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Experimental and Theoretical Investigation of Combined Expansion Tube-Axial Splitting as Impact Energy Absorbers

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Response to Reviewers:	

Experimental and Theoretical Investigation of Combined Expansion Tube-Axial Splitting as Impact Energy Absorbers

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Abstract

In this study, the combination of an expansion tube and a deformable rigid tube with axial splitting is developed as a new mechanism for use as an impact energy absorber. The impact absorbing structure consists of two circular tube forming dies, with each die allowing the tube to expand and to split. The latter is used to remove away radially the debris after expansion and splitting, so that the absorption process can continue without being obstructed by the debris itself. This paper presents the experimental and theoretical investigation of the combined expansion tube-axial splitting as an impact energy absorber. The experiment by the laboratory scale impact testing has been done with a variation of the parameters such as pipe thickness (t), angle of splitter (α), comparison of dies upgrading diameter (D_2) and inner pipe diameter (D_1) (D_2 / D_1). The theoretical investigation is carried out with a literature study related to the mechanics of material and theoretical studies from previous research studies. The final result of this paper, i.e., a new formula has been proposed to calculate the mean load, is reflective of the study of a combined expansion tube with axial splitting. The difference between the results of analytical calculation and experiments is 10.13 %.

Keywords: impact, energy absorber, expansion tube, axial splitting

1. Introduction

Impact Energy Absorbers (IEA) is a system that convert totally or partially of kinetic energy into another form of energy. Energy converted is either reversible, like pressure energy in compressible fluids and elastic strain energy in solid, or irreversible, like plastic deformation energy. IEA has been applicated in collision to limit the loads that may act on the main structure immediately after a collision. In the mass transportaion equipment, there are the component of the main structure may serve a secondary purpose as energy absorbers in case suffered more severe collisions. Accident risk reduction due to collisions on mass transportation (railways) can be divided into 2 main strategies, that are prevention of accidents and minimization of the impact of accidents with crashworthiness. The first strategy in the railways transportation was implemented with double track development, signaling technology and Automatic Train Protection (ATP). With ATP technology, each train is equipped with a set of sensors to detect possible collisions and at the same time provide preventive measures. In addition to the first strategy, the second strategy, that is the minimization of the impact of accidents is also important, especially given the condition of railways in Indonesia which are not all equipped with multiple crossings. The first strategy is called active safety, while the second strategy is called passive safety. Railways transportation have a large mass and higher speeds, the consequences of accidents will also increase. Although the possibility of an accident can be suppressed by the first strategy, it still cannot eliminate the possibility of an accident. For this reason, accident risk management must be complemented by a second strategy with crashworthiness technology.

The impact energy absorber module is one of the most important components in the application of crashworthiness technology to improve the safety of transportation facilities. The effective mechanism for absorbing impact energy is through the modular deformation of the module structure. The effect of impact energy absorber, the impact energy and impact force which passed to the main structure of the vehicle will be limited during a collision, so the impact of collision on passengers or cargo can be minimized.

