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Numerical Simulation Study on Lateral Collapse of Kenaf-Foam Composite Filled in Cylindrical Tube Subjected to Dynamic Loading

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Abstract

In this paper the energy absorption of kenaf foam filled cylindrical tube has been investigated. First, a finite element model for empty cylindrical tube was constructed and followed by a foam-filled cylindrical tube model. In this study, there were five samples of kenaf foam density that been used and they are 5%, 10%, 15%, 20% and 0% (100%PU) for three different thickness cylindrical tube. The implemented models were used to simulate the behavior of empty and foam-filled tubes under lateral dynamic loadings. An impact mass of 10kg with three different impact velocity, 10m/s, 15m/s and 20m/s were used in the empty tube model simulation. Meanwhile, for foam-filled tube, impact velocity had increased to10m/s, 20m/s and 30m/s. The energy absorption capability was increased with foam filler in the cylindrical tube and the best kenaf foam density was obtained at 15%. For 15% kenaf foam, the value of energy absorption was higher than 100% PU but the energy absorption decreases for 20%.The results showed that increases wall thickness and kenaf foam filler will increase the energy absorption.

Keywords: Kenaf Foam; Energy Absorption

1 INTRODUCTION

In recent years, vehicle crashworthiness has been improving with attention mainly directed towards reducing the impact of crash on the passenger. By establishing safe theoretical design criteria on mechanics of crumpling, it provide to engineers the ability to design vehicle structures so that the maximum amount of energy will dissipate while the material surrounding the passenger compartment is deformed thus protecting the people inside [1]. Most of the energy absorbing devices and structures are currently used from metallic and composite materials. Metallic tubular crash structures are now commonly used to absorb impact energy during collision [2]. Foams are ideal energy absorbers due to its performance that can undergo large deformation at nearly constant load. In the other hand, applications of bio-foams filled in circular structures give numerous potential in absorbing the impact energy. In the past few decades, foam-filled structures are given much attention in research and development to be used in the crashworthiness applications. Foam is currently being used as a filler material in bumper and as reinforcement in roof and door beams. Foam has been the subject of numerous experimental, numerical and theoretical investigations.

In Malaysia, the road accidents problem is now regarded as one of the most serious social problems. According to the road accidents statistics of Jabatan Keselamatan Jalan Raya (JKJR), about 363,319 cases had been reported in 2007. Among those cases, fatal accidents are 6,282 which are about 17 people are killed a day. Lack of consider safety aspect of vehicles is one of the crucial factors that cause the fatality. Low cost consideration is the most desired criterion for vehicles made by Malaysia which causes the safety aspects had been ignored. In an accident, the most inevitably serious injury for occupants is the side impact crash if compared to others impact crash types. Therefore, a safety device which can absorb the impact energy those specifically for lateral collapse should be designed.

2 RELATED STUDY

From the vehicle crashworthiness to the protection of human bodies, the engineering background study of energy absorption of structures and materials are reviewed. The research into and development of energy-absorbing structures and materials, which dissipate kinetic energy during impact or intense dynamic loading, has received attention since 1970s, especially in the automobile and military industries [3]. The term 'crashworthiness' is refers to the ability of a vehicle to reduce the damage and injury of the vehicle and its occupants when it undergoes an impact. Crashworthiness features includes side impact protection, air bags, seat belts, crumple zones and so on.

The fatal crash types involved in accident in the NHSTA's statistic was side impact crashes. The statistic show that the fatality levels of side impact crash are highest among the other crashes, 34% of fatalities from 25% of all fatalities and injuries crash type [4]. This situation may be caused by the limitation of crumple zone at the side part of the vehicles. In common, multiple-vehicle and passenger vehicles were involved in side impact crash, which directly increase the difficulty of protection to the victims involved.

In design of automotives, structural properties of material is the most considered aspect which will directly affect the performance and safety of a vehicle. Application of crumple zones are generally used in structural crashworthiness criteria. By applying the crumple zones, majority of the crash impact energy had been dissipated through plastic collapse. Many researches had been studied for the crashworthiness design. For numerical method, nonlinear, large deformation finite element analysis (FEA) is relatively sophisticated and had been successfully used for crashworthiness design at all major automotive companies. In recent, the finite element analysis is preferable than other method for manufacturer's design analysis method. It is because of the cost of physical testing a large parameter study (crashworthiness study) is prohibitive.

