THE EFFECT OF KENAF FIBRE AS A CUSHIONING MATERIAL IN PACKAGING

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ABSTRACT

Biodegradables material nowadays selected as a solution for replace the current material in packaging industry. Kenaf fibre is a good material for substitution of chemical material according to their properties. Comparison between Simulation of MATLAB Simulink and cushion of Kenaf fibre by analyzed their dynamic shock properties and dynamic cushion curves are the focus of this project. Generally, this project is using Stress Energy method to evaluate the capability of a Kenaf fibre cushion to withstand the sudden shock resulting from free fall. The result will be guide by the simulation of Matlab Simulink software. A series of cushion test for 50 samples was carried out to determine the peak acceleration, (G's) for simulation and Kenaf fibre cushion at difference drop height, thickness and mass. There are 5 mass type used to generate the Static loading. These static loading choose by Dynamic energy calculation in Stress energy method. There are 3 type thickness of Kenaf fibre cushion used in this project. The result of peak acceleration, (G's) from both methods used to develop the Dynamic stress versus Dynamic energy graph. This graph generates Stress energy equation and regression percent. The equation also give the value of (a) and (b) used in generate the cushion curve. The regression value R^2 will indicate of how well the equations fit the data and; R^2 simulation 81.2% and experiment 92%. Generally, the shape of curves for experiment same shape as simulation but difference at minimum peak acceleration and static loading. Kenaf fibre cushion with thickness 25 mm at drop height 406 mm give peak acceleration 121.7 G compare to simulation 170.6 G, while for sample thickness 50 mm peak acceleration 62.0 G and simulation 83.6 G. Thickness 75 mm gives the lowest peak accelerations where for Kenaf fibre 40.7 G and simulation 59.6 G. Comparing the minimum peak acceleration will give the conclusion that there is decreasing of G peak when thickness increases. The result can conclude that kenaf fibre cushion with 25 mm thickness suitable for handheld part, 50 mm suitable for durable part and 75 mm suitable for stable part according to table of fragility levels.

ABSTRAK

Penggunaan bahan yang boleh dihancurkan oleh bacteria menjadi pilihan untuk industri pembungkusan. Sifat-sifat fizikal dan ciri-ciri kekuatan yang sama dengan bahan sedia ada menjadikan serat kenaf sesuai dan menjadi bahan pilihan Perbandingan ciri-ciri kejutan dinamik dan lengkung kusyen menjadi tujuan projek ini dengan menganalisi hasil pecutan puncak diantara Simulasi MATLAB Simulink dan kusyen daripada serat Kenaf. Secara amnya, projek ini menggunakan kaedah Tekanan Tenaga untuk menilai keupayaan kusyen berserat Kenaf menahan kejutan secara tiba-tiba. Hasil ujikaji akan dibandingkan dengan hasil daripada simulasi perisian Matlab Simulink. Ujian ini dijalankan berdasarkan kombinasi pada ketinggian jatuh yang berbeza, tebal dan beban statik. Terdapat 5 jenis jisim yang digunakan untuk menjana pelbagai beban statik yang dipilih berdasarkan kepada pengiraan tenaga dinamik oleh kaedah Tekanan tenaga. Terdapat 3 jenis ketebalan kusyen gentian Kenaf digunakan. Hasil pecutan puncak, (G's) daripada simulasi dan eksperimen akan digunakan untuk membangunkan graf tekanan dinamik berbanding tenaga dinamik. Graf ini akan menjana persamaan Tekanan tenaga dan peratusan ketepatan data iaitu R^2. Persamaan ini akan memberi nilai (a) dan (b) dan digunakan dalam menjana lengkung kusyen. Nilai R^2 akan menunjukkan sejauh mana persamaan bersesuaian dengan data. Bagi simulasi adalah 81.2% dan ujikaji adalah 92%. Kusyen berserat kenaf dengan ketebalan 25 mm dan pada ketinggian jatuh bebas 406 mm akan memberikan nilai pencutan puncak sebanyak 121.7 G manakala simulasi sebanyak 170.6 G, sampel berketebalan 50 mm pecutan puncak 62.0 G bagi ujikaji dan 83.6 G bagi simulasi. Sampel berketebalan 75 mm kusyen berserat kenaf pula memberikan pecutan puncak terendah iaitu sebanyak 40.7 G dan 59.6 G bagi simulasi. Perbandingan pecutan puncak minimum akan memberikan kesimpulan bahawa terdapat penurunan nilai pecutan puncak apabila ketebalan meningkat. Keseluruhannya jika dirujuk pada jadual tahap kerapuhan serat kenaf berketebalan 25 mm sesuai sebagai kusyen untuk alat yang dibawa ditangan, 50 mm sesuai untuk alat yang tahan lasak dan 75 mm sesuai untuk alat yang kukuh.

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LIST OF ABREVIATIONS

ASTM	-	American Society of Testing Material
cm	-	Centimeter, unit for Length
G's	-	Peak Acceleration
h	-	Height
Hz	-	Hertz, unit for Frequency
in	-	Inchi, unit for Length
kPa	-	Kilopascal, unit for Stress
kg	-	Kilogram, unit for Load
mm	-	Millimeter, unit for Length
ms^{-2}	-	Unit for Gravitational Acceleration
s	-	Static Loading
t	-	Thickness
UTHM	-	Universiti Tun Hussein Onn Malaysia
UTEM	-	Universiti Teknikal Melaka

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CHAPTER I

INTRODUCTION

1.1 Project background

Green technology and recycling issue become global issue for today life. In modern life, new material needs to develop to substitute current material that causes so many challenges for the environment. Packaging industry also one of the issues discusses that will cause some challenge to the environment and human health in the future if do not have proper plan. Development in packaging industry can help government to reduce the environment problem and have new alternative for packaging source. Also will help in minimize the cost of packaging but still can maintain the same quality of current material.

Today, million packages are transported everyday in difference package configurations according to their distribution environment. These difference distribution situation determine difference hazards that product must survive. Shock, vibration and compression are the common hazard during transportation. Shock occurred with the impact to a package system. This can happen when package drop or packages impact each other. Shock protection is the focus for this study.

Paper and paperboard have long been the main packing material for different product and goods. Paperboard also is one of the best energy absorption in market [1].The main problem of paper board is raw material to create paperboard because of need too many woods. This will affect the environment and ecosystem challenge. Although plastic industry is developing rapidly, the usage of paperboard as a cheap and ecological packing material is not decreasing. Paperboard is made from renewable resources and easily can decompose under the effect of humidity and usual atmospheric condition.

Nowadays, many materials had been chosen to produce the best paperboard for the design of packaging material. In this research, kenaf fibre was used as the main raw material which has highly potential for mechanical pulping and paperboard making. Kenaf (*Hibiscus cannabinus*) was introduce to Malaysia since 10 years ago and popular in east Malaysia. The popular type of kenaf cultivated was V36, G4 and KB6. In Malaysia type V36 were choose because of suitable with environment and will produce good quality of fibre.The main used of kenaf fibre are to make the rope, twine and carpet backing cardboard and packaging material [2].

