundant, and low cost. Besides, they can be biodegradable, recyclable, do not cause carcinogen to human beings, and have not created a greenhouse effect, unlike synthetic composite fibers (Wambua *et al.,* 2003; Chin and Yousif, 2009). Among natural fibre reinforcements, jute fibres have gained much attention during recent years. Generally, jute is a relatively inexpensive vegetable bast fibres, with some intrinsic advantages, such as low extensibility, high strength, silky luster, and high modulus. It also shows a more densified and compact structure than other natural fibres. Applications of jute fibre reinforced composites are found in such products as automotive parts (Gujjala *et al.,* 2014; Ahmadi and Dastan, 2017). Furthermore, the addition of jute fibres in glass fibres showed an increase in the composite's mechanical properties. Hence, jute fibre shows an effective and value-added application (Gopinath *et al.,* 2014; Torres *et al.,* 2017).

Apart from the preceding mentioned, the crashworthiness of transportation structure as a factor for the safety of structures has become a serious issue with the society's development and daily vehicle usage. Crashworthiness is defined as structures' ability to protect their passengers in a survivable collision (Sivagurunathan *et al.,* 2018a). However, natural composite structures' findings exhibited that specific energy absorbing (SEA) value is somewhat low compared to synthetic composites such as carbon or glass fibers. Therefore, they may not be suitable for many structural components in which high energy absorption and excellent post-failure integrity are required. Hybridizing jute with glass fibres can be proposed as a suggested technique to address this problem (Ahmadi and Dastan, 2017). For that, it was proposed to add a small quantity of glass fibers to the jute fiber-reinforced polymer matrix to enhance the mechanical properties of the composite structure. Combining two or more fibres in the same composite is expected to provide performance improvement using individual fibres' merits.

In most cases, one of the fibres in the hybrid composite is high modulus fibre, such as glass, while the other one is low modulus fibre, such as jute. The high modulus fibre contributes to stiffness and load-bearing capability. In contrast, the low modulus fibre makes the composite more damage tolerant, where the damage tolerancea property of a structure relating to its ability to safely sustain defects is a property of a structure relating to its ability to sustain defects safely during use. This approach provides a balance of strength, stiffness, toughness, and weight reduction (Reddy,

Reddy, and Madhu, 2016). Thus, it is predicted through the hybridization process to obtain a higher energy absorption capacity than non-hybrid jute tubes.

1.3 Objectives

In the current study, there are three main objectives, which are:

(i) To examine the influence of different number of layers and gradual thermal treatment on the energy absorption and progressive crushing behaviour.

(ii) To investigate using different cross-section effects onto energy absorption using jute fibre reinforced epoxy composite.

(iii) To study crushing performance for tubular using hybrid jute-glass fiber reinforced epoxy and compare with the existing products reports.

1.4 Scope of research

The present study consists of three main parts, which are the type of manufacturing for the composite tubular specimens, an experimental study on the crushing characteristics for the fabricated tubes and interpretation of the results of the existing samples with support from other literature, as well as evaluate the results by comparison with the previous studies.

Firstly, in manufacturing of the specimens, two groups of composite tube specimens were fabricated:

1) Group 1: five different geometrical shapes (corrugated, circular, hexagonal, octagonal, and decagonal) with different numbers of layers (two, three, and four layers) were chosen using natural jute fibre reinforced epoxy. Furthermore, temperature treatment for post-curing was adopted.

2) Group 2: based on the first stage's best results, hybrid tubes were made using jute-glass fibre reinforced epoxy with the best geometry to improve the proposed design's crashworthiness performance. For both types of tubes, the principle of a combination of manual layup and vacuum compression bladder technique was used. All tube specimens were fabricated with the same length of 100 mm and an inner diameter of 50 mm.

Secondly, the fabricated composite tubes had undergone experimental testing. The testing included axial quasi-static crashworthiness, and analysis was done to understand failure mechanisms.

For the final part, the test data have been interpreted with support from other literature. Moreover, the prior works benchmark has been used to reference these newly fibre reinforced epoxy composite tubes.

1.5 Significant of the study

This study seeks to find alternative composite materials to manufacture structures that will maintain the environment through their ability to decompose and biodegradability. It reduces carbon dioxide through the weight reduction of the vehicle without compromising its occupants' safety.

1.6 Thesis layout

This thesis is organized into five chapters.

In chapter 1, the introduction covers three main objectives, which ultimately determine the direction of this research study and the activities undertaken towards its completion.

Chapter 2 provided the literature regarding the studies related to the axial crushing of the composite structures, recent crashworthiness of natural and natural-hybrid fiber reinforced plastics composites, and designs related to the current works.

Chapter 3 described the steps taken on fiber preparation, composite preparation, and experimental procedures.

Chapter 4 presented the results and discussions on the crashing characteristics and failure analysis of the scale structures and prototype structures.

Last but not least, chapter 5 gave a highlight summary of the studies. Moreover, the recommendation of the future work was hinted at to improvise the current work.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter displays a review of researches that has been achieved by employing fiber-reinforced polymer for crashworthiness, which comprises natural fibers and synthetic fibers such as glass and carbon fibers. This review concentrates on some of the essential matters related to composite elements testing for crashworthiness parameter estimation. First, the energy absorber concept was being presented. Secondly, failure modes and their relationship to the energy absorption amount will be discussed during the axial crushing test. Third, factors affecting crashworthiness during loading testing with an emphasis on experimental collapsing responses and the associated methods will be reviewed. The focus on using natural fibers as an essential component of the structure. Finally, it draws a close by remarking on the main results of these researches and their relevance to the topic of this study.

2.2 Background

The usage of advanced materials with high ratio of strength/weight and stiffness/weight is highly required mechanical properties for the manufacturing of the structure that is used in the transportation and engineering fields in particular, where reduction of weight is a significant criterion as well as the ability of structural crashworthiness (Stapleton and Adams, 2008). As such, safety is being concerned when structures were made from fiber-reinforced composite materials when they failed especially in collapsible events. Therefore, it is critical to do research for the crashworthiness of recently designed materials and structures. Moreover, the application of fiber-reinforced polymer composites demonstrate to have preferable energy absorption per unit mass or specific energy absorbed (SEA) compared to metallic structures (Hosseini and Shariati, 2018). According to the literature (Bambach, 2010; Palanivelu *et al.,* 2011), many researchers choose to use synthetic fibers, like kevlar, carbon, and glass fiber reinforced polymer composite materials because their properties can be enhanced or changed the characteristics of resins such as polyesters and epoxy resins (Ochelski and Gotowicki, 2009). However, due to the increased awareness of greenhouses effects, the current trend of energy-absorbing structures have shifted to using natural fibers instead of synthetic fibers (Ataollahi *et al.,* 2012; Alkbir *et al.,* 2014; Eshkoor *et al.,* 2014). The natural fiber materials are regarded as one of the modern engineering materials. The concern in this field is quickly mounting whether in fundamental research or industrial applications, due to its fully or partially recyclable, biodegradable, renewable, cheap, and abundantly available. Among all natural fiber-reinforced materials, jute seems to be an encouraging material to use as it is relatively cheap and available in the desired form, as well as its acceptable mechanical properties (Sanjay and Yogesha, 2016).

