Energy Absorption Analysis of aluminum Filled Foam Tube Under Axial Load using Finite Element Method with Cross Section Variations.

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Abstract. This study aims to determine the effect of the use of aluminum-filled foam tubes on crash boxes and the effect of cross-sectional variations in the use of aluminum-filled foam tubes on crash boxes. There are several parameters to determine crashworthiness performances such as energy absorption and deformation. Test specimens used are single walled (SW), single walled foam filled (SWFF), and double walled foam filled (DWFF), where DWFF is varied into 4 different wall thicknesses. All models have validated with experiment data from relevant reference and it evident that there are good agreement between simulation and experiment results. Tubes are impacted by rigid wall as impactor with velocity 0.4 m/s. From the simulation results, it was concluded that the aluminum crushbox construction added with aluminum foam is able to absorb more energy, where the recommended thickness is neither too thin nor too thick. Tube of DWFF 3 has energy absorption of 11.911 Joule, however the highest of deformation value is 178.66 mm for SWFF.

1. Introduction

The design of a new lateral safety system with better crashworthiness is the most relevant thing to reduce the risk of death and injury in traffic accidents and improve vehicle performance in energy absorption. Crashworthiness is the ability of the vehicle to absorb impact energy and protect vehicle passengers when an accident occurs. The car is designed with several protective systems that aim to increase the vehicle's suitability [1].

Crash Box is one of the passive safety system technology developments that has been widely studied. The function of this crash box is as a device in kinetic energy absorption when a car experiences a collision or accident, both collisions from the front or collisions from behind. The design of the device component crash box serves to reduce the occurrence of forces distributed to the entire body of the vehicle during a collision or collision. The use of a crash box is placed between the buffer and frame of the vehicle [2].

Various studies had been conducted with the purpose to develop devices that reduce the risk of accidents in collisions, one of which is testing on a crash box device where collisions are given at a predetermined rate of change in plastic deformation. It could be concluded that this incident shows the energy absorption in the crash box. However, the phenomenon obtained shows that the faster the plastic deformation changes in the crash box, the remaining speed due to collisions is still a lot that can endanger the mainframe of the vehicle, so this phenomenon considered to be still low for the driver's safety level [3].
The structure of thin-walled test specimens is known as a promising and efficient way of absorbing energy from an impact force on structures in the frame of the concept car, train structure and helicopter frame [4]. There are two main considerations that need to consider in designing the structure of the specimen to present the function as a device that can absorb energy, namely: how to achieve the right ductility to reduce the force of a collision, and how to reduce the extreme force at the first interaction on a collision. The first case relates to the collision resistance capacity of the structure, while the second case relates to the level of safety for passengers.

![Test specimen model is tube-shaped](image)

In general, the simplest way to increase the resistance to collisions with axial forces is to adjust the wall thickness of the structural frame, although this is not the best way because the mass of the structure will automatically become heavier too. One effective solution to reduce the extreme force of impetus in the first interaction on a collision, usually how to overcome it is to implement a thin wall structure. With the discovery of new material, as an alternative, which becomes a modification of parts of the structure by adding material that has a light density can be a solution in increasing resistance to collisions that occur with axial forces and on the other hand this material is lightweight so that it can streamline weight and overcome force extreme push on the first interaction on a collision. An alternative way is to fill polyurethane foam to strengthen thin wall components which are recommended by Thornton [5].

The use of aluminum foam material as one of the materials in a crash box device is one solution to prevent traffic accident victims from the side of the vehicle. Aluminum foam is lightweight, strong, and anti-rust. In recent decades, metal foam such as aluminum foam had been developed as a very light engineering material. This material has unique mechanical properties, which can withstand large deformation stresses while this material has only a small constant tension. One application of this material is a structure that absorbs energy. Filling the structure with aluminum metal foam can improve the energy absorption properties and stabilize the curve of the structure. Great efficiency in weight had been obtained by combining the structure with a thin wall and filled with metal foam as a core, as studied by Santosa et al. [6]. In another study, it was revealed about the analysis of structures that been filled with metal foam and given axial force interaction

| Specimen wall thickness | SW & SWFF | DWFF |
|-------------------------|-----------|------|
|                         | thickness | length | thickness | length | thickness | length |
|                         | outer \(h_0\) (mm) | outer \(l_0\) (mm) | outer \(h_0\) (mm) | outer \(l_0\) (mm) | outer \(h_1\) (mm) | outer \(l_1\) (mm) |
| 3                       | 210       | 3      | 210       | 3      | 210       | 3      |
The average ability to withstand the force of collisions resulting from structures that been filled with metal foam is higher than the average ability to withstand the force of collisions produced from each of which is only metal foam or thin-walled structures, which is confirmed by Kavi et al. [7].