1.2 Objective

Main objective of this study are:

- To fabricate the cushion using kenaf fibre and latex.
- To design a sample of kenaf fibre as a cushion packaging at difference thickness.
- To evaluate the package performance and cushion performance in the packaging system.

1.3 Scope

To make sure the study achieve the objective setting, many scope of study already set suitable with the time given. The scopes of this study are:

1. Produce kenaf fibre as a packaging material at difference thickness (25 mm, 50 mm and 75 mm).
2. Testing the sample using Cushion tester at various height, static loading and thickness.
3. Design model cushioning system for packaging.
4. Simulate cushion model using Matlab Simulink software.
5. Plot cushion curve using stress energy method between simulations and experiment result.
6. Analysis and compare peak acceleration (G's) between simulation and testing.
7. Evaluate the package performance between testing and simulation.

1.4 Problem statement

Until now, only few research and studies has been conducted about the development of paperboard from kenaf fibre and its cushion properties. A lot of research focuses for foam, plastic bubble and corrugated board already done. This entire product actually sources from synthetic material that not green technology material. Some studies that involve kenaf fibre were done on strength of kenaf fibre using the old corrugated containers (OCC) pulp and subject to blending with virgin fibres of kenaf pulp [3], paperboard and paper using kenaf whole stem pulp, kenaf core buffer packing materials cushioning properties and others.

This study was undertaken to produce a good and high quality of cushion using kenaf fibre with different length and different percentages of composition mixture.

1.5 Significant of the study

This study was focusing on kenaf fibre as the main raw material in cushion making for packaging industry. The main idea is to process kenaf fibre into cushioning material like paperboard. Kenaf is chosen because it comes from natural fibre. Natural fibre is cheap, easy to find and it is also did not harm the environment. Natural fibre usually grows fast and the problem of not having enough resource for making paperboard will never occur. By doing this, the cost of raw materials will be reduced and at the same time it can save the environment.

Paperboard properties are a crucial topic in the design of packaging material. It is required to investigate their strength and cushioning properties because they have to protect the goods contained from lateral crushing and compression loads due to impact and stacking.

In this study, the cushioning material using kenaf fibre can be determined. Cushion material from kenaf fibre are expected to have good cushioning behavior than other paperboard which is excellent material in the design of packaging material.

CHAPTER II

LITERATURE REVIEW

2.1 Introduction

Literature review is an investigation to previous research by others researcher about kenaf, paperboard and cushioning properties from fiber base material. This review is to add knowledge about process, testing, analysis and result obtain. Also will help to be more understanding and have a guide to plan this study. This topic will be discussed regarding kenaf usage, advantage, comparison and cushioning properties.

2.2 Cushioning definition

Cushion from the term language is a kind of a pillow or something used as litter for comfort [4]. In packaging engineering, cushion is a device or substance which has a capability of nature to absorb shock and vibration. It is used for the purpose of protective substance to the product before reach the customer in good condition and not affected the quality.

Characteristics of a good cushion can be identified by their ability to protect the product from the ruins. Fragile products usually require the features of a good cushion material and high quality like paper fiber and less vibration transport system, such as through the air. Shock and vibration tests are two common methods used for evaluating the performance of the cushion material. The design height of drop shock test identified in advance and test results are usually displayed in graphical dynamic cushioning curve. Figure 2.1, showed the example of dynamic cushion curve graph [5].

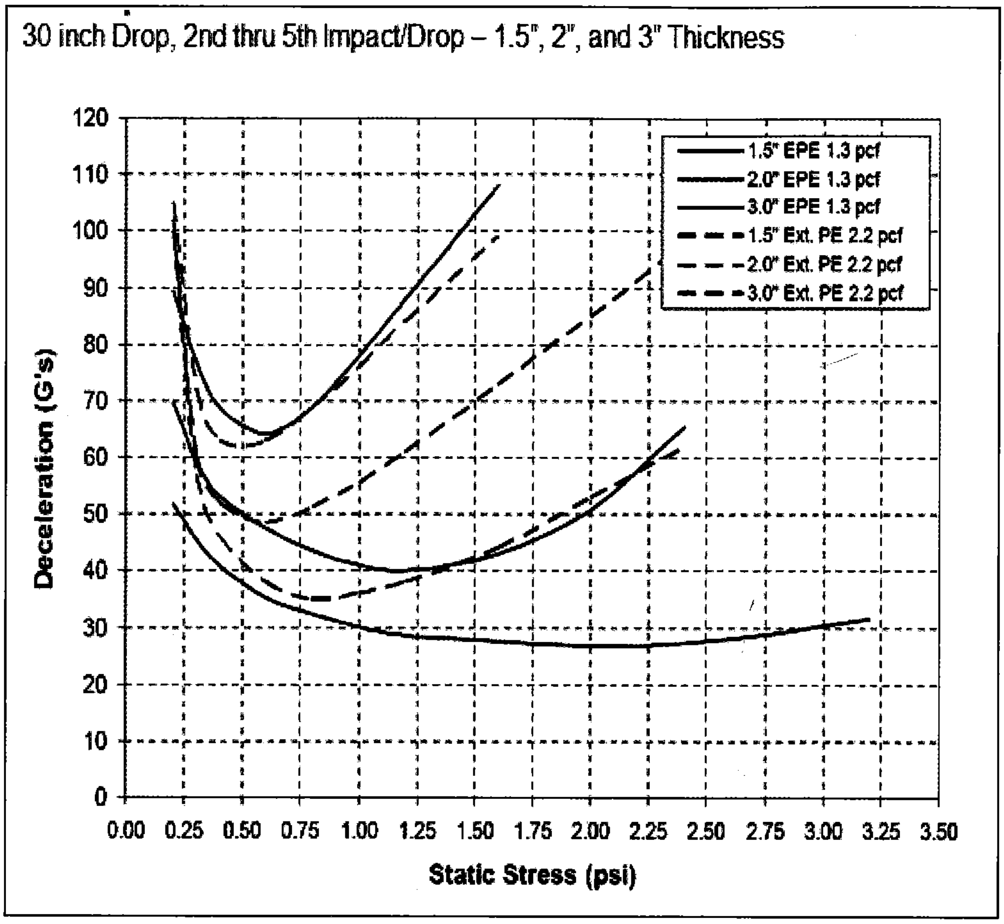


Figure 2.1: Dynamic Cushion Curve for ARPLANK Expanded Polyethylene and Extruded PE [5].

Shock is one of the most common hazards in the transportation of goods. Isolating the packaged product from shock events that could result in damage is one of the challenges of package designers. Shock may result from a sudden acceleration or deceleration caused by events that are very common in the distribution of goods [6].

Trucks containing packages may go over pot holes, and start and stop several times during a trip. Since products are designed only to withstand the hazards at intensities according to their normal use, cushioning material might be added to a package system to absorb some of the energy of shipping related shock events before it reaches the packaged product. Cushioning materials absorb energy through deformation. In other words, the energy it takes to deform or deflect the cushion during an impact is not transmitted to the product.