However, an important aspect that must be considered in the design is the crashworthiness and damage tolerance to provide the highest level of safety, which is through improving the ability of the structure to dissipate energy during the collision (Kalhor and Case, 2015). Crashworthiness is the structure's ability to dissipate the crash force in a controlled mechanism. Thus, it ensures that the designed structure is able to reduce the external force to which passengers are exposed and results in reduced injury to passengers during crash events. The assessment of crashworthy is decided by the execution of series crushing tests (Paul, Ramachandran, and Gupta, 2019).

The structure during a collision accident must dissipate impact energy through a sustainable crashing force and bring the occupant cell to rest with the least possible acceleration. Fast alteration in deceleration must be evaded. The structures that lessen the influence of the impact are called the energy-absorbing body. If the peak load acceleration drops slowly and in a controlled form during the collision, the injuries to the vehicle occupants can be reduced. Therefore, impact of energy absorption systems must be restricted by controllable deformation as much as possible (Reddy, Rao and Narayanamurthy, 2017).

2.3 Characterization in energy-absorption

In the axial deformation, the test is performed by quasi-static or dynamic compression. For static compression, the tube is placed between parallel steel platens, pressurized by a hydraulic press at usually usual speeds between 1-11 mm/min of the upper platen. For the dynamic test, it is performed by utilizing impactor or dropping a hammer. Accordingly, the dimensions of specimens were determined depending on the initial calculations to define the geometry of tubes to avoid buckling failure (Rabiee and Ghasemnejad, 2017). Tested tubular specimens have typical dimensions of (20-100) mm in width/outer diameter, (50-125) mm in length, and (1-3) mm tube thickness. However, varied geometrical shapes were used for the test like square, hexagon, circular (Palanivelu *et al.,* 2010a), semi-hexagonal (Esnaola *et al.,* 2018), corrugated (San and Lu, 2020), decagonal (Hussain, Regalla and Rao, 2017), and cone (Kathiresan, 2020).

Crashworthy is one of the crucial parameters that need to be deemed during evaluating the safety of structural components. Besides, it is apprehensive with the absorb energy by controlling the failure manner so that the impact energy is absorbed by progressive manner while maintaining a gradual decay in the load profile (Vinayagar *et al.,* 2020). The crashworthiness parameters can be analyzed and computed mathematically based on a typical load-displacement history which is illustrated in Figure 2.1.

The test is an actual indication of a response during the crushing process. The crushing force and energy-absorbing capability can be evaluated by the load-displacement graph (Othman *et al.,* 2014). Data acquired by the axial deformation test of a specimen is employed to plot the load-displacement graph, as depicted in Figure 2.1. The initial stage of a load-displacement graph begins with a dramatic increment in force until it attains a peak load. And then an insignificant drop in loads and followed by a sustainable deformation region. A sustained collapse force will be noticed as the specimen is constantly pressed until it arrives at a point where the graph starts to increase. This zone is known as the condensation or compaction zone when sustained collapsing is finished (Magkiriadis *et al.,* 2006). Thus, the graph consists of a pre-crushing zone, a post-crushing zone, and a compaction zone, which indicated the main points on the curve to exhibit the initial deformation point, the maximum load, and the compaction area (Aziz, 2015).

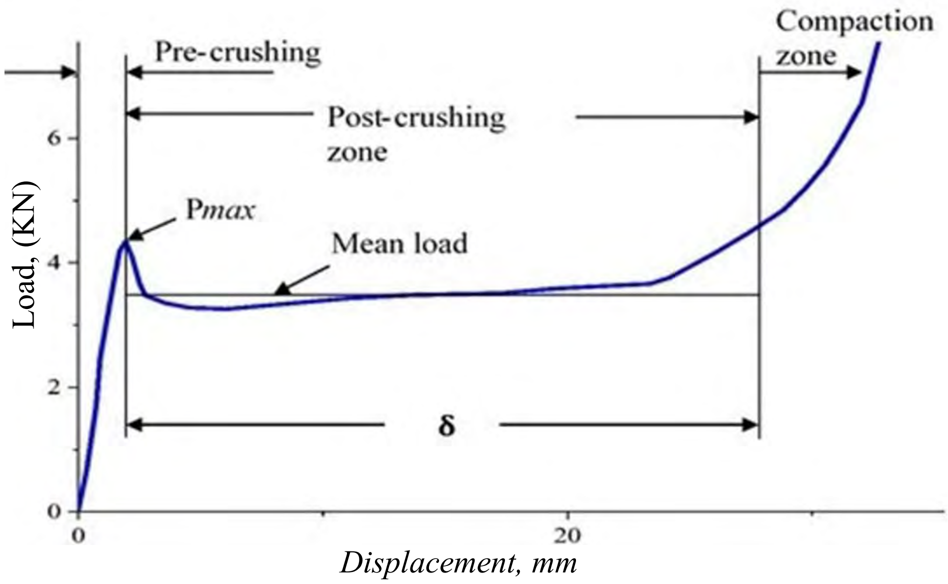

Figure 2.1: Typical load – displacement zones history of a pattern tested under quasi-static loading (Aziz, 2015)

2.3.1 Peak load (P_{max})

The peak load (P_{max}) is the maximum impact force required to initiate plastic deformation in the EA structure. If it is low, the structure will deform at low-speed impacts with low TEA. If it is high, it induces high-intensity decelerations, which are unsafe for the occupants. The structure should exhibit an initial peak force whose accelerations are within the human tolerance limits (Reddy, Rao, and Narayanamurthy, 2017). It is the highest load value except for the compaction region. It normally lies in the elastic or plastic region over a load-displacement graph (Sivagurunathan *et al.,* 2018a).

2.3.2 Mean load (P_m)

The mean load (P_m) can be evaluated by averaging the total crushing load over the post-crushing zone's total deformation length. Thus, the mean load can change over collapse length distance based on a crush fashion (Sivagurunathan *et al.,* 2018b), computed by the equation below

$$P_m = \frac{1}{\delta}\int_0^{\delta} P \, d\delta, \tag{2.1}$$

Where P and δ are total load applied (kN) and displacement (mm), respectively. Moreover, the energy absorption amount is extensively based on the mean load value (Eshkoor *et al.,* 2013a). Mean load (P_m) depends on the rate of sustainable loads. Therefore, it mainly contributes to increasing the total energy absorption by raising the average loads that will be further explained in the following section. In this study, the compression test was conducted for full compaction. However, in the calculation, only 80% of the deformation was considered for easier verification.