There are many types of structures that are used as energy absorbing module that are expansion tube and axial splitting. There are two reasons which make expansion tube one of the most efficient energy absorbing units. One is the easy producibility and the other is the high efficiency in energy absorbing. Many types of thin-walled energy absorbers were studied experimentally, theoretically and numerically extensively in the past years. Among all such thin-walled structures, the most frequently appeared axial compressive member in literature is circular tubes and square tubes. The crushing behavior of these thin-walled structures energy absorbing units have been investigated in the past. The problem of progressive buckling of tubes under axial compressive load has been the subject of extensive research over the past four decades. The early work by Alexander, J. [1,2], Harris, J., & Adams, R [3], Corbett, G., & Reid, S [4], Langseth, M., & Hopperstand, O [5-7], among others, was aimed at predicting the average force level and energy absorption capacities of hollow columns. Later, Alghamdi, A. A [8], Huanga, X., Lua, G., & Yu, T. X. [9], Huh, H., Kim, K.-P., & Kim, H. S [10], M. Shakeri, Yuung-Ming, H [11], S. Salehghaffari, & R. Mirzaeifar [12], D.Y. Abebe and J.S.Jeong [13], Harhasa, A. D [14], Setiawan R [15], focus on predicting the entire load-deflection curve of the folding process. The expansion of deformable tubes by a rigid tube under axial compression is introduced as a very efficient process for absorbing impact energy, which has not been taken into consideration so far. In this proposed method of energy absorption, two cylindrical tubes with different material properties, where one of these tubes is considered solid compared with the other one, are used. There is also specific clearance between the surfaces of the rigid and deformable tubes, and the rigid tube is press fitted onto the top end of the deformable one up to 30 mm by hydraulic press. When this arrangement is subjected to axial compression, the rigid tube is driven into the deformable one. Consequently, the impact energy is absorbed by the plastic expansion of the deformable tube (because of the clearance between rigid and deformable tubes) and the frictional energy between them. The value of mean load (P_m) required to expand the deformable tube by the rigid one is derived from the following expression [12]:

$$P_m = [\pi t(D_1 + t)\sigma_0] \times \left\{\left(1 + \frac{t}{AD_1}\right) - \left[\left(\frac{D_2}{D_1} + \frac{t}{AD_1}\right) e^{\frac{A(D_1-D_2)}{t}}\right]\right\} \quad (1)$$

Where are, t : the thickness of tube, σ_0 : Stress, A : cross-sectional area, D_1: inner pipe diameter, D_2 : dies upgrading diameter

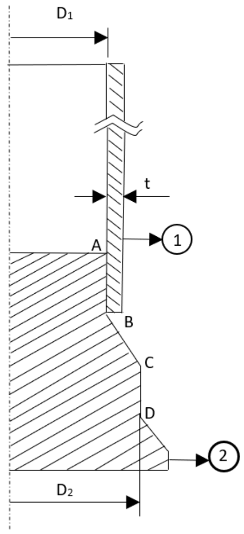
Splitting mode of deformation is special of tube inversion where the die radius is large enough to cause splitting instead on infertion [16]. Ezra and Fay [17] identified the combined modes of axial splitting and subsequent culing of split ends of tubes as an efficient means of energy dissipation in the absorber. The absorbed energy is dissipated in tearing of the metal of tube into strips. Based on their, expansion tube is efficient in absorbing energy and widely used as energy-absorbing devices. Metallic cylindrical tubes have attracted much attention due to their high stiffness and strength combined with a low weight and wide range of deformation which may be generated when they are subjected to axial loading. However, the type of expansion tube module still has some disadvantages. One disadvantage of the expansion tube type absorbent module is the limited length of the deformation step. On the characteristic map the expansion tube has specific energy 42 Nmkg-1 x 10-5 and stroke efficiency of 0.45.

2. Combined Expansion Tube-Axial Splitting

To reduce the low strike efficiency it was modified by adding an axial splitting type impact absorber module [18]. The combined module type expansion tube and axial splitting, the expansion tube impact absorption module has pipe construction and solid cylindrical dies. When the pipe gets an axial load, the inner diameter of the pipe will deform to be greater than before following the diameter of the solid cylinder that hit it. Axial splitting impact absorber modules have basic construction which pipes and dies. Dies in this module are conical with certain angles. The direction of pipe deformation if exposed to axial loads is to divide following the shape of the dies. This paper aims to compare theoretical calculations with experimental results especially in the combination of impact absorbers and axial splitting.

Theoretical calculation for expansion tube was presented Shakeri M, Ghaffari SS and R. Mirzaeifar [12], Azizi R & Ghaffari SS [19], and Yan J, Yao S, PingXu, YongPeng, HengShao & Zhao S [20]. The experimental and theoretical calculation of axial splitting was presented [9]. In this section, a theoretical formulation was presented for this particular impact absorption mechanism divided in four segments based on the process that occurs consider friction in the impact absorbing process. The theoretical formulation based on material assumption is rigid material (dies) and elastic-perfectly plastic (expansion tube) with average flow stress. There is no variation in tube thickness during process expansion. Based on metal plastic forming technology, horizontal and vertical axes are considered as the principal axis of stress and strain.