2.2.1 Cushioning material classification

There is a wide variety of cushioning materials used in packaging. The most common are polymeric foams in form of molded parts, sheets, planks, foam in place, and free flowing shapes. There are also other polymeric cushioning options such as bubble wrap and air pillows. Molded pulp and corrugated boards are examples of non-polymer based cushioning materials.

The most important characteristics of a cushioning material that affect its compressive behavior are the material composition, density and cell structure. The most important characteristic is the material composition.[6]. The focus of the work presented here is on Cushioning material from kenaf fibre and can be recognize as environmental friendly foam (ERP) [7].

In terms of their elasticity, foams are classified as either elastic or non elastic [8]. Elastic materials are those which don't sustain permanent deformation after deflection caused by an impact. Non elastic materials, on the other hand, sustain permanent deformation. In packaging for distribution this classification is important, since it is necessary to consider multiple impacts as likely for most products. The permanent deformation sustained by a non elastic material on a first impact will greatly influence its ability to deflect on subsequent impacts.

Expanded polystyrene and expanded polyethylene are two common cushioning materials used in packaging. Expanded polystyrene is classified as non elastic, whereas expanded polyethylene and expanded polyurethane are available in elastic form [9].

2.3 Introduction to Kenaf

Kenaf or scientific name *Hibiscus cannabinus* is a warm season annual row crop in the same family with cotton or Malvaceas. Kenaf plants originally come from Africa. Kenaf plants are able to grow for 20 feet height under favorable condition. The stalks consist of two kind of fiber:

1. Bast – an outer fiber
2. Core – inner fiber

This fiber can be comparable to softwood tree fiber for bast and hardwood fiber for core. Kenaf fibre already widely used in various products includes bagging, carpet, rope and paper [10]. The absorbency of kenaf fibre also gives some alternative to agriculture industry to use it for animal litter. Kenaf also have difference name in others country like Brazilizznsch at Netherlands and Apondo at Spain.

Kenaf plant can produce about 25% of long fiber at bast or an outer skin. About 75% short fiber can produce by inner or core. Table 2.1, is showing comparison between core and bast in fiber size and dimension [11]. Shape for bast and core from kenaf plant can be view in Figure 2.2. Kenaf fibre also can categorize in natural fibre and have a good size compare to others natural fibre, Table 2.1 [12].

Table 2.1: *Bast* dan *Core* dimension for kenaf fibre [12].

Item	Fiber Length (mm)	After Process Fiber Length(mm)	Fiber Width (mm)	Lumen Width (mm)	Cell Thickness (mm)	Weight (%)
Bast	2.26	2.6	16.4	8.4	4.0	40
Core	0.52	6.0	34.0	20.4	6.8	60

Table 2.2: Kenaf fibre size compares with others natural fibre [12]

Fiber Type	Length (mm)		Width (mm)	
	Average	Range	Average	Range
Jute	2	2~5	20	10 ~ 25
Kenaf	5	2 ~6	21	14 ~ 33
Sisal	3	1 ~ 8	20	8 ~ 41

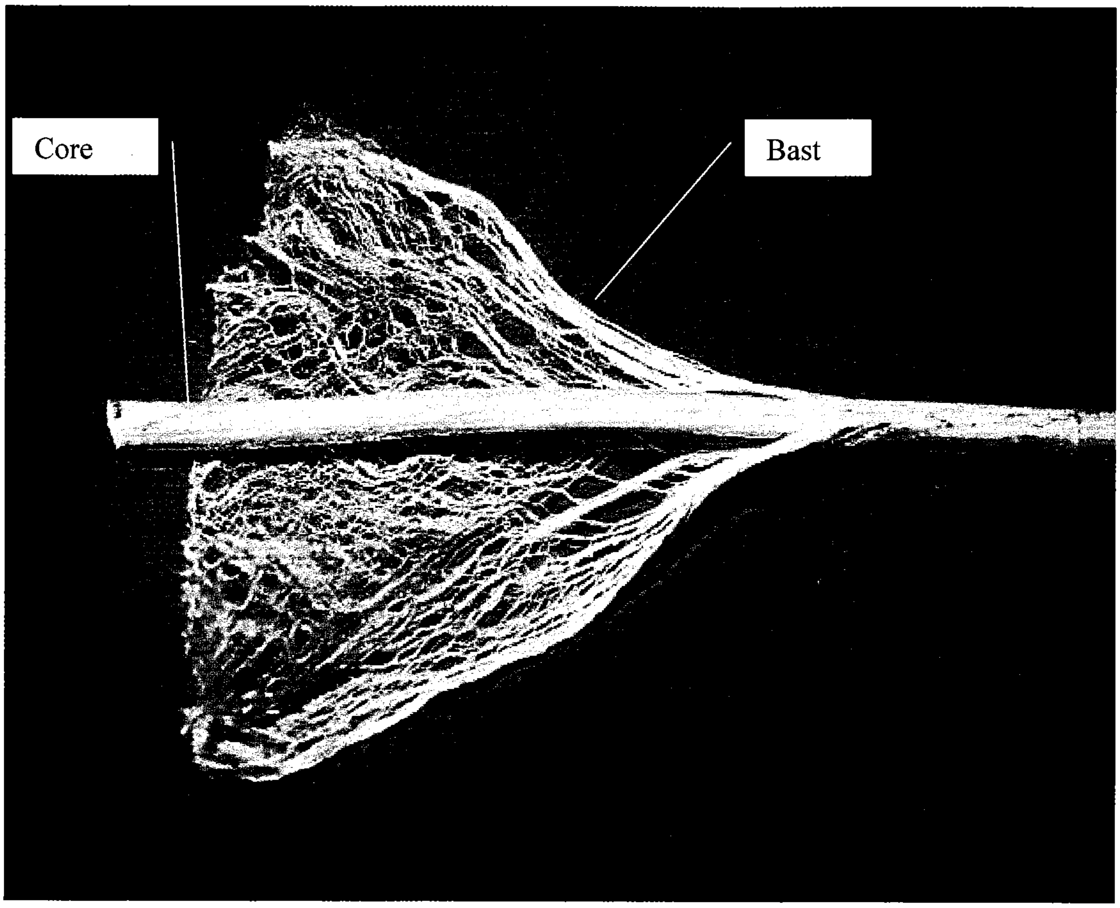
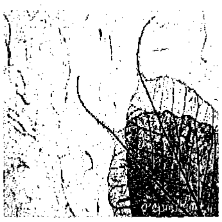
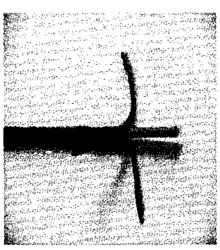


Figure 2.2: Bast and Core at Kenaf plant [12]

2.3.1 Type of fibre

Natural fibres are greatly elongated substances produced by plants and animals that can be spun into filaments, thread or rope. Woven, knitted, matted or bonded, they form fabrics that are essential to society. Kenaf fibre classified as plants fiber and used to reinforce many materials in today industry [3]. Table 2.3 shows the category of fibre. Figure 2.3 show the classification of fibre.

