Eccentric Crushing Behavior of High Strength Steel Tubes

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***Abstract*— This paper described numerically the crushing responses of empty- and hybrid-tubes subjected to eccentric compressice loading using ANSYS finite element program. From the previous works, tremendous amount of works available in discussing the axial crushing of empty tubes under compression. However, lack of works related to the crashworthiness behaviour of tube under eccentric. Therefore, the eccentric compressive loading on the empty- and hybrid-tubes were focused and emphasized. The steel tube was wraped with glass-fiber reinforced with epoxy resin and their orientations were [+/- 30^0]. It was found that when the tubes were compressed eccentrically, the capability of mechanical energy absorption reduced depending on the contact areas with the tubes.**

I. Introduction

Numerous impact events are needed by many practical engineering systems must absorb various levels of energy have existed [1-9]. Therefore the practical engineering systems for using of energy absorber devices with higher capacity have increased. The crashworthiness builds as energy absorber devices to protect and minimize passenger injury. The crashworthiness becomes the first protecting devices when collisions happen on the subject like a car.

Many previous works have developed various models for analysing the axial crushing behaviour of thin-walled members based on the plastic hinge theory [1-2], experimentation or numerical simulation [10-11]. The most shapes of absorber devices are circular tubes as are energy dissipating devices that absorb the kinetic energy of impact events. Energy resolutions due crushing, friction, shearing and plastic deformation generated was several of energy absorber [12]. The computer program has been created based on the practical engineering system requirement to analyse the crushing and energy absorption behaviours in simulation. Thus, and the most previous investigations of the crushing behaviour of crashworthiness metal tubes were purely experimental.

A large number of experimental and theoretical studies have been conducted in the past examined that used a lot of time and costs. Then numerical simulation was carried out using the explicit non-linear finite element commercial software ANSYS/LS-DYNA as an alternative in the investigation of this paper [13-14]. In the simulation, the property of high strength steel was found to be insensitive to the strain rate, which was consistent with the experimental result [15-16]. One of examined of thick-walled tubes absorber on high-strength steel and mild steel used to analyse the axial compression behaviour and energy absorption under an impact load [14]. The hybrid model developed for to reduce weight and to increase strength with added some composite wrap. Some of past investigation of the axial crush performance of square hybrid-aluminium tube with filament wrap with various angles in the overlap between [+/- 30^0] and [90^o] on the fibre orientation [13]. Mirzaei et al. [10] investigated the behaviour axial crushing of circular aluminium/glass-epoxy hybrid tubes experimentally and analytically.

They used quasi-static axial crushing condition to carry out the effect of different parameters such as metal and composite wall thicknesses based on composite layers [10]. Moreover, most the previous studies investigated the crushing behaviours of the composite components, and some [17-19], also considered other shaped tubes in the vertex angle. The crushing behaviour of circular hybrid tube carried out the energy absorption on this paper examine based on numerical methods in simulation programmer in eccentric loading condition. However, the past works most discussing about axial crushing on an empty tube under axial loading. Thus, lack of work related to the crashworthiness characteristics of energy absorption under eccentric compression loading. Therefore, crashworthiness characteristic under eccentric loading of hybrid tube was identified.

Hence, eccentric compressive loading of the hybrid tube was focused. These works have taken advantage of hybridization of composite material as a new concept in the design of energy absorption devices. In this investigation work a comprehensive finite element simulation was carried out to evaluate the response and analysis energy absorption capacity of circular hybrid tubes under eccentric loading. The principle objective of this investigation was to examine the effects of cylinder steel tubes wall, fibre orientation angle on the eccentric crush performance of hybrid tubes. The crush performance of hybrid tubes was included empty steel tubes comparison. The energy absorption parameters included the maximum force at the initial folding, mean crush force, crush efficiency and energy absorption.