2.3.3 Energy absorption (EA)

The energy absorption or work done represents the zone underneath the load (kN) versus displacement (mm) graph during the compression test. The EA was calculated in the computation until the area before the compaction point occurs, as given by equation 2.2 (Aziz, 2015).

$$EA = \int_0^{\delta} P \, d\delta, \tag{2.2}$$

Where P and δ are the applied load (kN) and the incremental displacement (mm) over the deformation process, respectively. However, the compaction region was not considered because it produces slight absorbing energy compared to the post-deformation region. Otherwise, the effect of the failure manner effectively influences the behaviour of the load (kN) versus displacement (mm) graph. When a gradual failure of the material occurs, it will produce a larger area below the curve and become more stable. In contrast, when a catastrophic failure results in a steep drop in the load, thus the space below the curve is as little as possible with the load curve's instability (Lau *et al.,* 2012).

2.3.4 Specific energy absorption (SEA)

Due to the difference in materials and geometry of each specimen used in studies, the evaluation through total energy absorption to determine the structure's capability to dissipate energy may be misleading (Mahdi and Sebaey, 2014a). To make a more realistic comparison among the geometric specimens, it should be based on SEA. It represents the efficiency and capability of energy absorbed during the deformation of structural, which is defined as the total energy absorption resulting from the sum of the areas under the curve until the densification area divided by the crushed mass of a specimen, which is calculated by following equation (Xu *et al.,* 2016b).

$$SEA = \frac{EA}{m}. \tag{2.3}$$

Here, SEA is the energy absorbed per unit mass (J/g) and m is the mass of the specimen's crushed portion (g). Likewise, the SEA parameter in the J/g unit is utilized to compare the findings among the various researches when the lightweight structure is the priority. The larger SEA value reveals the higher energy dissipation efficiency concerning weight (Mahdi and Sebaey, 2014a).

2.3.5 Crush force efficiency (η_c)

Specific Energy absorbers (SEA), peak load (P_{max}), and crushing efficiency(η_c) are the most important criteria that should be taken into account in assessing the crashworthiness of designed structures (Alkbir *et al.,* 2016b). Here, η_c is defined as the ratio between the mean load (P_m) to peak load (P_{max}), as illustrated in the equation below:

$$\eta_c = \frac{P_m}{Pmax}, \tag{2.4}$$

Where η_c, P_m, and P_{max} are the crush load efficiency, mean crushing load (kN), and the maximum peak load, respectively. When η_c has a high value, it is a clear indication of effective crush and stability near the value of unity. In contrast, when the efficiency value is low, it indicates a sharp decrease in the average loads from the peak load, as illustrated in Figure 2.2 (Boria, Scattina, and Belingardi, 2018). Typically, when the mean load is close to the peak load, energy is absorbed in a controllable way. However, for the quasi-static test, the η_c value from (0.6 - 0.8) has been considered a favourable value for effective structure, while in the impact test, this value is as minimum as 0.4. The larger the variance between P_{max} and P_m, the greater the abrupt increment in acceleration, leading to increased injuries to passengers (Roslan *et al.,* 2017).

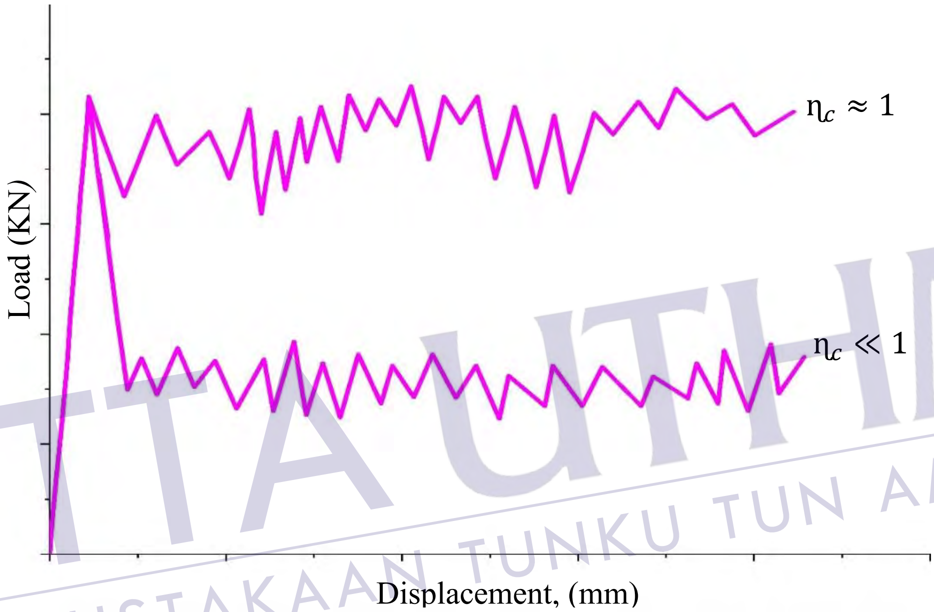

Figure 2.2: Crush load efficiency (Boria *et al.,* 2018)

2.4 Failure mechanisms of FRP structures

Numerous parameters, including the maximum peak load, the sustained deformation load, and the stroke displacement, are considered in typical crashworthiness designs. The energy absorber capacity of a structure is characterized by the space underneath the load versus displacement graph, heavily dependent on the failure mechanisms (Aziz, 2015). The failure mechanism of composite includes fiber fracture, matrix cracking, fiber-matrix deboning, delamination, and interplay separation. Generally, composite failure modes are divided into two main categories of catastrophic and progressive modes (Jimenez *et al.,* 2000).

2.4.1 Catastrophic failure

The effective designs for energy-absorbing structures need to evade a catastrophic collapse manner. This is because of the sudden and rapid increase in the load value during catastrophic failure, followed by a sharp decrease in load with the beginning of the post-crushing stage. Thus, great harm is caused to passengers during the collision, as the structures of this type are unable to absorb the impact energy adequately to avoid the danger. After catastrophic failure, the specimen is no longer qualified to maintain a large compression load (Meidell, 2009).

A thin specimen might buckle due to column instability, as depicted in Figure 2.3a. Likewise, interpenetration might happen when the buckling stress is large as circumferential cracks form nearby the center of laminates and the wall split, as illustrated in Figure 2.3 (Hosseini and Shariati, 2018). However, upon interpenetration happens, the structure does not completely fail, and the two halves of the specimen continue to support each other. Lastly, laminate delamination can happen unstably. Specifically, the outer and inner layers may bend outward while the laminate layers remain in the center of a specimen layer without support to fail at low load. This failure is known as a barreling, as depicted in Figure 2.3c (Hosseini and Shariati, 2018).