Table 2.3 Category of natural fibres shape

Category	Description
Seed Fibre 	Fibres collected from seeds or seed cases. e.g. cotton and kapok
Leaf Fibre 	Fibres collected from leaves. e.g., sansevieria, fique, sisal, banana and agave.
Bast/Skin Fibre 	Fibers are collected from the skin or bast surrounding the stem of their respective plant. These fibers have higher tensile strength than other fibers. Therefore, these fibers are used for durable yarn, fabric, packaging, and paper. Some examples are flax, jute, kenaf, industrial hemp, ramie, rattan, and vine fibers.
Fruit Fibre 	Fibres are collected from the fruit of the plant, e.g. coconut (coir) fiber.
Stalk Fibre 	Fibres are actually the stalks of the plant. E.g. straws of wheat, rice, barley, and other crops including bamboo and grass. Tree wood is also such a fibre.

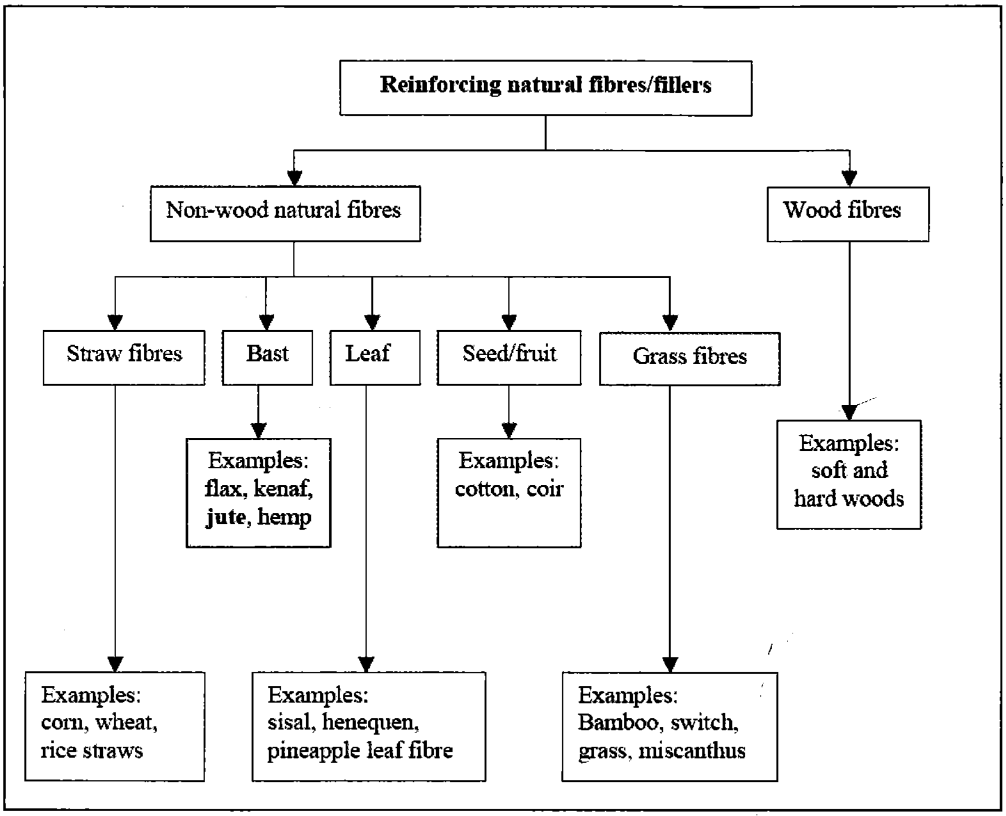


Figure 2.3 Classification of natural fibre [13]

2.3.2 Advantage of Kenaf plant

There are so many advantages that already found at kenaf plant. Kenaf plants are capable to grow at 6m (20 feet) under favorable condition [2], however generally average 2m to 4m for 4 to 5 months. There is no need much fertilizer to produce a good quality of fiber. Kenaf plant is able to breeding itself by self pollination way and can flowering a day only. Kenaf plant also can harvest many times in a year depending on soil fertility level and have a good reliable to pest resistance. Harvesting kenaf plant is accomplished either by hand or mechanically with farm equipment. Yield potential has been report 6 to 8 ton per acre.

Kenaf is a fast growing crop and has a high potential to be used as an industrial crop globally since it's contain higher fiber materials or lignocellulosic. The stalk of this plant is composed of two distinct fiber types; the bark of the kenaf stalk contains the long fiber strands that are composed of many individual smaller bast fibers. The woody core material of the stalk which is the portion remaining when the bark is removed contains core fibers. Whole stalk kenaf, bast and core fibers have been identified as a promising fiber source for the production of pulp and paper [14].

The whole stalk plant material can also be used in non pulping products like building materials, such as particle board and within injection molding and extruded plastic. The kenaf fibre also can serve as a virgin fiber for increasing recycled paper quality and paper strength.

In addition, this plant also lives in various types of soil and at any suitable climatic condition. It would be fine and able to generate a lot of revenue if the climate is warm and the soil is moist. Kenaf plant also has a strong resistance against water stagnation. Besides that, kenaf plant growth will be stunted if the ambient temperature below 10°C. In addition, the usage of this plant is environmentally friendly because of obtained from nature and an organic material and can be recycle. Figure 2.3, is showing kenaf plant cultivation. Table 2.4 show the advantage and disadvantage of kenaf fibre harvesting type.

Figure 2.4: Cultivation Kenaf plant [15]

Table 2.4: Advantage and disadvantage of Kenaf fibre harvesting type [16]

Item	Harvesting of green sterm	Harvesting of dry sterm
1. Loss of production	Generally minimum as the crop remains in the field for a very modest period of time.	They can be tall due to the flattening of the plants or due to attacks of fungus that occur in the field in poor weather conditions.
2. Post-harvest processes	No problems arise if the stems are used immediately by a paper mill.	Need low humidity content of the material when deliver.
3. Juice from the stems	Can be extracted in the field. This restoration of nutritional elements reduces the quantity of chemicals required for the pulping process.	The juice of the stems cannot be recovered.
4. Weight of harvested material	Heavy. Green stems can be more than six times heavier than dry stems.	Minimum, because the material is almost ready for being sold on the market.
5. Environmental problems	None.	Serious potential problems due to: the transport of the herbicide mixing on the nearby crops, the drying residual on the ground and in the irrigation water.
6. Other kenaf products	Integrated process to produce seeds and leaf panel.	Only the stems can be used for the production of cellulose fibre.

2.3.3 Usage of Kenaf plant

Traditionally, Kenaf bast fibre are used and known for twine, course sacking material and rope. Kenaf fibre also has a potential as reinforced fiber in thermosets and thermoplastics composites. However modification for the fiber is required to improve mechanical properties for composite product. This is the advantage that we can see in the future to improve others material or multi used kenaf fibre as a good natural fibre.