In maximizing the potential of implementing metal foam as a lightweight fill material at the core of the structure, an alternative concept that can be done is to duplicate the structure with walls that filled with metal foam, where the metal foam is placed between the structure with the inner wall and the structure with the inner wall externally, this solution has been shown to improve efficiency in the weight of suitable structures according to Santosa and Wierzbicki [8], but so far not much information is available regarding the nature of these double-walled structural parts given collisions with general axial force directions. One of the publications regarding the nature of the dual structure is Santosa and Wierzbicki using a non-linear dynamic finite element analysis approach. In its publication, the level of resistance to impulses in collisions from structures with double foam-filled structural members of the wall is shown to be significantly higher, compared to structures that are only covered by a foam-filled wall which gets the same loading.

A study on experiments with quasi-static loading experiments with axial emphasis has also been investigated by Zhibin Li, Rong Chen, Fangyun Lu [10] where with two different types, namely round and box structures and with variations of structures filled with Aluminum Foam, including structures round filled with metal foam and metal foam filled with tube boxes, double walled round structure filled with metal foam and double walled box structure filled with metal foam, and metal foam filled with box structure at the corners. The results show that the dimensions of the structural part with walls on the type of structure that is double walled and filled with metal foam in between can have a very significant effect in responding to a collision.

In the research of Niknejad et al. [11], published several validated theories of experiments that predict the response to collisions of rectangular structures filled with metal foam (polyurethane) during the initial fold formation under initial axial force collisions. The analysis considers the effect of the interaction between the metal foam and the inner walls of the structure. The results show that there is an influence of interactions on the nature of the collision.

Zheng et al. [12], compared the energy absorption properties of a single structure filled with metal foam with quality density and looked at the effects of density distribution for specific energy absorption capacities. The results show that 12% is better in the specific energy absorption capacity by a single structure filled with metal foam with quality density compared to the use of materials with normal density where the same loading is given.
| Code  | thickness $h_0$ (mm) | Diameter outer $d_0$ (mm) | Diameter inner $d_1$ (mm) |
|-------|---------------------|--------------------------|--------------------------|
| SW    | 110                 |                          |                          |
| (as in Table 1) |          |                          |                          |
| SWFF  | 110                 |                          |                          |
| DWFF 1| 110                 | 82                       |                          |
| DWFF 2| 110                 | 60                       |                          |
| (as in Table 1) |          |                          |                          |
| DWFF 3| 110                 | 40                       |                          |
| DWFF 4| 110                 | 20                       |                          |

## 2. Geometrical Specimen

In this study, there are three configuration models based on the previous research references, namely single-walled (SW), single-walled foam-filled (SWFF), and double-walled foam-filled (DWFF). The results of the previous studies regarding SW, SWFF, and DWFF were conducted by aerospace et al. [13] who used square-shaped specimens. What makes it difficult in this study is to use a tubular specimen. The geometry of the test tube according to Figure 1. The length of all test specimens is 210 mm. The tube wall of the test specimen used is aluminum. Where in this test the condition of the tube wall was filled with metal foam material. The metal foam material used is aluminum foam. In this test compare the quality of the specimen in absorbing energy when given the impact force from the axial direction with several conditions, namely specimens without foam and specimens using foam which with 3 different thickness variations.

Single-walled (SW), single-walled foam-filled (SWFF), and double-walled foam-filled (DWFF) geometries are detailed in accordance with Figure 2. All dimensions of specimen wall thickness are the same, namely 3 mm because they use a type of material that is the same, as can be seen in Table 1. In this study, the specimens were analyzed in simulation software to determine the effect of aluminum tubes without being filled with metal foam on the ability of the specimens to absorb energy from the impact force applied. Specimen size specifications in this first test are in accordance with Table 2.
In this study, there are two categories of testing, the first of which is to compare the effect of the use of metal foam and the number of walls in a specimen tube on the ability to absorb energy as shown in Table 1. The second category is to compare the effect of metal foam thickness on the ability to absorb energy as shown in Table 2.