Fig.1 shows the schematic diagram of the combined tube expansion and axial splitting mechanism with the segments of staging. The tube (1) serves as energy absorbing element deforms plastically due to insert form to the dies (2) while impact takes place.



1. Tube
2. Dies

Stage process:
A-B = Pre-compacting process.
B-C = Expansion process.
C-D = Extended expansion process.
D-E = Axial splitting process

Figure 1. The segmented process of expansion tube-axial splitting (1) tube, (2) dies

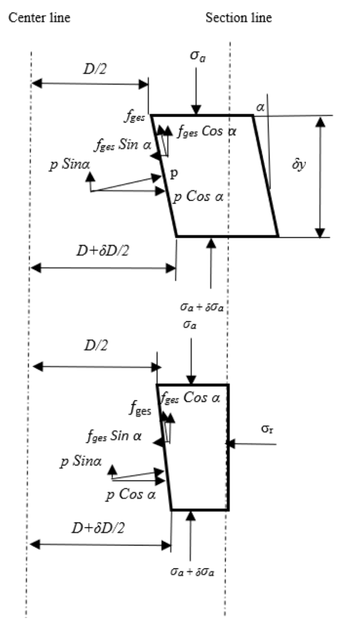
The energy absorption process occurs in several stages, i.e. pre-compacting, expansion, extended expansion and axial splitting. The process and the derivation of the energy absorbed be divided as follows.

a. Pre-compacting process (stage A-B)

At this stage the tube is given a load so that the tube enters the dies and the material is still in the elastic zone. The assumption are tube diameter with diameter dies have the right fit and change of stress at the initial load are ignored.

b. Expansion Process (stage B-C)

At this stage the tube will be expanding to follow the shape of the dies. Free body diagrams at a point in this segment can be explained as figure 2.



σ_a = axial stress
σ_r = radial stress
D = diameter
p = axial load
μ = friction
f_{ges} = friction force
α = slope angle of expansion dies

Figure 2. analitic model of expansion of deformable tube

The Equilibrium equation in the vertical direction is given by :

$$-(\sigma_a)(\pi D t) + (\sigma_a + d\sigma_a)(D + dD)\pi t + P\left(\pi D \frac{dx}{\cos\alpha}\right)\sin\alpha + \mu_p\left(\pi D \frac{dx}{\cos\alpha}\right)\cos\alpha = 0 \quad (1)$$

The formula is derived from the equilibrium equation of the horizontal and vertical direction. Using the assumption, Tresca yield criterion, $dy = l\cos\alpha$, and $dD = 2\tan\alpha\, dy$, we will have the new equilibrium equation in the vertical direction (2) and equilibrium equation in the horizontal direction (3) can be written as below:

$$\frac{\sigma_a + d\sigma_a}{D} + \frac{d\sigma_a}{dD} + \frac{P}{t}\left(\frac{\mu + \tan\alpha}{2\tan\alpha}\right) = 0 \quad (2)$$

$$P\cos\alpha + \mu_p P\sin\alpha - \sigma_\gamma = 0 \quad (3)$$

In this investigation, since the material used normally has a constitution relationship closed for elastic-perfectly plastic.$\sigma_a - \sigma_\gamma = \sigma_o$. We have mean crasshing force Pm (4) and constant value K (5);

$$Pm = (\pi t)(D_1 + t)(\sigma_o)\frac{-\frac{K}{t} + ln\lfloor D_2 - D_1\rfloor}{\frac{1}{D_1} + \frac{K}{t}} \quad (4)$$

$$K = \left(\frac{\mu + \tan\alpha}{2\tan\alpha(1 - \mu\tan\alpha)}\right) \quad (5)$$

Extended Expansion Process (stage C-D)

At this stage, tube has the same emphasis as the previous process, there is no change in diameter that occurs, but the tube will increasingly enter the dies. The formula at this stage has same with the formula as the previous stage.