In current situation kenaf plant already popular in fiber industry and wood because of good mechanical properties compare to acasia plant. Acasia plant actually is a productive plant, but not so economic to floor and furniture industry due to high cost of process and sustainable period demand.

Kenaf fiber demand in the future having a good opportunity. Kenaf fiber not just focuses to furniture industry only right now, because some research to expand the fiber usage already done in paper and pulp application. According to Latifah J.*et al.* [3] kenaf fibre has become one of the promising raw materials for paper making due to adaptability in tropical region as well as its desirable fiber and pulp properties.

Kenaf fibre used as a reinforcement in fiber –reinforced plastic (FRP) to replace synthetic fibers such as glass and carbon fiber [17]. Kenaf plant also can be an alternative to agriculture industry as a food source to cow, goat and others.

Development in composites material and rising of green technology issue assist to popularize the kenaf fiber. Kenaf fiber also can be an alternative natural source for engineering field such as packaging industry and engineering component as develop by UTEM to make a piece of wood [18]. They used same process of wood fiber composite to develop the wood and improve the fibre quality by chemical addition. This process also used to enhance the strength and avoid decay. This study also giving some info about kenaf fiber and an ability to replace the synthetic fiber from chemical base without reduce the quality of product.

In Malaysia almost 50% of the total paper consumption comes from packaging paper such as kraft paper. However, there is no local production of kraft pulp and this implies a high reliance on imports. In 1990s under Seventh Malaysian Master Plan, kenaf fiber was recognized as a potential alternative material for production of panel product such as fiberboard and particle board [19]. Under the plan, the National Kenaf and Tobacco Board (LTN) engineered the development of kenaf cultivation in order to replace tobacco cultivation. At the same time will help the farmer to have and alternative source of cultivation and improved their earning.

Kenaf fiber can be core material in building construction such as concrete [3] .She done a research by developing kenaf fiber reinforce foam concrete. In their study this cube and aerated concrete beams containing kenaf fiber were formed, cured and testedin compression load and bending load until failed. In this study also found that the presence of kenaf fiber in the foam concrete can increase ductility and able to accommodate the maximum bending load for a long time before it breaks. Besides that, this foam concrete lighter and easier to handle compare to current concrete. This new product also environmental friendly used. Table 2.5 is showing the usage of kenaf in real industry.

Table 2.5 Kenaf usage in industry [20]

Usage	Description
1. Kenaf Fiber/Plastic Compounds	i. Replace glass reinforced plastics
2. The Automotive Industry	i. In 1996 Ford Mondeo interior automobile panels
3. Construction and Housing Industry	i. Molded into lightweight panels and can replace wood and wood based products
4. Food Packaging Industry	i. Molded into commercial food storage containers ii. Bulk chemical and pharmaceutical packaging, parts packaging in the electrical and electronics industries
5. Oil & Chemical Absorbents	i. Uses is to clean up oil spills and similar chemicals ii. Clean up operations in refineries, utility companies, land and sea spills and oil rigs

2.4 Production of Kenaf fibre

After harvesting, the kenaf stems were subjected to water retting for fiber yield determination. According to Shinji Ochi (2008), the best kenaf fiber obtain from kenaf stem is from the bottom (around 0~500mm from the ground).Kenaf stem will be submerge in water ratting for about 14 days without adding any chemical. This is for showing kenaf is naturally natural fiber. To make sure this process completely environmentally friendly process it will test by include a fish in water ratting. If the fish still can survive that mean the process is safe.

After 14 day submerge, kenaf fiber known as bast kenaf stem will break off from core. These fibers were then washed with running water, dried and weighed for bast and core yield determination. Core fiber will be machined untill become a wood powder and used as pulp in paper making. In this study kenaf fiber or bast will be selected to study as a support the cushioning properties. Figure 2.5, is showing kenaf fiber and kenaf powder [21].

Kenaf Fiber

Kenaf Powder

Figure 2.5: Kenaf fiber and Kenaf powder

2.4.1 Characteristic of Kenaf fiber

Kenaf fiber is one of the natural plant fiber that was investigated to replace the synthetic fiber such as glass in market. This is because of low density, renewability and high specific strength of the natural fiber and increasing environmental pressure is giving natural fiber an advantages. However, natural fiber typically combined with polypropylene, polyester or polyurethane to produce a product in market right now.

Kenaf fiber structure and chemical makeup can be dividing by three components as cellulose, pectins and lignin. Cellulose can be considered the major framework component of the fiber. Cellulose is the main component providing the strength, stiffness and structural stability. Lignin is less polar than cellulose and acts as chemical adhesive within and between fibers. Pectins acts as improve structural integrity of fiber. This three main component also function as adhesive and help to hold together.

Most natural fiber has maximum density of about 1.5gm/cm^3. Their low density makes them attractive as reinforcement in applications where weight is a consideration. The cultivation environment can affect the tensile strength of the kenaf fiber [17]. To study on tensile strength and elastic modulus, kenaf fiber taken from four deference section of plant (0-500, 500-1000, 1000-1500, 1500-2000mm from ground). Result by Shinji [17] mention that the values of bottom section of the plant have the greatest value for tensile strength.

Any recycles fiber that blends with kenaf will result greater strength of tensile [3]. Density is the most fundamental properties importance to evaluating the paper properties and slightly descend the recycle fiber density when blend with kenaf pulp. Bursting strength is importance strength for require for corrugated container and show increased upon kenaf pulp increase. Also tear and fold index increased to the material that combine with kenaf pulp. Refer to appendix A for detail.

2.4.2 Type of fabrication

There are numerous methods for fabricating composite components. Some methods have been borrowed, but many were developed to meet specific design or manufacturing challenges. Selection of a method for a particular part, therefore, will depend on the materials, the part design and end-use or application. Method of fabrication in manufacturing is:

i. Injection Molding
ii. Hand Layup
iii. Resin Infusion Process
iv. Vacuum assisted resin transfer molding
v. Automated tape laying

The most basic fabrication method for composites is *hand layup*, which typically consists of laying dry plies or prepreg plies by hand onto a tool to form a laminate stack. Resin is applied to the dry plies after layup is complete. In a variation known as wet layup, each ply is coated with resin and "debulked" or compacted after it is placed. [22].

2.4.3 Compaction method

After samples were layup and resin applies, compaction is a method to hold the sample into recommended shape. The principle goal of the *compaction process* is to apply pressurize and bond the particles to form a cohesion among the powder particles [23]. General process of compacting:

i. Mixing
ii. Pressure
iii. Holding

2.5 Concepts in closed-cell cushioning material deflection

Working length of a cushioning material is defined as the maximum deflection in which the cushion will behave linearly, for a constant change in force, there is a constant change in deformation. The ratio between the change in force and the corresponding deflection of a block of foam is known as the spring constant (K). The spring constant is dependent on material geometry, orientation, and of course material composition.