3. Mechanical Properties

In this study, the material used is aluminum and metal foam made from aluminum. The type of aluminum foam used as a test specimen is a material with a density of ~ 480 kg / m³. The other parameters used relating to aluminum foam material are crushable foam with a compression yield stress ratio of ~ 1732 and a modulus of elasticity with a value of ~ 625 MPa, where the equation used is:

$$E = \frac{\sigma}{\varepsilon}$$  \hspace{1cm} (1)
The second material is aluminum, where the type of aluminum used as a test specimen is a material with a density value of ~ 270 kg/m³. Other parameters used relating to aluminum material are aluminum elasticity value ~ 68200 MPa and plastic values according to Figure 3.

4. Finite element model
The calculation of the finite element method in this study uses simulations to get the right results. The simulation run on Abaqus CAE, which can operate analytical simulations with explicit non-linear dynamic types. The finite element testing model is tubular as in Figure 1.

In this study, the model was made in Abaqus CAE. All tests use two of additional plates that touch directly on the front and back of the specimen according to Figure 4, where the front plate moves and gives a boost to the specimen.

The process of making parts carried out in this study in Abaqus CAE has different amounts in all specimens tested according to the number of parts in single-walled (SW), single-walled foam-filled (SWFF), and double-walled foam-filled (DWFF).

The meshing process carried out in this study in Abaqus CAE uses sizing controls ~ 4 and the largest deviation used is 0.1.

In the interaction process, there are two interactions included in the simulation. The first interaction is the surface to surface, where this interaction is arranged on the surface of parts that touch each other directly. The second interaction is the self-interaction, where this interaction arranged in one whole part because it is only intended for the results of interactions that occur in a part.

Speed determination is also carried out in carrying out simulations on Abaqus CAE with a speed value of ~ 0.4 m/s.

Table 3. Comparison between experimental test and finite element

| Impact Angle (°) | FE     | Li ZB at al [13] | Error (%) |
|------------------|--------|------------------|-----------|
| Energy Absorption (j) | 0      | 3427.34          | 3524      | 2.74       |
| Specific Energy Absorption (j/g) | 25.93  | 26.7             | 2.88      |
| Energy Absorption (j) | 15     | 3197.28          | 3286      | 2.69       |
| Specific Energy Absorption (j/g) | 24.25  | 24.8             | 2.19      |

5. Model validation
The finite element model being compared uses references from experiments that been carried out by Li et al. [13] to ensure that our design tests are quite accurate with their experiments. The previously validated model is a double circular aluminum foam tubular with oblique loading [14-17]. The material used in the test specimen is AA6063T6 aluminum alloy [13]. Loading is given constant with a speed of 0.09 mm/s for double circular aluminum foam tubular. The geometric length of the pecimen is 90 mm, with an outer diameter of 38 mm and an inner diameter of 24 mm. The thickness of the specimen tube wall is inner 2.0 mm and outer 1.2 mm. A comparison between finite element method research [13] and our design testing with the same specifications and loading can be clearly seen in Table 3.
Figure 5. Comparison between deformation and time, (a) SW, (b) DWFF, (c) DWFF 1, (d) DWFF 2, (e) DWFF 3, (f) DWFF 4.
**Figure 6.** The final length of all specimens.
Figure 7. Comparison between energy absorption and time, (a) SW, (b) DWFF, (c) DWFF 1, (d) DWFF 2, (e) DWFF 3, (f) DWFF 4.
6. Simulation Result

The data collection technique used in this study was to simulate the test material in the form of an aluminum wall filled with aluminum foam with several variations of different wall thicknesses. Specimens used in this experiment include single walled (SW), single walled foam filled (SWFF), and double walled foam filled (DWFF). DWFF specimens varied into four different wall thicknesses. The object under study is designed on Abaqus CAE software where the test material in the form of a pipe with aluminum foam is then measured its quality of resistance by simulating the test material that been made.