An energy absorber can be defined as a system that converts, totally or partially, kinetic energy into another form of energy. Energy converted is either reversible as the pressure energy in compressible fluids or irreversible, such as involving plastic dissipation energy associated with the permanent deformation of a solid. The energy absorption for an energy absorber, E can be calculated using following equation.

$$E = \int F \, du$$

where F is a applied force and du is a small distance of the displacement along the force-displacement curve.

In the study of the lateral collapse of cylindrical thin wall tube, the energy absorption capacity of tubular members under lateral impact loading can be determined by modeling it with shell finite elements. The research was examined in two-dimensional where lateral loading is imposed by two rigid plates which are shown in Figure 1. Reddy and Reid [5] investigated the lateral compression of tubes with side constraints and found the energy absorbed in a constrained system is three times more than that of free system.

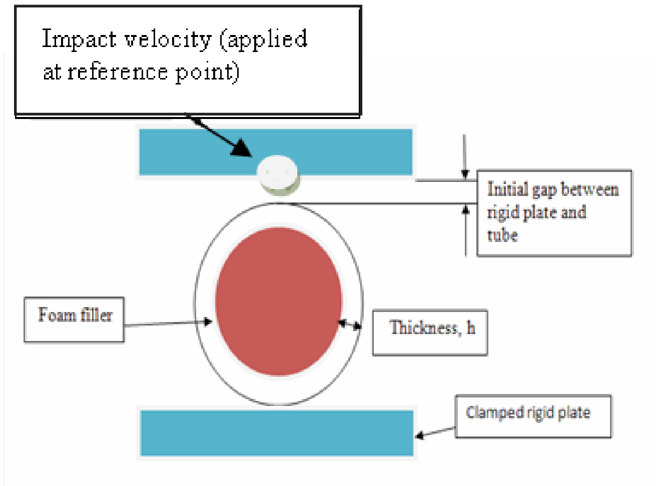

Figure 1: Cross-section of Numerical Model

Presence of foam filler is to improve the energy absorption capacity of the structure and can be generally expressed by the following equation:

$$F_{m,f} = F_m + F_f + F_I$$

where F_m is the mean force of empty column, F_f is the mean force of the foam material and F_I due to the interaction effect. Song et al. [6] stated that there is a significant interactive effect between foam-filler and thin-walled tube; these cause the total energy absorption of filled tube substantially higher than the summation of their individual contributions. In the recent findings, Nariman-Zadeh et al. [7] attempted to minimize the weight and maximize the energy absorption capacity of vehicles. Nowadays, the trend of crashworthiness design is mainly emphasis on economical, lightweight and safety consideration. Therefore, the kenaf foam which have the combination of the above parameters had becomes an attractive material of impact structure.

3 METHODOLOGY

3.1 Geometry of Composite Structure

In this research two types of numerical simulation ware performed. In the first study, the effect of thickness of tube on the energy absorption was investigated. The impact mass was 10kg, the impact velocity was 10m/s, 15m/s, and 20m/s. The material for the model was mild steel. The thickness of the tube was set at 2.5mm, 3.2mm, and 4mm with constant outer diameter of 76.2mm. The total numerical runs were nine. In the second study, the effect of density of foam-filler material on the energy absorption was investigated. The impact mass was 10kg, the impact velocity was 10 m/s, 20m/s, and 30m/s. The material of tube was steel with foam-filler material of 0%, 5%, 10%, 15% and 20% kenaf foam. The thickness of the tube was set at 2.5mm, 3.2mm, and 4mm with constant outer diameter of 76.2mm. The total numerical runs were forty-five.

3.2 Model Development

The collapse of tubes under lateral loads can be treated as a two-dimensional problem, assuming that the tube is significantly longer than its diameter (L≥D), and the load and deformation do not vary in the axial tube direction which called plane strain conditions. The empty tube models are modeled with reduced-integration four-node shell elements (S4R) from the general purpose program ABAQUS. All the parameters used for empty tubes and foam-filled tubes are same in the simulation. The foam-filled models are modeled with three-node linear plane strain triangle element.

3.2.1 Constitutive Modeling of Materials

3.2.1.1 Tube Walls

The tube wall made from mild steel can be modeled as an elastic-plastic material model with isotropic hardening. A nonlinear analysis is done to determine the response. Input of effective plastic strain and effective yield stress pairs data are required for the steel material model. In order to determine the plastic strain and the yield stress values from the engineering stress-strain data, the following relationships were used:

$$e_T = \ln(\varepsilon + 1)$$
$$\sigma_T = \sigma\,(\varepsilon + 1)$$
$$e_p = e_T - e_E\,,\; e_E = \sigma_T / E$$

where e_T is total true strain, ε, σ are the engineering strain and stress, σ_T is the true stress, e_p is the plastic strain, e_E is the elastic strain, and E is Young's modulus. Other relevant mechanical properties of steel are Young's rnodulus, Poisson's ratio, and power law exponent. By applying the overstress power law incorporated into the FE model, the parameter values t= 6844s^{-1} and q^t= 3.91 were used, as in the previous studies for the dynamic axial crushing of mild steel tubes [8].