Axial Splitting Process (stage D-E)

The crack process on the tube occurs at this stage, cracks will occur if the real strain that is greater than the permit strain ($\varepsilon \geq \varepsilon_{\text{permited}}$). The a new formula has been found to calculate the prediction of maximum expanded diameter (6-8), that tube will be collapse can be written as below :

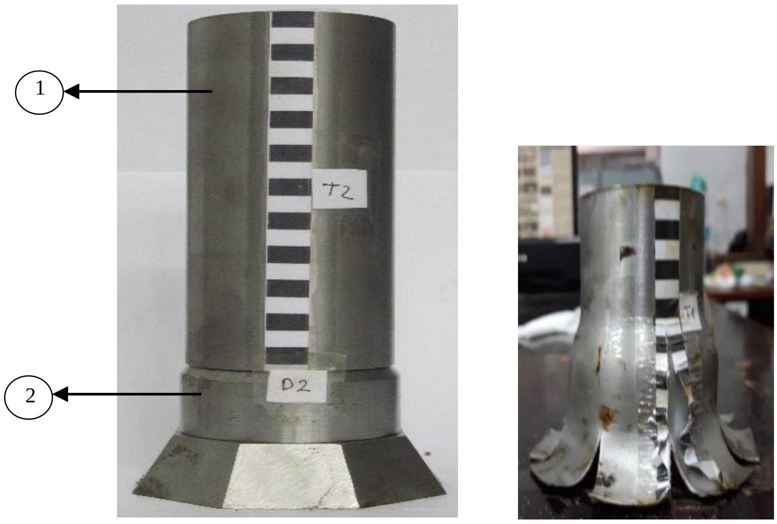
$$Pm = EA\varepsilon \quad (6)$$

$$\frac{(\pi t)(D_1 + t)(\sigma_o)\frac{-\frac{K}{t} + ln\lfloor D_x - D_1\rfloor}{\frac{1}{D_1} + \frac{K}{t}}}{\pi D_x t E} \geq \varepsilon_{ijin} \quad (7)$$

$$\frac{LnD_X}{(D_x)} - \frac{{}^{K}/_{t} + LnD_1}{D_x} \leq \frac{\varepsilon\pi D_x t E(t + K)}{(\pi t)(D_1 + t)(\sigma_o)D_1 t} \quad (8)$$

3. Experimental Investigation

In order to validate the theoretical formulation discussed previously, quasi-static test on specimens have been carried out. All the experiments were performed in a droop test machine. The module consists of the tube as the deforming body, and the forming dies, The combination of the two mechanisms is carried out by designing an integrated dies, that consists of expander and splitter, as can be seen in Fig. 3.



(a) (b)

Fig. 3 (a) Specimen: tube (1), dies (2), (b) Specimen after the test

The tube used API 5L Grade B seamless, with mechanical properties according to the mechanical test conducted as can be seen in Table 1. The material has relatively high elongation, which is ideal for impact absorber application, and is easily available on the local market. Whilst, a harder material was selected for the dies, i.e. from DIN 1623-2 Grade St 60-2G. The seamless construction of the pipe ensures that there is no unexpected failure due to welded joint of the pipe or tube.

Table 1 Mechanical Properties of API 5L Grade B from mechanical test (except for Poisson's ratio)

Property	Value	Unit
Density	7865	kg/m^3
Modulus Elasticity	200	GPa
Poisson Rassio	0.3 (assumed)	
Yield stress	352.7	MPa
Ultimate Tensile Strength	513.4	MPa
Elongation	25.4	%