The mode-III occurred due to the broken in the specimen's mid-plane, as illustrated in Figure 2.4 (Bambach, 2010), or had longitudinal cracks (Palanivelu *et al.,* 2010c). Likewise, the composite energy-absorbing device deform conduct is the most unstable, with energy-absorbing increasing and dropping erratically. The instability is one of the most critical problems in utilizing composite structures for crushing energy management (Abosbaia *et al.,* 2003).

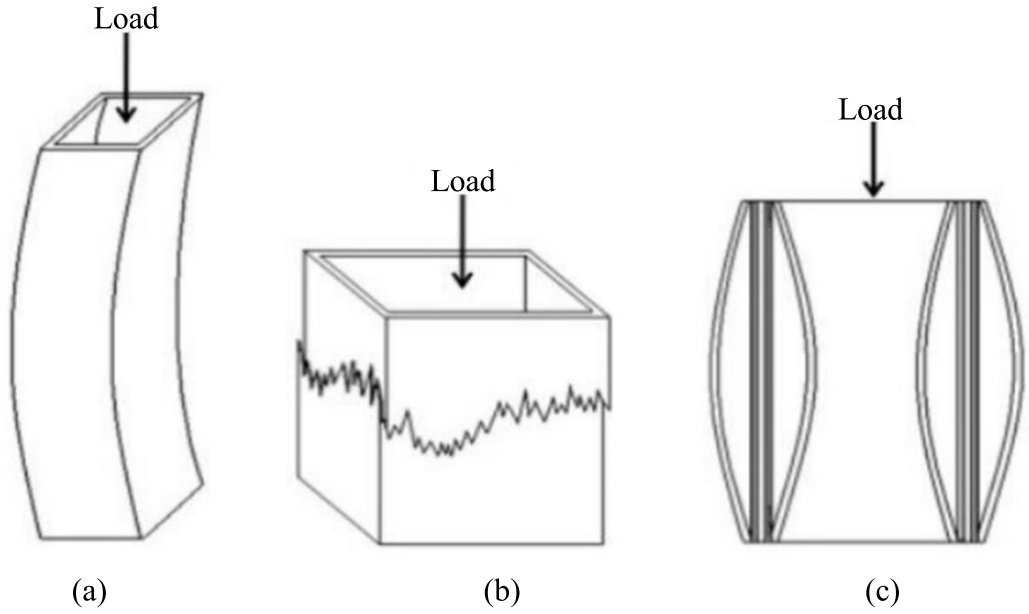

Figure 2.3: Unstable failure manner of, (a) global buckling, (b) interpenetration, and (c) barreling (Hosseini and Shariati, 2018)

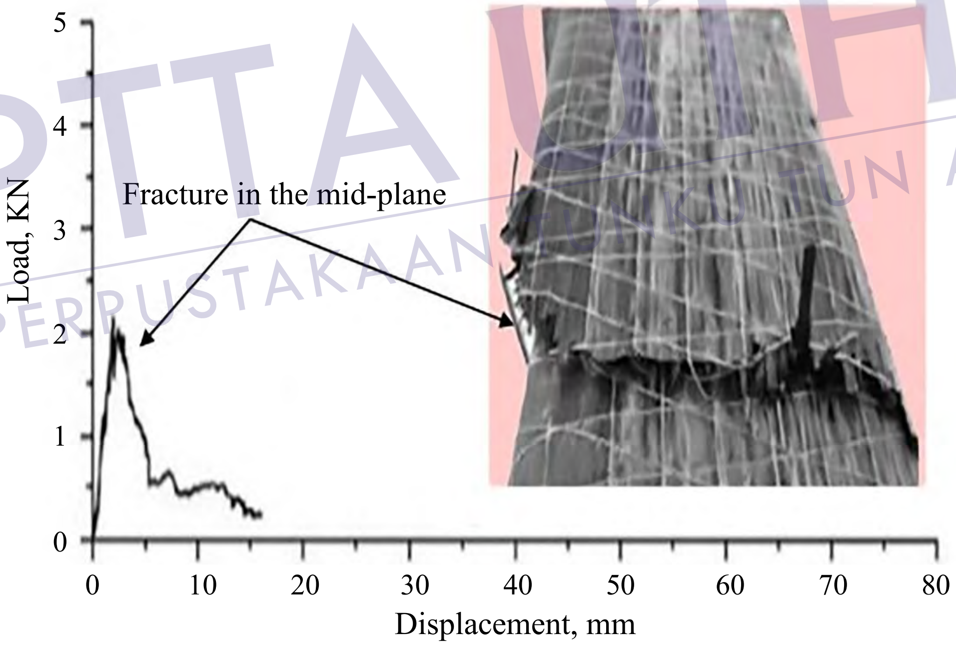

Figure 2.4: Mid-plane break in catastrophic failure (Bambach, 2010)

2.4.2 Progressive failure

Progressive failure in the composite specimen is characterized by a gradual increment in load until the onset of failure, which is continued by a systematic gradual deformation. This manner of failure greatly contributes to improving the energy absorption capability of the composite specimens. Therefore, with a large energy dissipation capacity by a gradual decay of crushing, there is no need to increase the structures' weight (Chen *et al.,* 2020). The failure manner influences the behaviour of the load (kN) vs. displacement (mm). It is represented by an increment in the energy absorption area beneath the curve and the load stability during the post-crash phase, as illustrated in Figure 2.5 (Lau *et al.,* 2012).

Four types of progressive failure have been reported through the previous studies in this area, namely a fragmentation or transverse shearing manner, lamina splaying or bending manner, a brittle fracture, and progressive folding or local buckling manner. These crushing modes are very useful in manufacturing the structures to decelerate an object, essentially during a crash or impact event. Both ductile and brittle fibers reinforced composite shown the local buckling modes. However, only brittle FRP can crush in the lamina bending and transverse shearing manners (Rabiee and Ghasemnejad, 2017). In this section, each mode is described and further discussed.