II. Energy Absorptions Characteristics

Crashworthiness characteristic defined as the capability of a vehicle to protect occupants from structure response by dynamic crush load with probability of injury. Therefore, it is an important parameter for vehicle design and it has been a hot topic of engineering study and researches for engineers and scientists over the years. The circular high – strength steel tubes are modelled as an absorber device to absorb several energy absorptions when collapsible impact applied in eccentric loading condition.

The load – carrying capability can be evaluated for the following two force levels [12]. Maximum force which is generally defined as peak force, $P\sigma$. The peak force of a component is the highest load required to cause significant permanent deformation or distortion. The value of peak load was concerned by two factors, it's because of low – speed and low – energy impact. It also peaks load was occurring when the maximum load observed in the useful stroke of the energy absorbing device [13]. Absorbed crush energy which refers to the area under the force – deformation curve.

$$E = \int_{o}^{d\,max} Pd\partial \quad (1)$$

Specific absorbed energy, E_S is defined as the absorbed crush energy per unit of the crushed specimen mass.

$$E_S = \frac{E}{m} \quad (2)$$

Average crushing force, *Pm* obtained by the following equation, when the load and post – crush deformation was defined as δ and Pm respectively.

$$P_m = \frac{1}{\partial}\int_{0}^{\partial} Pd\partial \quad (3)$$

Crush force efficiency, η is the ratio of the average crushing force, P_m to the peak force, P_σ. The information from the force-deformation curve got the average and peak force is important parameters to be determined the deceleration that will be experienced by the crashworthiness impact. It also as the ratio to determine the crush force efficiency and in general their value approaches unity, the better is the performance of the energy absorbing structure.

III. Finite Element Model

In this work, three dimensions, *3D* finite element model are developed. There are three main parts, moving upper plate, steel tube and composite wrap. Where, the composite model is wrapped around the steel tube and as an outer layer. Dimension of steel tubes modelled with 170 mm length *L*, 58 mm outer diameter *D* and 1.0 mm thickness *t*. The composite material thicknesses on a round steel tube with 0.8 mm. The composite material is used three layers for each wrapped around steel tube. The size for moving upper plate is 100 mm length *L*, 100 mm width *w* and 1 mm thickness *t*.

For overall parameters of hybrid tube has been shown in Fig. 1. Hence, moving the upper plate is modelled as a rigid part using the SOLID164 solid element. Then steel tube and composite wrap are modelled using SHELL163 which is a shell element shape. Since all the parts are modelled based on Belytschko-Tsay quadrilateral elements. Belytschko-Tsay fully integrated element formulation was used in order to eliminate the hour glassing problems that are likely to occur when large deformations take place [20].

Belytschko-Tsay quadrilateral shell elements were used to model bold steel and composite wall in hybrid tubes. The finite element model characteristics of the given problem are necessary capabilities of modelling a system in ANSYS/LS-DYNA features [20].

A. Material Modeling and Meshing

The mechanical properties of high strength steel tube and composite wrap are required for use as a material model in ANSYS/LS-DYNA. Hence, the both of mechanical properties are tabulated in Table I and II. Composite material E-glass/epoxy is selected as a wrapper on a round steel tube. In this hybrid tube was wrapped three different orientations in each layer.

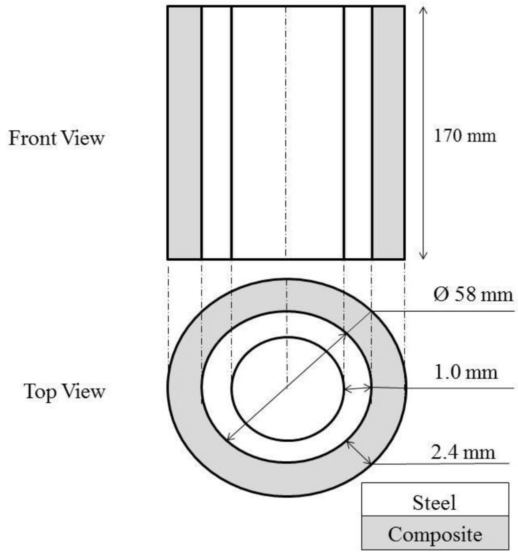

Fig. 1. The model structures of steel-composite hybrid tubes.