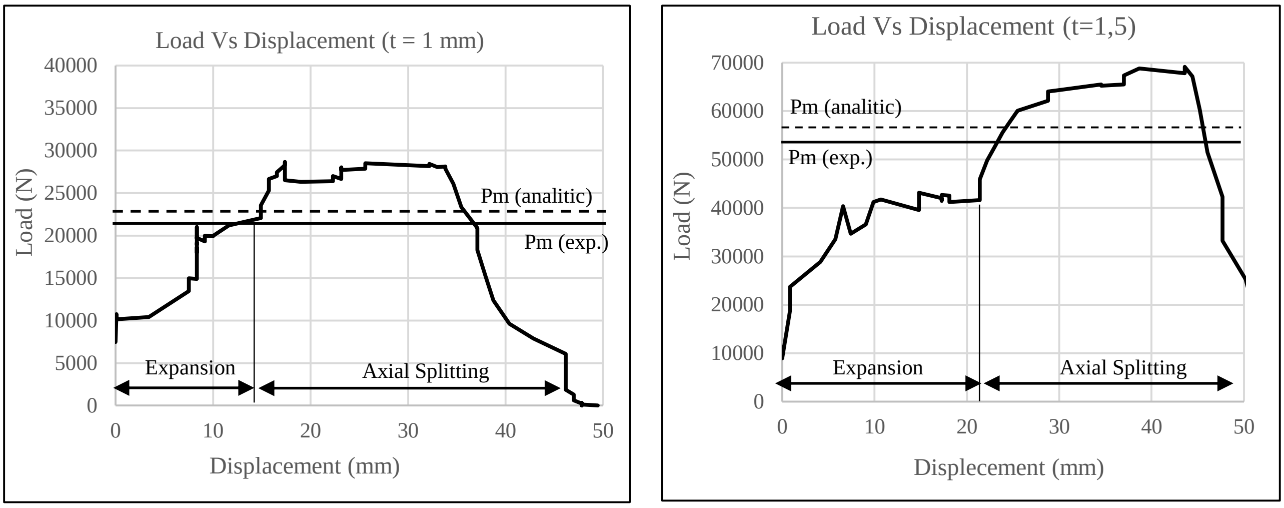
The impact characteristics of the module was observed using vertically drop test method. It used 81 and 107 kg impact mass, Hight of drop test: 2000 mm, 2200 mm, 2400 mm, 2600 mm. The dimension of tube and dies with tube thickness (t) : 1 mm and 1,5 mm, expanded pipe diameter (D_2) : 60,48 mm, tube inner diameter (D_1) : 54 mm, pipe length (L_o) : 100 mm, expander dies angle (α) : 25 ^{O}, and splitter angle (β) : 25 ^{O}. The load was measured through a load cell with maximum load of 30 kN and data acquisition with the sampling rate of up to 30 kHz. The experiment was also observed using high speed camera with the speed of up to 10.000 frame per second. Fig. 4 shows the experimental set up.

(a) (b) (c)

Figure 4. Experimental set up: a) Specimen position prior the drop test, b) Preparation of impactor, c) High speed camera monitoring

4. Result and Discussion

Mean crushing force (Pm) can be calculated with equation (4) with the material properties and dimension the same as with experimental conditian, we get the Pm = 22.310 N for tube tickness 1 mm, and Pm = 56.312 N for tube tickness 1,5 mm. The graph of load Vs displacement in experimental result shown in Fig.5. The result of mean crushing force (Pm) and peak crushing force (Ppeak) shown in Table. 2 . Fig 5.(a) shows the graph of load Vs displacement of spaciment sample with t = 1, with mean crushing force experimen (Pm exp.) = 21.860 N and mean crushing force analitical (Pm analitic) = 22.310. Fig 5.(b) shows the graph of load Vs displacement of spaciment sample with t = 1,5, with mean crushing force experimen (Pm exp.) = 54.826 N and mean crushing force analitical (Pm analitic) = 56.312 N



(a) (b)

Figure 4. Load Vs Displacement: a) tube tickness (t=1 mm) , b) tube tickness (t=1,5 mm)