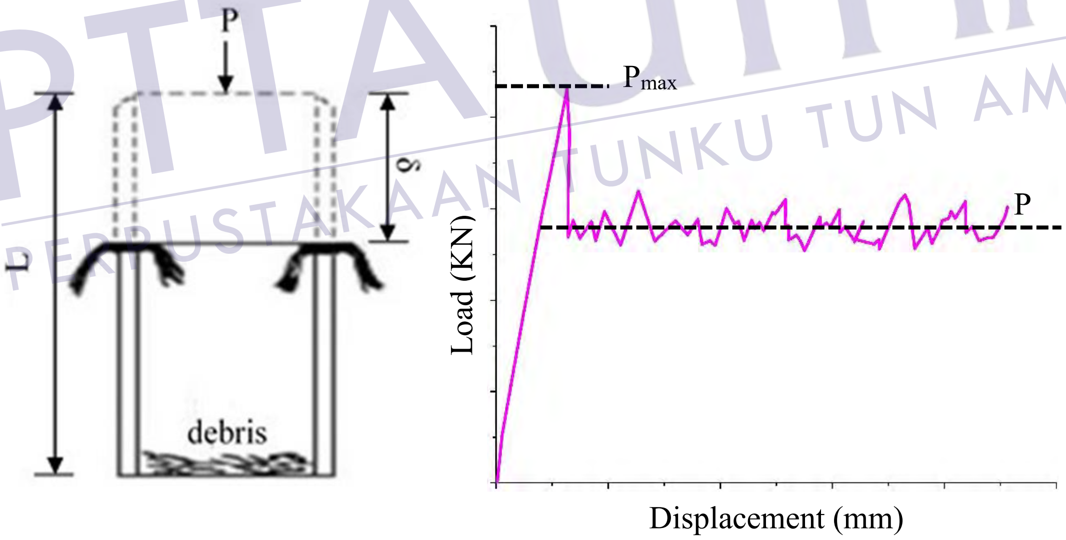

Figure 2.5: Energy absorption in progressive failure (Lau *et al.,* 2012)

2.4.2.1 Lamina bending or splaying mode

It is characterized by a long intralaminar, interlaminar, and parallel to the cracks of the fibers, as depicted in Figure 2.6. This mechanism results in the formation of continual laminate fronds, which propagate outwards and inwards. Frictional effect and inter/intralaminar fractures control the energy dissipation of laminate splaying mode.

These laminate bundles are split and bend down either outside or inside the specimen walls and compelled through the curvature radius by compression load. This radius depends on matrix, fibers, and lamina properties (Rabiee and Ghasemnejad, 2017).

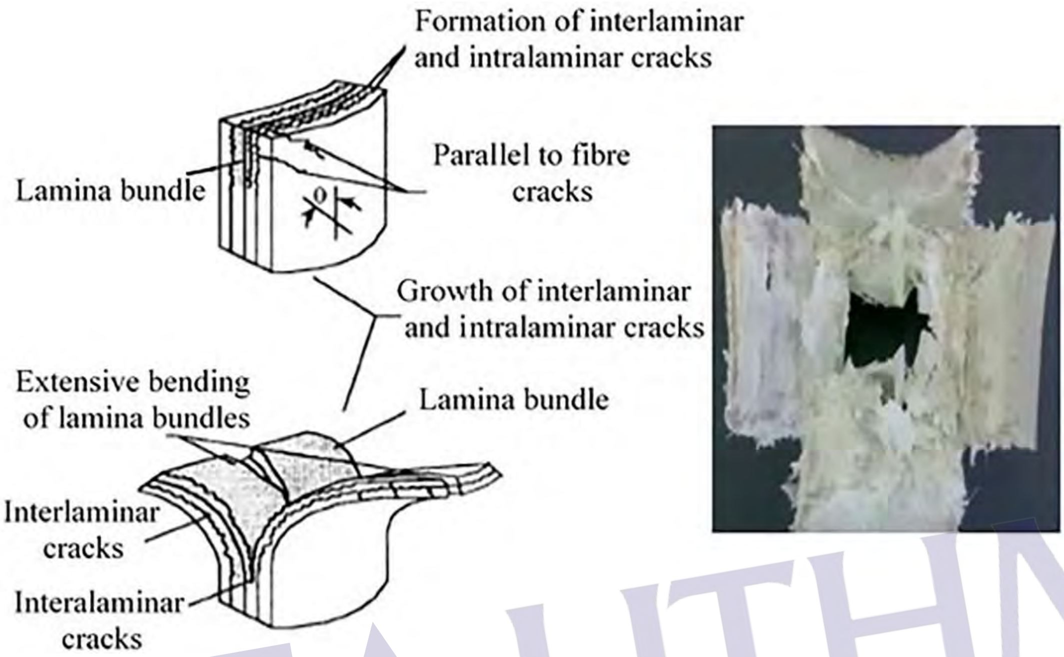

Figure 2.6: Laminates bending crushing modes (Rabiee and Ghasemnejad, 2017)

2.4.2.2 Fragmentation (transverse shear) mode

It is described as a wedge-shaped lamina cross-section with one or multi longitudinal and short interlaminar cracks, as illustrated in Figure 2.7. This mechanism, interlaminar cracks spread, and bundles fracture dominate the energy dissipation (Wang *et al.,* 2016; Rabiee and Ghasemnejad, 2017). In this failure mechanism, lamina bundle fracture and interlaminar crack propagation dominate the energy absorption. The specimens that deform in a fragmented manner have a minimal failure strain and large stiffness. This failure manner is only shown by a structure that is made utilizing brittle fiber. The compression loads result in an irregular load transfer to the composite structure, which forms a scalloped surface when the specimen is deformed, as depicted in Figure 2.7.

The number of cracks, location, and length depends on the structure's material properties and geometry in a composite structure. The process of transverse shearing or fragmentation failure shows interlaminar cracks and longitudinal, which are lower than the laminate thickness (Hadavinia and Ghasemnejad, 2009).

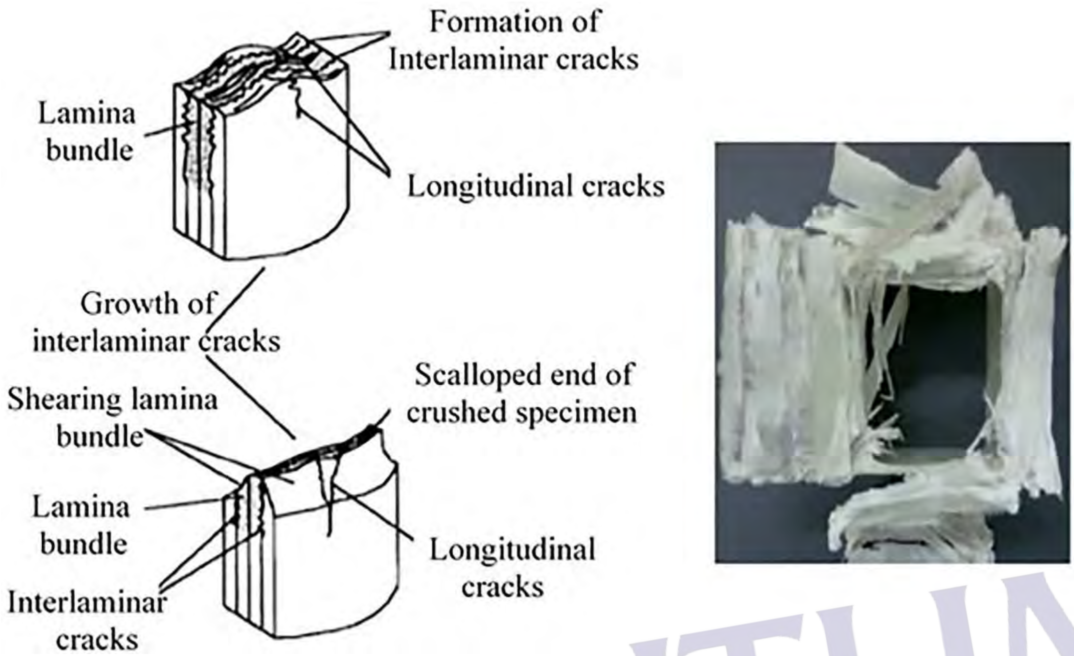

Figure 2.7: Fragmentation-crushing mode (Rabiee and Ghasemnejad, 2017)