3.2.1.2 Crushable Foam Core

In ABAQUS/Explicit, crushable foam model is based on the plasticity theory. In the current study, the foam-filler which located inside the tube was modeled as crushable foam model with volumetric hardening. Thus, the input data to the hardening law by only specifying, in the usual tabular form, the value of the yield stress in uniaxial compression as a function of the absolute value of the axial plastic strain.

3.2.2 Section Properties

The properties of each part which created in the part module were defined through sections module in ABAQUS. Two sections were created for two materials defined when input of material.

3.2.3 Steps

The dynamic response of the cylindrical tube to loads applied at the top rigid plate was to be investigated. This is a single event, so only a single dynamic, explicit analysis step is generated for the simulation. In ABAQUS/CAE, the initial step was generated automatically, but the analysis step has to be created by user manually. Thus, the simulation was consisted of two steps overall.

3.2.4 Boundary Conditions and Loading

For the boundary conditions, the bottom rigid plate which attached to the foam-filled tube was clamped by retaining all degrees of freedom of the nodes on the surface. The nodes of the top rigid plate of the tube with foam-filler were retrained in all but the crash direction. In the simulation, the top rigid plate with its rigid reference point is fixed in all directions except axial direction. For the bottom rigid plate, the rigid reference point is fixed in all directions. The details boundary condition are shown in Figure 1.

Each contact interaction must refer to a contact interaction property that governs the interaction behavior. There were two different contacts in this research, tangential and normal contacts. One was between rigid plate and deformable tube. Rigid plate surface toward tube was defined as master surface. In dynamic case, the internal and external surfaces of tube are defined as slave surfaces. The friction coefficient in contacts was defined by 0.2.

4 RESULT AND DISCUSSION

4.1 Collapse Pattern

In this study, the deformation patterns of an empty tube and foam-filled tube were observed. When the impact velocity was applied, the cylinder deform to oval shape mode. By the time increase, the empty and foam-filled tube models were compressed to the deformation form of the steel tube at the final stage of failure that is called "figure of eight". The fastest deformation happened subjected to the cylindrical tube without foam. The deformation was decreased by increasing kenaf percentages for every thickness. The deformation period was influenced by the impact velocity applied. As the velocity increased, the time taken for model to achieve the deformation pattern will be decreased. All the models deformation modes occurred similarly. In this simulation, the deformation time for 10m/s, 15m/s and 20m/s are approximately 6.5ms, 3.3ms and 2.2ms. Both empty tube and foam-filled tube models were simulate in the same step time as mentioned above to get a consistent results. The deformation pattern of a 2.5mm wall thickness model with impact velocity of 10m/s is depicted in Figure 2. The deformation pattern of a 4mm wall thickness foam-filled tube with impact velocity of 30m/s is depicted in Figure 3.

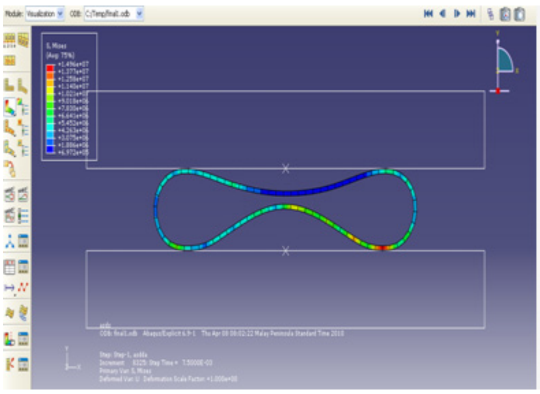

Figure 2: Collapse pattern of empty tube

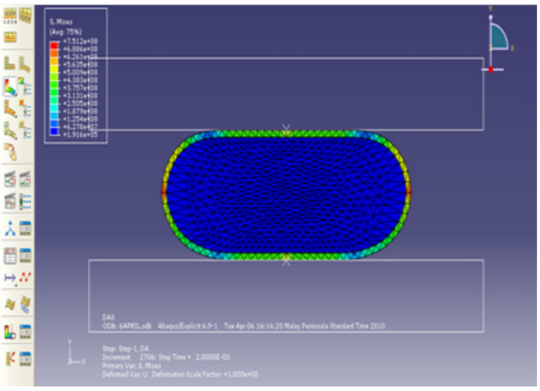

Figure 3: Collapse pattern of foam-filled Tube

The model assumes linear elastic behavior prior to the formation of the four plastic hinges, and perfectly plastic behavior upon activation of the collapse mechanism, the deformation pattern of the model will be considered as in Figure 4 and 5. Generally, the exact mode of deformation is difficult to predict as imperfection in the geometry influence the initial buckling. The initial imperfection in the tube was considered which lead to a symmetric mode of collapse and initiate the collapse occurs. Nevertheless, the overall collapse pattern is considered satisfactory for the purpose of the present work.