Table 2 Comparison between experimental result and analitical result

No	**Specimen**		**Experiment Result**			**Analitical Result**	**Difference**
	Load (kgf)	**Heigh of drop test (mm)**	**L (mm)**	**Pm (N)**	**Pmax (N)**	**Pm (N)**	**%**
A	**Tube Thickness (t) = 1.0 mm**						
1	81	2000	56.5	21860	32732		
2	81	2000	63.8	26261	43927		
3	81	2000	63.7	25445	43928		
4	81	2000	79.44	26224	28884		
5	107	2000	58.88	22880	38309	22310	6.77
6	107	2200	56.41	22530	36542		
7	107	2400	65.46	22280	36152		
8	107	2600	67.93	23090	42723		
			Average	**23821.25**	**37899.63**		
B	**Tube Thickness (t) = 1.5 mm**						
1	107	2200	71.22	46153	55778		
2	107	2400	54.77	52101	57122	56312	9.38
3	107	2600	52.93	54826	62149		
			Average	**51026.67**	**58349.67**		

The average of mean crashing force (Pm) from experiment as shown in Table 2. Pm for tube tickness (t=1)= 23821.25 N. If compaire with analitical result the Pm =22310 N with diferrence 6.77 %. Pm for tube tickness (t=1.5)= 51026.67 N. If compaire with analitical result the Pm =56312 N with diferrence 9.38 %. That comparation shows that the result of mean crashing force (Pm) from analitical and experiment similar with pracentage eror under 10 %.

5. Conclusion

The new formula of analitical calculations to calculate the combination of expansion tube and axial splitting has proven to implementation in impact energy absorber, with with maximum pracentage eror 10.52 %. The theoretically calculation combined expansion tube-axial splitting divided in four segment based on the process. The calculation of combined expansion tube-axial splitting can be explain as follows.

1. Pre-compacting (stage A-B), at this stage the tube is given a load so that the tube enters the dies and the material is still in the elastic zone.
2. Expansion process (stage B-C), at this stage that a new formula has been found to calculate the mean load. The formula mean load Pm (9) is as follow:

$$Pm = (\pi t)(D_1 + t)(\sigma_o)\frac{-\frac{K}{t} + ln[D_2 - D_1]}{\frac{1}{D_1} + \frac{K}{t}} \qquad (9)$$

$$K = \left(\frac{\mu + \tan\alpha}{2\tan\alpha(1 - \mu\tan\alpha)}\right) \qquad (10)$$

3. Extended expansion process (stage C-D), at this stage, Tube has the same emphasis as the previous process, so that at this stage it has the same formula as the previous stage

4. Axial splitting process (stage D-E), at this stage that a new formula has been found to calculate the prediction of maximum expanded diameter, that tube will be collapse.

$$\frac{LnD_X}{(D_x)} - \frac{K/_t + LnD_1}{D_x} \leq \frac{\varepsilon\pi D_x tE(t+K)}{(\pi t)(D_1+t)(\sigma_o)D_1 t} \quad (11)$$

$$K = \left(\frac{\mu + \tan\alpha}{2\tan\alpha(1-\mu\tan\alpha)}\right) \quad (12)$$

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Keywords: Impact ▪ energy absorber ▪ expansion tube ▪ axial splitting

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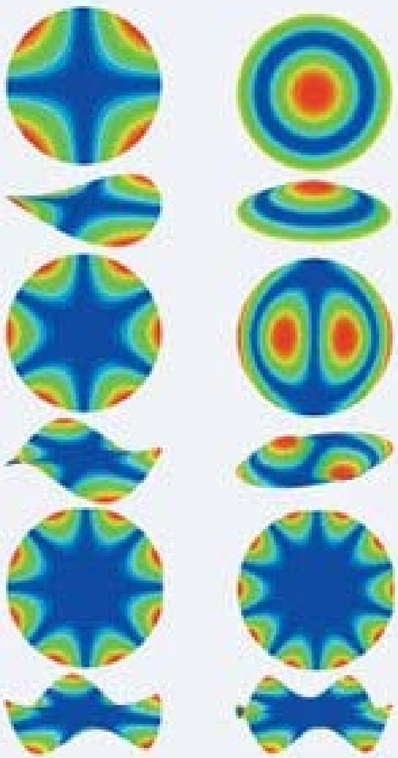

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