2.4.2.3 Brittle fracture mode

It is described by a combination of fibers laminate bending and fragmentation (transverse shearing) collapsing modes. In this manner, the interlaminar crack length is between 1 to 10 laminate thicknesses. This mechanism mainly contributes to the energy-absorbing by fractures of the laminate bundles. It has been observed that the greatest absorption energy for composite structures is by lamina bending and brittle fracturing collapsing mode (Hadavinia and Ghasemnejad, 2009). Interlaminar cracks shown in brittle fractures manner are smaller than those in the laminate splaying modes but bigger than those in transverse shearing (fragmentation) manner. The length of broken laminate bundles majorly affects the crush failure efficiency, where the smaller broken laminates will lead to the greater efficiency of energy dissipation. Laminate bundle in brittle collapsing manner encounters some bending, where it usually collapses at the end of the specimen. The fracturing mode causes load redistribution within the tube (Borazjani, 2017).

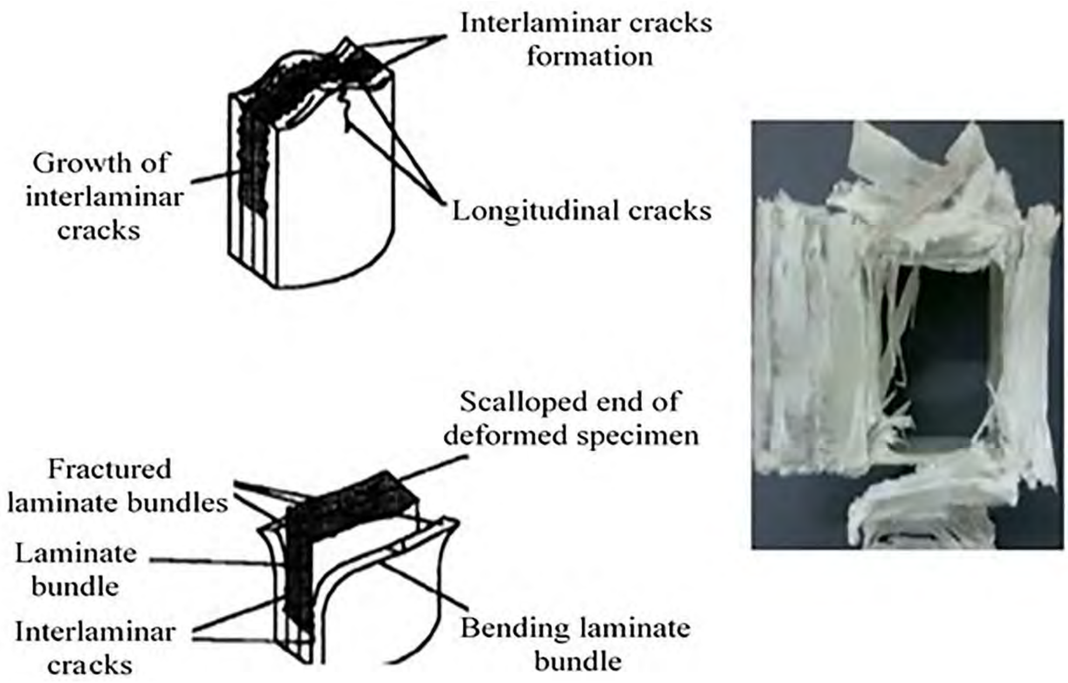

Figure 2.8: Brittle fracturing crush (Rabiee and Ghasemnejad, 2017)

2.4.2.4 Local buckling mode

It is characterized as progressive folding, which is fundamentally shown by ductile fibers reinforced composite specimen. This deformation mode is similar to metallic structures' failure mechanism when compression occurs in axial load (refer to Figure 2.9). Local buckling mode happens in brittle FRP composite specimen when (i) the fibers have less failure straining than the matrix, (ii) the interlaminar stress is low compared to the matrix strength, and (iii) the matrix shows plastic deformation failure under large stresses (Hadavinia and Ghasemnejad, 2009). Structures failing in a folding deformation mechanism may encounter many interlaminate and longitudinal cracks through hinges formation. Fibers fracturing also may occur, mostly on the hinge of the tension sidewalls. These composite specimens remain undamaged after being deformed, demonstrating the integrity of post-collapse. Progressive folding collapsing is also stated in slender-walled composite specimens. The folding process and crush load count on the specimens' shapes and dimensions (Ramakrishna and Hamada, 1998).

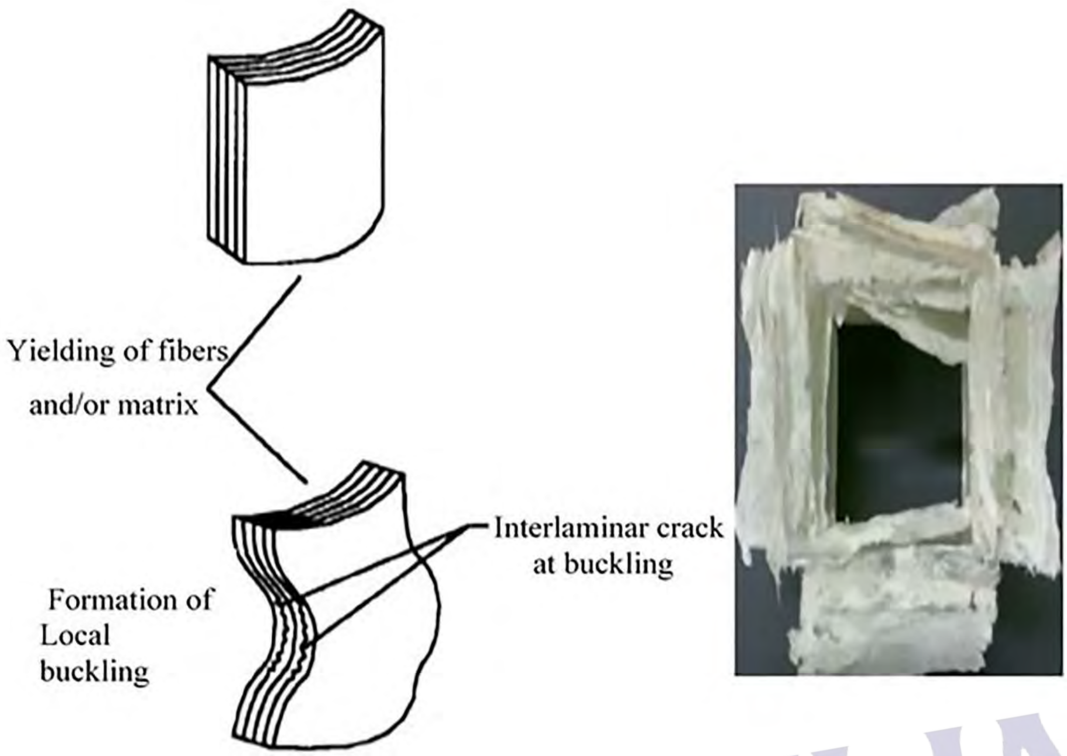

Figure 2.9: Local buckling crush modes (Rabiee and Ghasemnejad, 2017)