TABLE I
MECHANICAL PROPERTIES OF HIGH STRENGTH STEEL AND RIGID MATERIALS

Material properties	High strength steel [2]	Rigid material [5]
Density (kg/m^3)	7850	7600
Young's modulus (Pa)	210e9	195e9
Poisson's ratio	0.3	0.3
Yield strength (Pa)	-	495e6

TABLE II
MECHANICAL PROPERTIES OF UNIDIRECTIONAL E-GLASS/EPOXY

Properties	Description	Value
ρ	Density	1.80 g/cm3
E_a	Longitudinal modulus (fiber direction)	30.9 GPa
E_b	Transverse modulus (perpendicular to fiber)	8.3 GPa
G_{ab}	In-plane shear modulus (ab plane)	2.8 GPa
ν ba	Minor poisson's ratio	0.0866
X_t	Longitudinal tension strength (fiber direction)	798 MPa
X_c	Longitudinal compressive strength (fiber direction)	480 MPa
Y_t	Transverse tension strength (perpendicular to fiber)	40 MPa
Y_c	Transverse compressive strength (perpendicular to fiber)	140 MPa
S_c	In-plane shear strength	70 MPa

The composite wrap layer's orientation of [+/-30^O] is selected. It wraps around a steel tube for three times. Where the thickness of the wrapper is uniformly assumed. The thickness of each layer of wrap is 0.8 mm. The surface area of meshing size in three parts, finite element model is uniformly assumed. The meshed size of rigid part is 50×2 mm. At the time, the meshed size of the steel tube and composite wrap are 2.5×2 mm and 2.8×2 mm respectively.

These elements formed in a lumped mass matrix, as required by the explicit calculation scheme and were suitable for analysing large deformation [2]. The uniform size of each meshed is used in order to avoid hourglass. The hourglass control model was adopted to eliminate the zero-energy modes. Therefore, the meshed shell element is located at the steel and composite mid-plane, which is separated by a small gap that equalled the average thickness of two walls. Also, the different stacking orientation in composite wrapped are defined using integration points which represented one stacking lay-up.

B. Boundary Conditions and Contact Definition in Finite Element Model

The hybrid tube is positioned vertically. Then the moving plate is placed on the top of hybrid tube. The overall configurations of part located shown in Fig. 2. In all compression loading in this work, the bottom end of the hybrid tube was assumed to built-in and constrained in all degrees of freedom in rotations and translation. The moving plate at the upper end was constrained in X and Y direction. While the upper end was free in the Z direction and compressed by a rigid loading plate that moved at a downward initial velocity in quasi-static condition. In order to avoid penetration between upper end plate and composite tube, the interactions contact algorithms were defined. The “AUTOMATIC SURFACE TO SURFACE” algorithms contact was defined between upper end within hybrid tubes. On the one of contact algorithms was a self-contact algorithm to prevent interpenetration during the deformation.

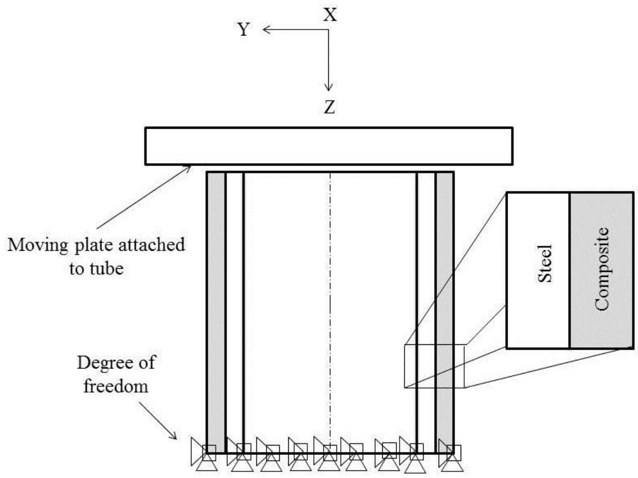

Fig. 2. Configuration of the steel tube and composite wrap in compression loading.