Another related concept is the stress-strain ratio or the modulus of elasticity (Young's Modulus) of a material. Stress is defined as force per area of material and strain is the ratio of the resulting deflection and the original thickness. The modulus of elasticity is a property of the material and does not depend on cushion geometry or orientation. When a foam is said to "bottom-out", it has reached its maximum strain and, therefore, its ability to absorb energy in a shock event. Static stress is also known in packaging as the static loading. It is the ratio of the weight of the product and the area of foam which bears the product.

2.6 Mechanical shock

A mechanical shock or impact occurs, when the packaged product position, velocity or acceleration suddenly changes. A shock may be characterized by a rapid increase of acceleration (x) followed by rapid decrease over a very short time (t). Shock to the package happens when it suddenly decelerates upon hitting the floor. The duration of a shock is typically expressed in milliseconds and its magnitude in units of G.

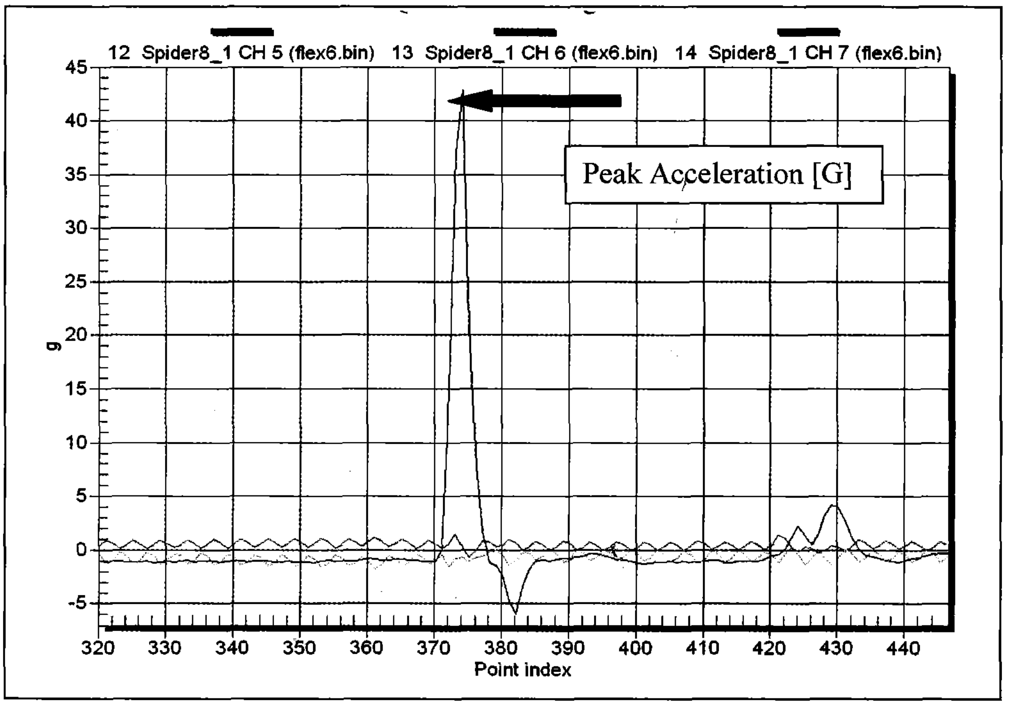


Figure 2.6: Registered shock during a drop on a packaged product [7]

Figure 2.6 is a simplified representation of a shock pulse. The area under the curve is the velocity change (ΔV) which is represented by equation 2.1, where impact velocity is (*Vi*) and rebound velocity is (*Vr*) figure 2.5. Velocity change also corresponds to the energy dissipated during that shock.

$$\Delta V = |Vi| + |Vr| \qquad \text{(Eq:2.1)}$$

Reflection velocity ratio versus velocity acceleration written as;

$$e = \frac{vr}{vi} \qquad \text{(Eq:2.2)}$$

Where;

$e = Velocity\ Coefficient$

Velocity coefficient will determine the material properties are good cushioning material or not. If rebound velocity value equal to impact velocity, velocity coefficient will be 1and vice versa. So, the range of velocity coefficient is between $0<e<1$.In practical, a good cushioning material properties will give the value of velocity coefficient between $0.25<e<0.75$.

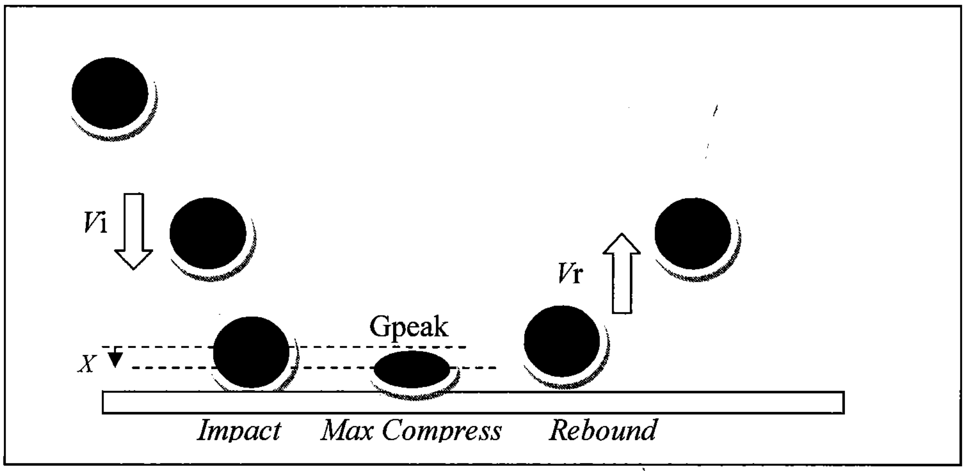


Figure 2.7: Object Freefall to surface [4]

The shock pulse represented in Figure 2.7 is defined as a half-sine pulse, and it is the most common shock pulse experienced by packages protected with foam. The area under the curve can also be represented by equation 2.3, where (G_{peak}) is peak deceleration and (τ) is duration in seconds.

$$\Delta V = \frac{2}{\pi}(G_{peak})(\tau) \qquad \text{(Eq: 2.3)}$$

Package damage is related to the three factors that describe a mechanical shock: Peak deceleration, duration, and velocity change. When two of these are known, the third can be estimated. When cushioning material is added to a package system, it deflects during a shock event. This increases the duration of the shock pulse, lowering the peak deceleration. Figure 2.8 showing good shock input and cushioning response.