Briefly, during the occurrence of a progressive crushing, the fronds bending or splaying mode following the increase of the center interwall cracks because of delamination in the sidewall lead to the highest energy dissipation. The main central interlaminate (interwall) cracks propagation are mode-I. Whilst, mode II is a combination of bending medium length and transverse shearing, which often occurs as a result of the bending stress within the lamina bundles (Hu, Luo and Yang, 2010). In other words, in modes (I and II), splay (bending) mode and laminate bundles that sliding within each other in the mode, respectively, lead to bigger energy dissipation (Ghasemnejad, Hadavinia and Aboutorabi, 2010) as depicted in Figure 2.10 on account of the frictional effect between lamina fibres and curvature (Mamalis *et al.,* 2005b; Lau *et al.,* 2012).

Furthermore, fibres orientation played a key role in mode I interlaminar fracturing toughness, matching with prior study (Hadavinia and Ghasemnejad, 2009). Moreover, Mode III exhibits an abrupt decline in load capacity directly after the initial maximum peak. The drop in the load is noticed to be higher than crushing by Modes I and II. This case is due to the cracking of the matrix that results in fragmentation fibers. Transverse shear (fragmentation) leads to a significant decrease in the carrying capacity. The fragmentation mechanism is described as a shear into smaller pieces in the circumferential direction. In this mode, the load (kN) vs. displacement (mm) curve grows progressively after the minimal value of the load, indicating load resistance (Rabiee and Ghasemnejad, 2017). Finally, mode IV is similar to the deformation failure mode by metallic structures when compressed in the axial load. This failure is large enough for local buckling to occur due to stress in the specimen wall, creating a hinge. Upon the stress increment to a certain boundary, one more hinge is created under the prior, and so on till the entire specimen wall length is deformed (Rabiee and Ghasemnejad, 2017).

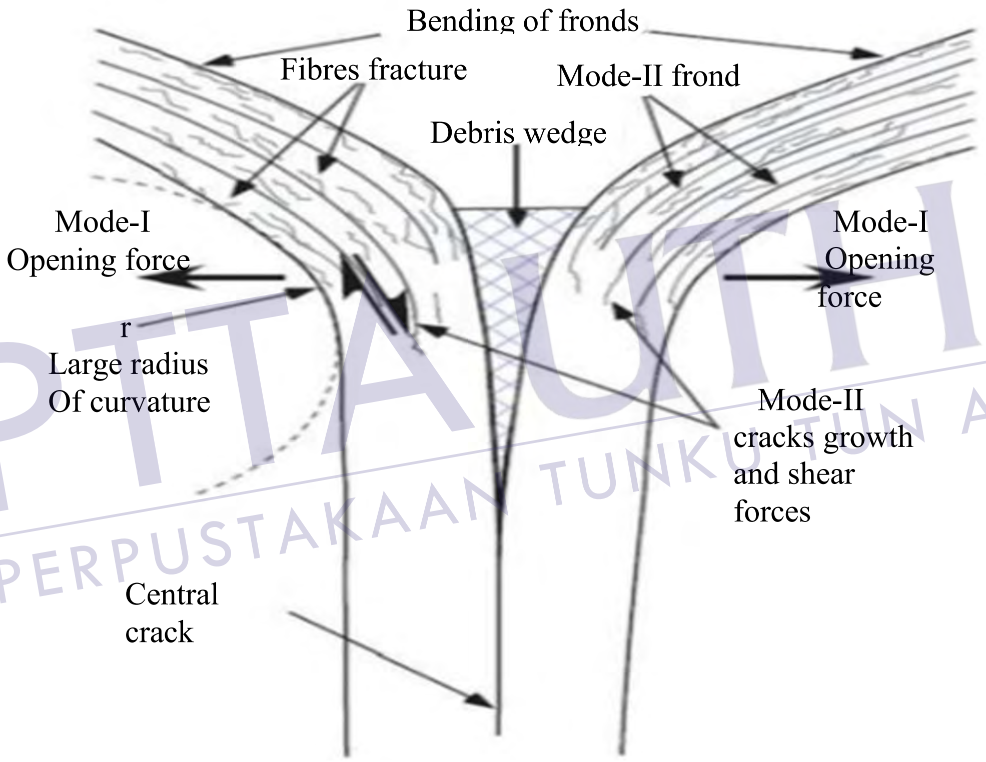

Figure 2.10: Splaying mode I and sliding mode II in axial collapsing (Lau *et al.,* 2012)

2.5 Factors affecting the improvement of energy absorption capability

Many researchers and designers have conducted investigations in recent years to design safer structures. One of the key factors that must be considered is the crashworthiness that attracted a good deal of importance to its multi-functions. The crashworthiness structures' functions are (a) energy absorption, (b) keeping the passenger cells intact, and (c) ensuring acceptable deceleration levels for the occupants during a collision accident (Xu *et al.,* 2016a; Huang, Zhang and Zhang, 2018). To meet the above functions, several factors related to energy absorption of the composite structures are discussed, as follows:

2.5.1 Geometric shape effect

Maximum energy-absorption has been achieved by the progressive deformation process, which depends on fibre and resin materials' mechanical properties, laminate stacking, fibre orientation, and the geometrical shape of the specimen (Luo *et al.,* 2016). However, various measurements of specific energy dissipation can be yielded by altering the geometry while maintaining the same other variable parameters for the structures made from a composite material (Rabiee and Ghasemnejad, 2017). Several engineering shapes and their collapsing behaviour have been investigated to determine composite structures' energy absorption capacity.

(Palanivelu *et al.,* 2010c) investigated the effect of cross-section shape on axial crushing behaviour. It was deduced that the hexagonal and square shapes with a t/w or t/D ratio of 0.045 were catastrophically crushed, while the circular specimen exhibited a gradual and uniform mode of crushing. However, when the t/ D or t/W ratio rises to 0.083, the hexagonal and square shapes gradually crushes. From this, it has appeared that circular specimens with a 0.083 aspect ratio recorded the greatest SEA value of 30.4 J/g compared to the hexagon and square sections, which recorded SEA of 16.4 J/g and 12.3 J/g, respectively.