On the deformation have been using the contact “AUTOMATIC SINGLE SURFACE CONTACT” in this simulation. The contact of “ERODING SINGLE SURFACE” used to prevent self-penetration within the inner layer and outer layer. The bonded two tubes where the steel and composite wrap layers are used “TIEBREAK SURFACE TO SURFACE” contact. The action of both normal and shear forces on the interface surface, according to the tiebreak criterion, both forces were assumed 100 N [2]. Their interactions are with static friction coefficient of 0.3 to all of algorithms contact.

C. Eccentric Compression Loading

The explicit non-linear simulation analysis has to define in term of time to work. The array component has been used to make movement of the upper part. The parameters “TIME” and “VELOCITY” by array component are used. The “TIME” of array parameter was used 1x2 arrays for setting the start time to zero and the solution end in one second. For “VELOCITY” array component is setup which the velocity of the moving upper plate was defined. The quasi-static loading worked with constant velocity of 100 mm/s. The movement of the upper plate of the hybrid tube is supposed to move in 100 mm compression displacement with the Z - direction of the tube. The Fig. 3 showed the loading configuration. The percentage of eccentrics is defined using equation (4):

$$\% \text{ of Eccentricity} = \frac{e}{D} \text{x}100 \quad (4)$$

where D is the outer diameter of steel tube and e the distance of the upper end plate was touched the steel tube in crushing process. There are four different percentages of eccentric loading, such as 25, 50, 75 and 100%.

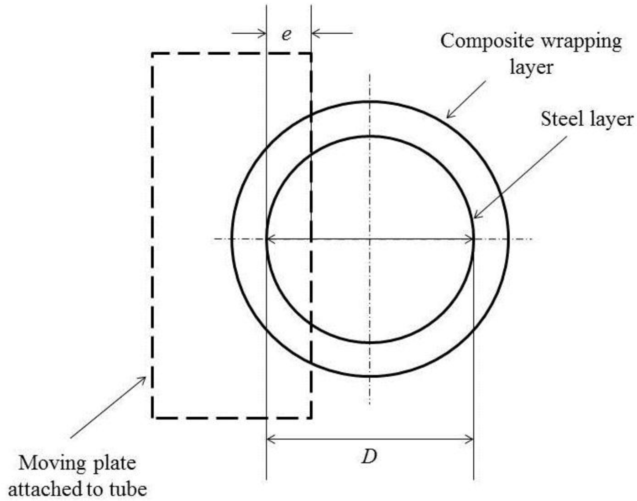

Fig.3. The configuration eccentric compression loading in the top view of hybrid tube.

D. Validation of Finite Element Model

There are two loading conditions are namely axial and eccentric quasi-static compression tests. Since, there are no previous tests on eccentric compression test, and then axial compression test is conducted to validate the present model with the existing model [2].

TABLE III
COMPARISON CURRENT BETWEEN PREVIOUS SIMULATION RESULTS ON HYBRID TUBE.

	Present work (kN)	Previous work (kN) [2]	Percentage of different, (%)
Peak force, P_σ	124.33	133.68	7.52
Average force, P_{mean}	45.30	46.70	3.00

Fig. 4 shows the axial compression loading of this hybrid tube to validate the present result [15]. Fig. 5 shows the comparison between the two results. It is found that the both results are well agreed. On the other hand, Table 4 listed the peak and average force extracted from both results obtained from Fig. 5. Therefore, the percentage of difference between peak and average forces are lower than 10 % and it’s an acceptable range.