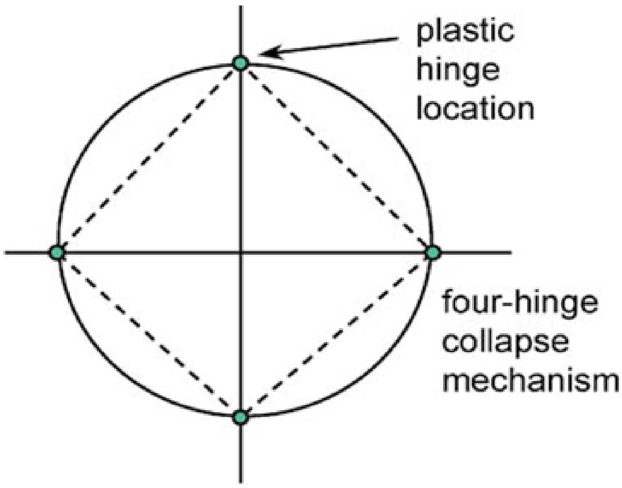

Figure 4: Four-hinge plastic mechanism

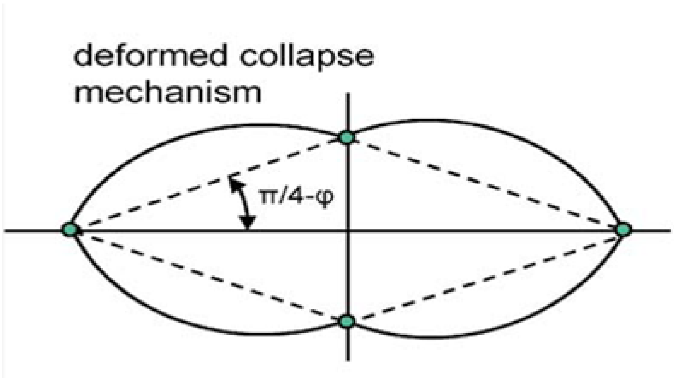

Figure 5: Deformed collapse mechanism

4.2 Effect of wall thickness

The analysis result for the each thickness with different impact velocity give a good agreement with the increasing in wall thickness will increase the energy absorption capability for both empty and foam-filled tube models. The effect of thickness on the energy absorption of an empty tube under impact velocity of 10m/s, 15m/s and 20m/s is shown in Figure 6. The figure shows that 2.5mm thickness model had the lowest energy absorption capability among others. The performance of loaded tube can be improved by adding foam fill compared to increasing the wall thickness of cross section as well. Figure 7 show the energy absorption capacity in various wall thickness of an empty tube at constant impact velocity of 30m/s.