Apart from that, (Estrada *et al.,* 2019) studied the effect of geometrical configurations such as cross-section, where configurations of these specimens include circular and square structures by numerical and experimental methods. The results indicated that circular shapes' crashworthiness performance is better than that of square and hexagon shapes. Moreover, (Zhang *et al.,* 2018) investigated the impacts of geometrical parameters, including circular, square, and tapered, on composite tubes' specific energy absorption (SEA) by experiments and simulations. In the comparison part, the SEA of circular, square, and tapered tubes was compared. For the hollow composite tubes of glass fiber reinforced polymer (GFRP), the SEA values of circular tubes are higher than tapered and square tubes. Also, (Rabiee and Ghasemnejad 2017) stated that circular cross-sectional composite tubes perform better than square and rectangular cross-sectional composite tubes.

Briefly, circular shape geometry has outstanding performance compared to other geometry shapes tested. Moreover, compared to other shapes apart from radial corrugated circular, circular shapes geometry absorbs most axial crushing energy. A similar conclusion was also reported by (Lau *et al.,* 2012) that circular shape gives a valuable comparison amongst all the shapes tested. Furthermore, it can absorb most of the axial crushing energy compared to the other shapes except for radial corrugated circular ones. A study by (Abdewi *et al.,* 2006) conducted an experimental study on the geometric shape effect on the crush behaviour of radial corrugated (RCCT) and circular cross-section (CCT) composite structures, as depicted in Figure 2.11. It was found that the radial corrugated structure shows a higher specific energy dissipation (SEA), as well as the peak load (P_{max}), compared to the composite tubes with circular shapes.

Likewise, another study investigated the combined radial corrugated and circular shapes (RCSCT) by surrounding the corrugated tube with the round tube shape, which failed to enhance the load-carrying ability, as seen in Figure 2.12. In the Figure, the radial corrugated shape showed a larger (P_{max}) at a bigger stroke length than the circular specimen and an (RCSCT). Moreover, the area underneath the graph, which refers to the EA of (RCCT), is bigger than both (Abdewi *et al.,* 2008). Furthermore, many publications have revealed that corrugated structures can collapse in a relatively controlled manner with a uniform force-displacement response. It has remarkable energy absorption efficiency compared with traditional structures without corrugations or tubes without corrugation (Eyvazian *et al.,* 2019; San and Lu, 2020).

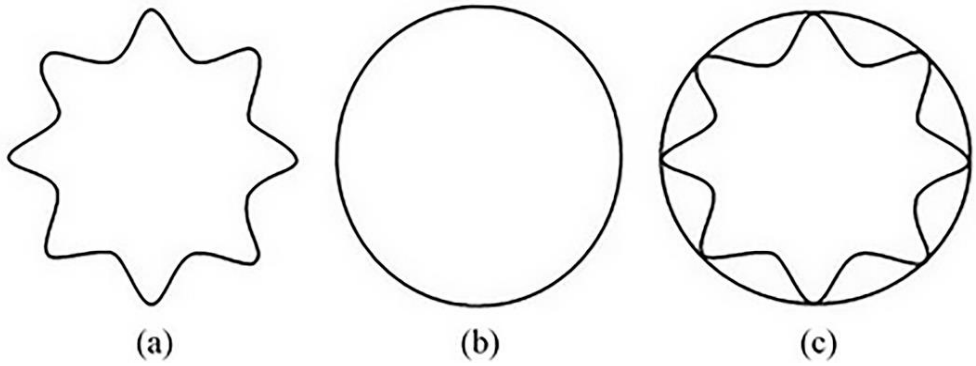

Figure 2.11: (a) Radial corrugated tube (RCCT), (b) Circular tube (CCT), and (c) Combination of radial corrugated and circular cross section (RCSCT) (Abdewi *et al.,* 2006; 2008)

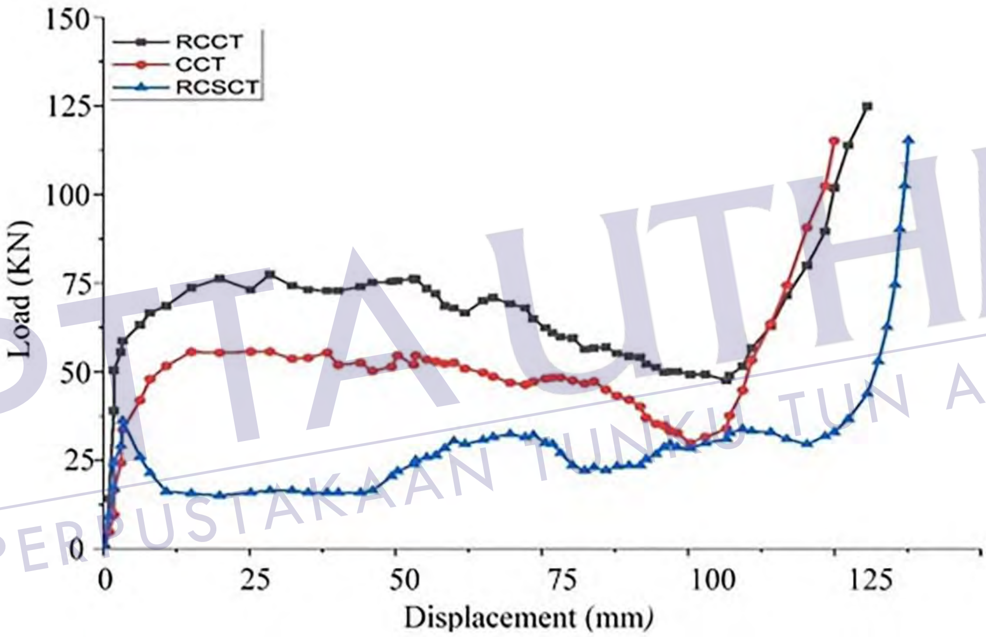

Figure 2.12: Load/deformation graph for (RCCT) cross section, (CCT) cross section, and (RCSCT) cross section (Abdewi *et al.,* 2008)

On the other hand, (Mahdi *et al.,* 2003) studied the influence of conical shell angle on the collapsing ability. It is stated that higher conical vertex angles reduce the initial peak load, SEA, in addition to the decrease in structural volume space, as depicted in Figure 2.13. However, the cylindrical tube's SEA absorbed a higher energy value than the conical shell, with a SEA of 24 J/g. Moreover, (Alkateb *et al.,* 2004) stated that the vertex angles in elliptical-cone designs were sensitive to specimen collapsing manner. Figure 2.14 shows the curve behaviour and its relationship between changing the cone vertex angle with the initial peak load (P_i) and the ratio of the

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