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TABLE IV
COLLECTED IMPORTANT DATA FROM SIMULATION

Percentage of eccentric compression (%)	Peak force, P_{σ} (kN)	Average force, P_m (kN)
100	119.75	45.22
75	78.79	38.45
50	62.54	32.52
25	47.16	24.73

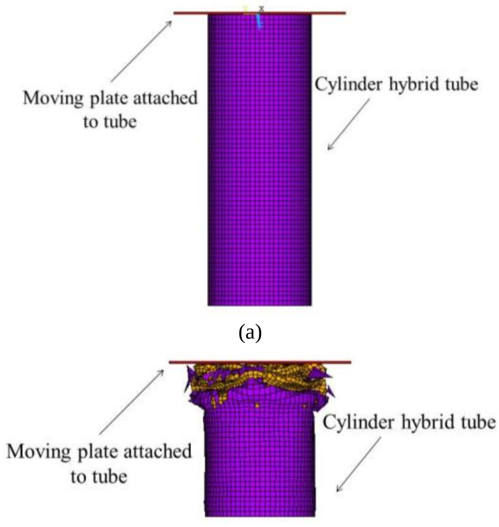


Fig. 4. Finite element models of deformation under quasi-static loading, (a) initial and (b) final conditions.

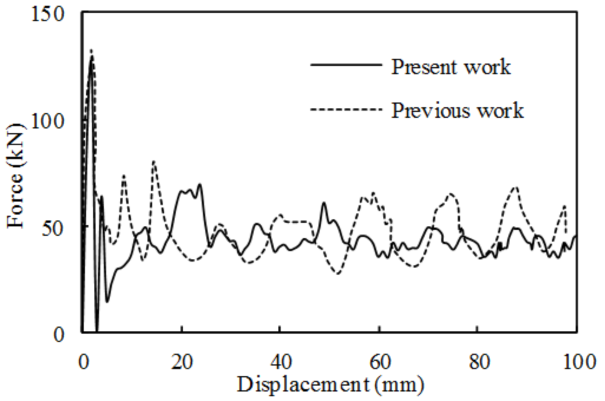


Fig. 5. The force - displacement curve of current research and previous research subjected to hybrid tube.

IV. RESULT AND DISCUSSIONS

A number of indicators of crashworthiness are typically determined for crush component to evaluate their performance and compare with that of other energy absorbing systems [2]. The peak and average crushing force were the primary data selected to evaluate the energy absorption. The parameter was selected to evaluate the energy absorbing capability was specific energy absorption and crush force efficiency. Fig. 6 show the configuration of hybrid tube compression loading with a force - displacement curve. Fig. 7 shows the effect of different percentages of eccentric compression loading with 50 mm compression displacement. The generally their responses of eccentric compression loading are summarized in Table IV.

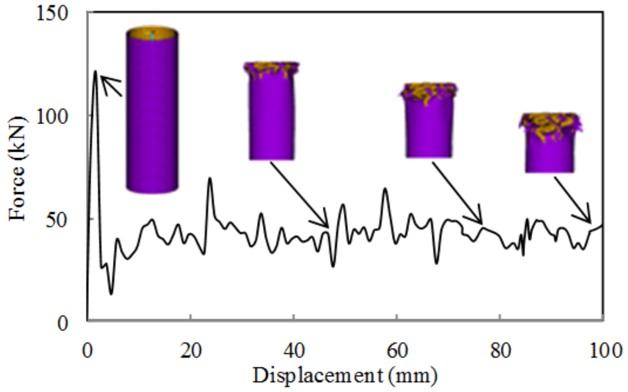


Fig. 6. 100% eccentric compression loading on hybrid tube by force-displacement curve.