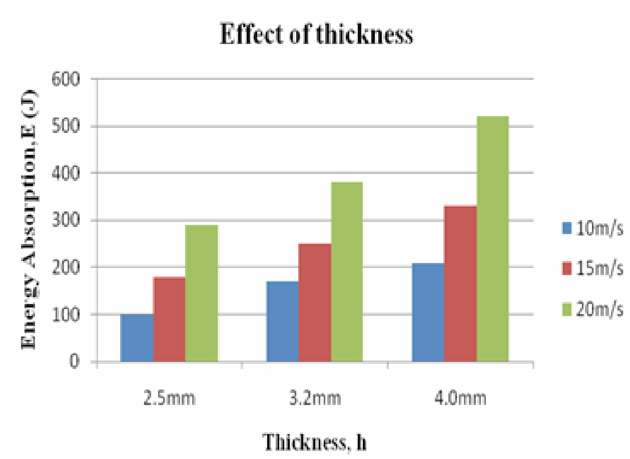

Figure 6: Energy absorption versus thickness for an empty cylindrical model

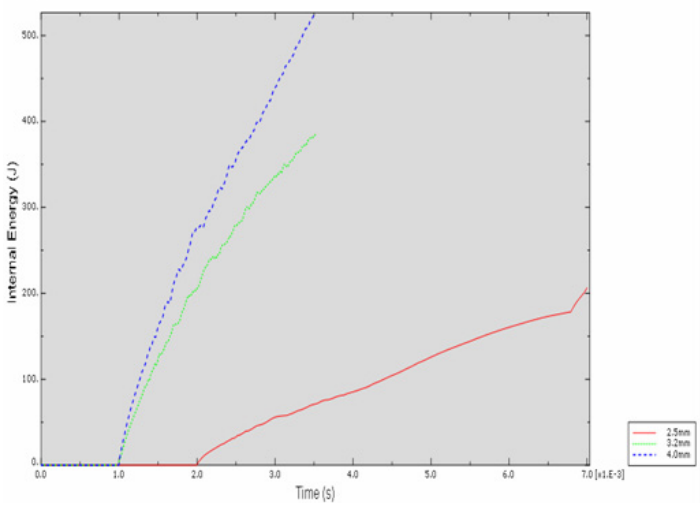

Figure 7: Energy absorbed for various wall thickness at constant speed 30m/s

4.3 Effect of Foam Density

There is a significant increase in the value of energy absorption when the kenaf foam density is increased. By refer to Figure 8, the highest energy absorption obtained at the 15% kenaf foam, but the energy absorption capability reduced where the 20% kenaf foam applied. The energy absorption due to the foam filled increase depends on the cross-sectional area and the foam strength, which is by increasing the kenaf percentages in the bio-foam. However, too much kenaf percentages, such as 20% kenaf foam had cause the low energy absorption which is averagely lower than the 0% kenaf foam model. It means consumption another material mix up with the polyurethane had its own limited proportion. However, foam-filled model contribute higher energy absorption capability compared to the empty tube model.

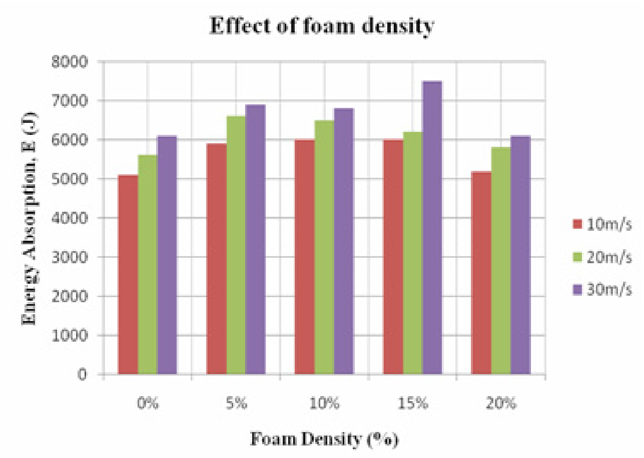

Figure 8: Energy absorption versus foam density

4.4 Effect of Impact Velocity

The impact velocity was modified to view the variation in energy absorption of the models. The three different impact velocities considered were 10, 20 and 30m/s respectively. The results obtained are shown in Figure 6 and 8. The result show that the energy absorption increase when the impact velocity was increased. The initial collapse load increases with impact velocity. The higher collapse load leads to an increase in energy absorption. This characteristic was advantageous in the crashworthiness design which demand the maximum energy absorbed in a high speed collision environment. Clearly, the foam-filled columns display a sensitivity to impact velocity.

5 CONCLUSION

The purpose of this study was to investigate the effect of foam filling on the dynamic response and energy absorption characteristics of thin walled tubes using finite element simulations. Energy absorption response was quantified with respect to variations in the parameter of wall thickness, foam density and impact velocity.

The results have demonstrated the feasibility and superior performance of foam filled cylindrical tubes as energy absorbers. The increasing foam density up to 15% appears to be the percentage of foam that had the highest energy absorption capability. The energy absorption increase significantly as the foam densities increases under impact loading due to the presence of foam filler and interaction effect between foam core and cylindrical tube. For equal crush length, foam filled tube absorbs significantly more energy than empty tube under dynamic lateral loading. In the other words, foam filled cylindrical tube would be effective in absorbing a large amount of energy with a short crushing deformation which can conform to the current design trends. The dynamic energy absorber for a foam filled cylindrical tube can be improved by increasing the wall thickness and the density of foam density which have to be experimental and numerical research required.

In this study, the result demonstrated that the highest energy absorption capability obtained by the 4mm, 15% kenaf foam model at 30m/s speed. This show that the model designed can be approach to be an optimal energy absorbing device that absorbs higher energy at high impact speed.

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