6.1. Deformation

One of the results of the analysis of simulation experiments on Abaqus CAE with variations in the thickness of the wall diameter of this specimen is the deformation that occurs so that the length of the specimen reduced because of the force from the axial direction. In testing single walled specimens (SW), the relationship between specimen deformation and time can be clearly seen in Figure 5(a). Figure 5(a) shows that the constant is increasing, which means that deformation is constant over time. This phenomenon occurs because of the influence of the blank wall of the specimen without the aluminum foam being filled in the middle. The final length of a single walled (SW) after experiencing deformation is 63.8 mm. In the single walled foam filled (SWFF) specimen, the relationship between specimen deformation and time can be clearly seen in Figure 5(b). In Figure 5(b) shows that deformation occurs fluctuatively, meaning that the phenomenon that occurs in the test specimen is not only a reduction in length but also an increase in length. This phenomenon occurs because of the elastic nature of the specimen so that the length of the specimen has returned after shortening, before finally experiencing a reduction in length again. The final length of the single-walled foam filled (SWFF) after being deformed is 178.8 mm. In testing the DWFF 1 specimen, the specimens used are aluminum outer diameter of 110 mm and aluminum inner diameter of 82 mm filled with aluminum foam between inner and outer. The relationship between specimen deformation and time can be clearly seen in Figure 5(c). In Figure 5(c) shows that deformation occurs fluctuatively, the final length of DWFF 1 after being deformed is 164.33 mm. In testing DWFF 2 specimen, the specimens used are aluminum outer diameter of 110 mm and aluminum inner diameter of 60 mm filled with aluminum foam between inner and outer. The relationship between specimen deformation and time can be clearly seen in Figure 5(d). In Figure 5(d) shows that deformation occurs fluctuatively, the final length of DWFF 2 after being deformed is 164.33 mm. In testing the DWFF 3 specimen, the specimens used are aluminum outer diameter of 110 mm and aluminum inner diameter of 40 mm filled with aluminum foam between inner and outer. The relationship between specimen deformation and time can be clearly seen in Figure 5(e). In Figure 5(e) shows that deformation occurs fluctuatively, the final length of DWFF 3 after experiencing deformation is 165.06 mm.
In testing the DWFF 4 specimen, the specimens used are aluminum outer diameter of 110 mm and aluminum inner diameter of 20 mm filled with aluminum foam between the inner and outer.

![Figure 9. Comparison between all energy absorption of specimens and time.](image)

The relationship between specimen deformation and time can be clearly seen in Figure 5(f). In Figure 5(f) shows that deformation occurs fluctuatively. The final length of DWFF 4 after experiencing deformation is 161.41 mm. Overall the final length of all specimens after the simulation can be seen based on the results of data processing in Figure 6. In Figure 6 shows that the shortest end of the specimen occurs in the type of SW specimen testing with a length of 63.8 mm and the longest end of the longest specimen occurs in the type of SWFF specimen testing with a length of 178.8 mm. Tests of DWFF specimens tend to be the same and the interval values between DWFF are not far adrift. The longer the specimen after testing shows that the less the reduction in the length that occurs due to pressure by the force from the axial direction and vice versa, the shorter the specimen after the test shows that the more reduction in the length that occurs due to the pressure by the force from the axial direction [18].

6.2. Energy Absorption

Other analysis results from the simulation experiments on Abaqus CAE with variations in wall diameter thickness of this specimen are the amount of energy that can be absorbed by the specimen when given treatment. The relationship between deformation and time is clearly shown in Figure 7. The SW specimen, from Figure 7(a) shows that energy absorption occurs fluctuatively and the maximum energy that can be absorbed by the SW specimen in this test is 10.206 joules. In the SWFF specimen, from Figure 7(b) shows that the energy absorption occurs constantly increasing and the maximum energy that can be absorbed by the SW specimens in this test is 11.711 joules. In all DWFF specimens, from Figure 7 (c), (d), (e), and (f) show that energy absorption occurs fluctuatively and maximum energy that can be absorbed by specimens DWFF 1, DWFF 2, DWFF 3, DWFF 4 in this test, each was 11.259 joules, 11.618 joules, 11.911 joules, 11.875 joules. Overall, the maximum energy that can be absorbed by the specimens in this test can be seen in Figure 8 based on the results of data processing in Figure 9. Figure 9 illustrates that all specimens have similar energy absorption characteristics, which tend to increase, except in the SW specimen, which shows fluctuating energy absorption characteristics and is far below other specimens [19].

7. Conclusion

The use of aluminum foam in crush box construction affects the level of energy absorption that occurs during testing, where the crush box construction that added with aluminum foam is able to absorb more energy. The thickness of aluminum foam in crush box construction also affects the level of energy absorption, where the recommended thickness is DWFF 3 which is neither too thin nor too thick. The least energy-absorbing specimen in this study was SW compared to other specimens, where
the energy absorbed was 10,206 joules. The least deformation so that the final length of the specimen is the longest in this study, namely the SWFF specimen with a final length of 178.8 mm. The most deformation occurred in the SWFF specimen, so that the final length of the specimen was the shortest with a final length value of 63.8 mm.

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