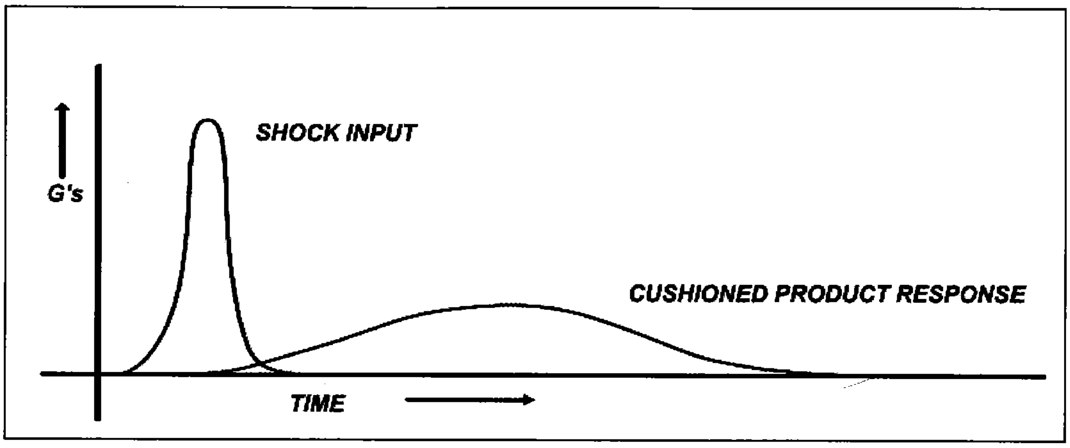


Figure 2.8 Ideal shock input and cushioning response [7]

2.6.1 Conventional evaluation of cushioning materials for protective applications

There should be a rational way to approach protective package design relying on knowledge of the distribution environment, the mechanical properties of the cushioning material, and of the product itself. These could be summarized by knowledge of the following three factors: the maximum acceleration transmitted through the cushioning material to the product, the form of the acceleration-time relationship, and the ruggedness of the structural elements of the product.

An ASTM procedure, D-1596 – "Standard Test Method for Dynamic Shock Cushioning Characteristics of Packaging Material," was designed to evaluate cushioning materials [24]. The latest revision of this procedure was in 2003. The procedure evaluates the maximum deceleration transmitted through cushioning materials. The data collected is reported in the form of cushion curves. Cushion curves are pairs of plots representing data specific to a cushioning material density, thickness, and drop height. One plot in the pair shows the results for the first impact. The other plot shows the averaged results of the 2^{nd} through 5th impacts.

The plots show the maximum deceleration transmitted through the material expressed in units of G over a range of static loadings. Curves for different thicknesses of the material are usually shown on the same plot. Figure 2.9 shows an example of a pair of cushion curves. The lowest portion of the curves represents the ideal area for that particular material.

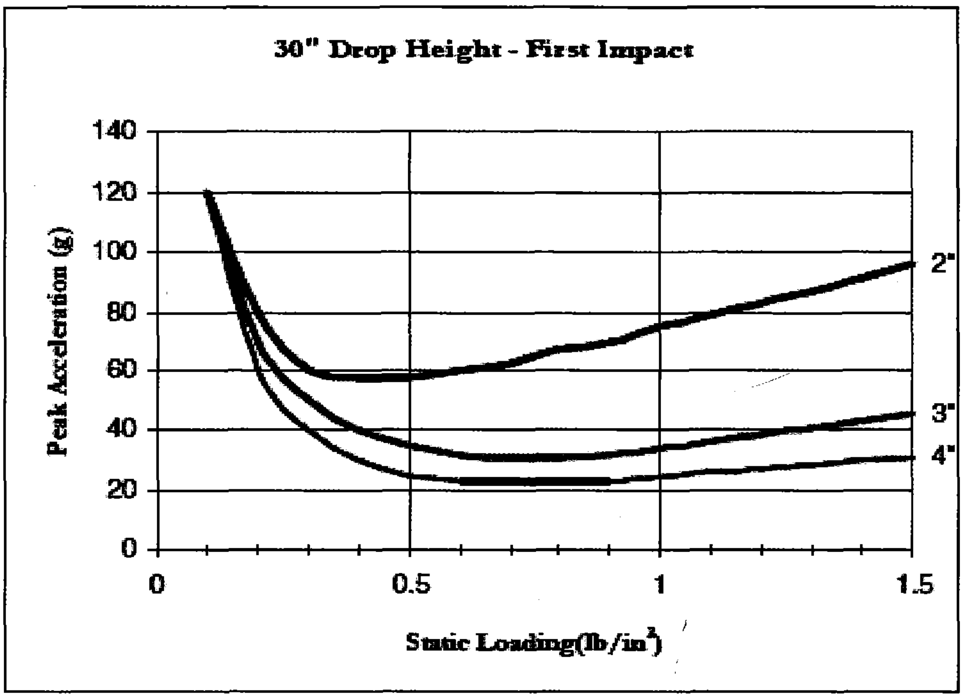


Figure 2.9 Cushion Curve graph [25]

2.6.2 Cushion curve

Cushion curve are graphical representations of a foam material's ability to limit transmission of shock to a product (called G level).Cushion curve develop based on spectral body freefall against difference static loading conditions at given thickness and drop height for cushioning material.

Md Zin [4] says if a body that have a weight (w) freefall at a velocity (v) and at control height (h), then a peak acceleration (G) versus shear at difference thickness (t)can be plotted. G level is plotted along the vertical axis versus static loading (weight divided by bearing area) along the horizontal axis. Curves are specific to a particular material, density, and drop height. Simply consulting the cushion curve will visually tell how many G's will be transmitted for a given height, thickness and static loading. Figure 2.10 showed at 25mm thickness, acceleration value is high but number of shock is brief to get the static stresses before cushioning material destroyed. At 75mm thickness, we can see a low acceleration value needed but high number of shock need to get static stresses before product destroyed.