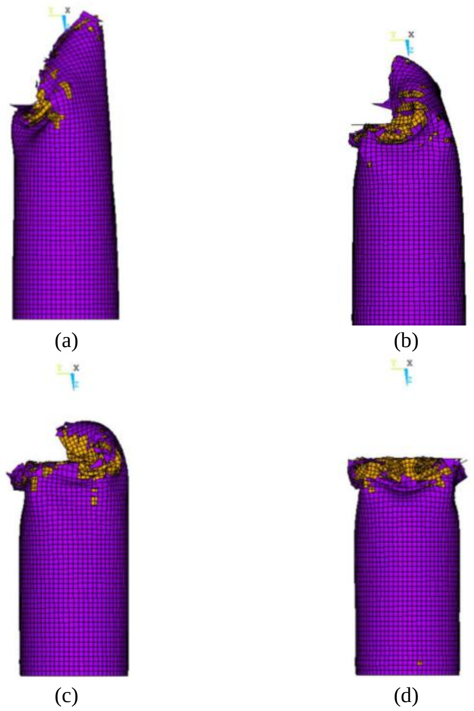
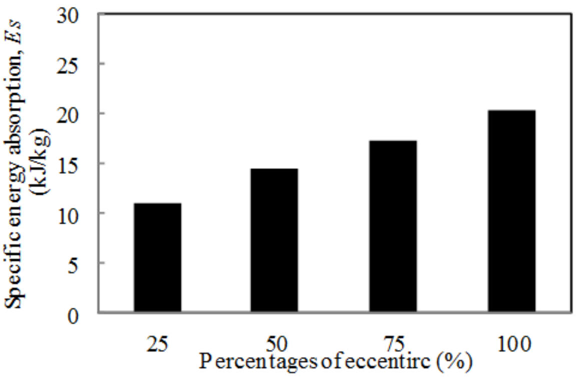


Fig. 7. Eccentric crushing loading condition with 4 divided percentages. (a) 25% eccentric, (b) 50% eccentric, (c) 75% eccentric and (d) 100% eccentric.

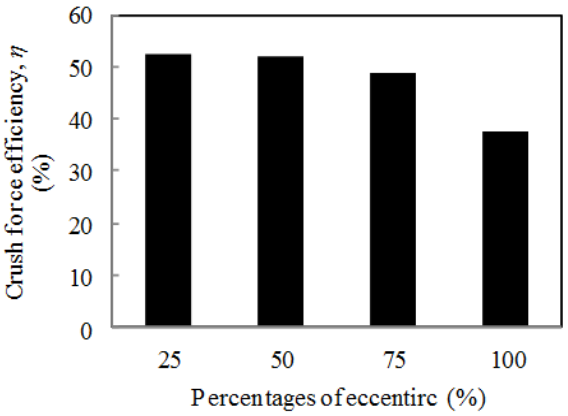
As shown in Table IV, from the highest to the lowest eccentric compression, the peak and average crushing force are reduced. The collected data in Table IV were form force-displacement curve liked in Fig. 6. Different of energy absorption reduced was 45.35% from 100% to 25% of eccentric compression loading. The response by specific energy absorption has been increased when the percentage of eccentric compression loading increased like shown in Fig. 8(a). Specific energy absorption increased effected by the average force increased. In the Fig. 8 (b) shown the crush force efficiency of this hybrid tube was decreased when eccentric compression loading increased. Crush force efficiently affected by the increased the peak force crushing at the increased of eccentric compression loading.

V. CONCLUSION

A nonlinear finite element analysis program with numerical simulations ANSYS/LS-DYNA was adopted to analyse the progressive collapse of high strength steel thin walled cylinder tube with E-glass composite wrapped under eccentric compressive loading. A series of quasi-static crushing test for cylindrical hybrid tube has been modelled and simulated in order to achieve the specified research goals. The numerical simulations are carried out for investigating the energy absorption capability of a variable percentage of eccentric compression loading. The crashworthiness characteristic such as Pσ, Pm, and ES were analysed and discussed. The results shown that the energy absorbed increased and crush force efficiency decreased when the eccentric compression loading increased. This feature is important, since it is provided the role of loading eccentricity on the energy absorption performances.



(a)



(b)

Fig. 8. The capacity of hybrid tubes under various percentages of eccentric area loading: (a) Specific energy absorption, E_s. (b) Crush force efficiency, η.

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