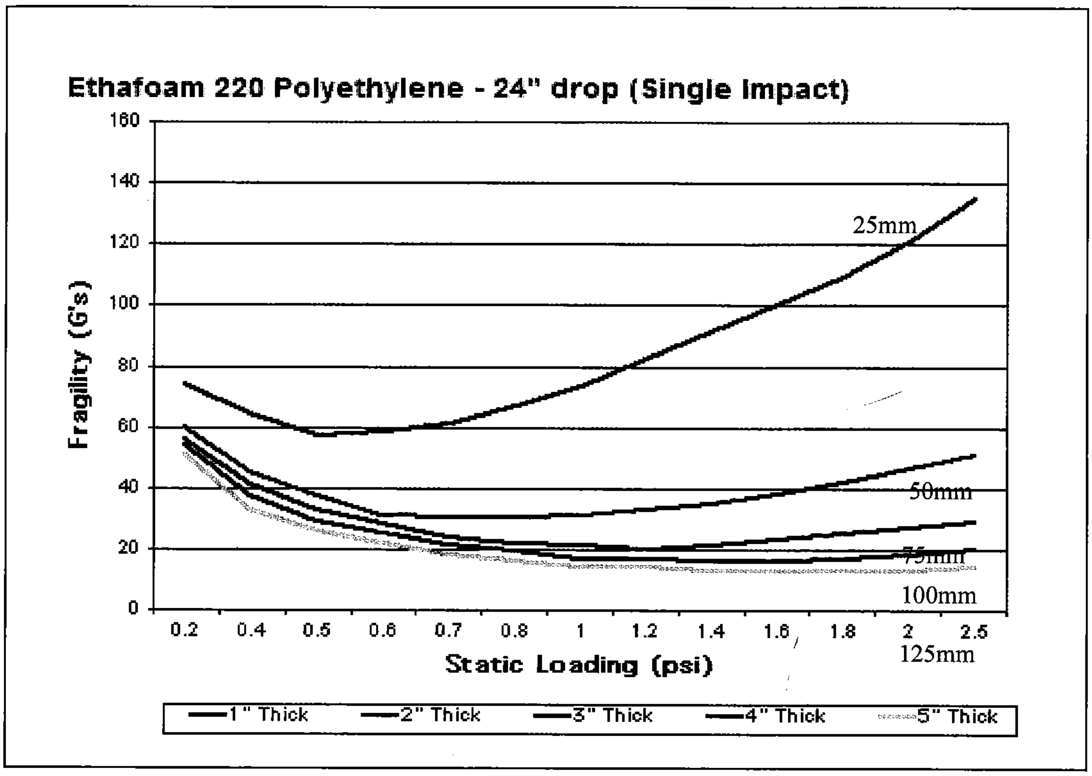


Figure 2.10: Cushion Curve for Ethafoam 220 Polyethylene [7]

2.7 Cushioning model

Proving the theory of cushioning, a sample of cushioning model needs to investigate. Figure 2.11 show a product cover by cushion. Cushion will absorbed energy shock that provide when product freefall at certain height. Cushion ability will determine the product can damage or not. In practice, product will damage at first freefall at Gpeak value.

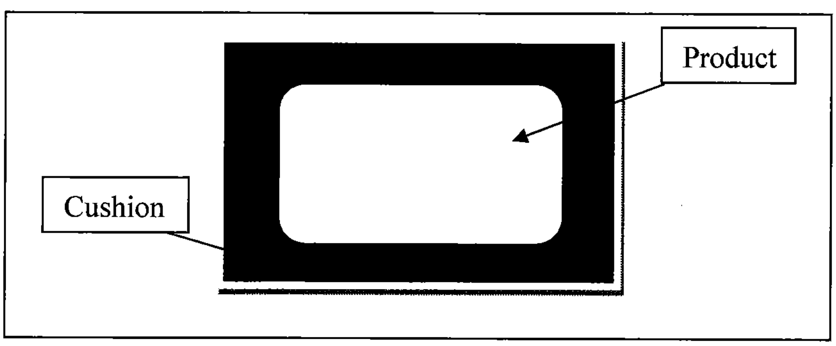


Figure 2.11: Cushion model

Mathematical model can be described from the cushion model[25]. In this model, elastic properties represent by spring (k) and damper (c) used for absorbed the shock energy. Figure 2.12 show free body model.

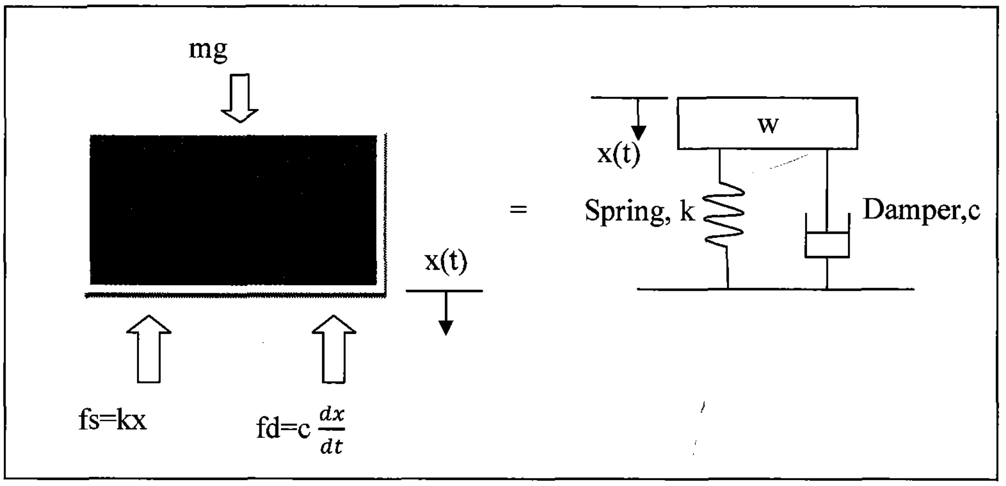


Figure 2.12: Free body model

Mathematical relation can describe from free body model as :

$$mg\text{-}fs\text{-}fd = m\frac{d^2x}{dt^2} \qquad \text{(Eq:2.4)}$$

Replace fs and fd in equation 2.4,

$$m\frac{d2x}{dt2} + c\frac{dx}{dt} + kx = F(t) \qquad \text{(Eq:2.5)}$$

Where;

x = displacement

c = damping coefficient

m = product mass

F(t) = mg = product weight

If F(t) = 0 , equation 2.5 can be perform in,

$$m\ddot{x} + c\dot{x} + kx=0 \qquad \text{(Eq:2.6)}$$

Using Laplace theorem, equation 2.6 can simplify,

$$(ms^2 + cs + k)\ x = 0 \qquad \text{(Eq:2.7)}$$

Given,

$$x = e^{st} \qquad \text{(Eq:2.8)}$$

So,

$$(ms^2 + cs + k)\ e^{st} = 0 \qquad \text{(Eq:2.9)}$$

Where, for all t value, when divide by m;

$$s^2 + \frac{c}{m} s + \frac{k}{m} = 0 \qquad \text{(Eq:2.10)}$$

Solve for two roots for equation 2.10,

$$S_{1,2} = -\frac{c}{2m} \pm \sqrt{\left(\frac{c}{2m}\right)^2 - \frac{k}{m}} \qquad \text{(Eq:2.11)}$$

So, general equation for x ,

$$x = Ae^{s1t} + Be^{s2t} \qquad \text{(Eq:2.12)}$$

Where,

A and B is constant. Replace equation 2.10 in equation 2.12.

$$x = e^{-\left(\frac{c}{m}\right)t}\ [\ Ae^{\sqrt{\left(\frac{c}{2m}\right)2 - k/m}}t + Be^{-\left(\sqrt{\left(\frac{c}{m}\right)2 - \frac{k}{m}}\right)}t\ ] \qquad \text{(Eq:2.13)}$$

Limit the equation 2.12 to Mass Spring Damper system, So,

$\left(\frac{c}{2m}\right)^2 = \frac{k}{m}$ and approaching zero

Value of Zeta (ξ) became damper system divide by critical damper system,

$$\xi = \frac{c}{Cc} \qquad \text{(Eq:2.14)}$$

Where,

c = damping coefficient

Cc = Critical damping

$$Cc = 2m\sqrt{\left(\frac{k}{m}\right)} = 2m\omega_n = 2\sqrt{km} \qquad \text{(Eq:2.15)}$$

Where;

$$c = \xi Cc \qquad \text{(Eq:2.16)}$$

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