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Analysis of Crashworthiness and Optimization of Bi-Tubular Thin-walled Structures

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Abstract:- This paper presents the performance of crashworthiness on multiple section bi-tubular thin-walled structures. The material of these models was from aluminum alloy 6060 and the structure consists of an outer tube and an inner tube with any one of various shapes such as triangle, square, hexagon, and octagon. The effect of different cross section of tube under dynamic axial impact is studied. As a result, the energy absorption capacity of various inner tubes was compared and it shows that octagonal inner tube has the better performance of crashworthiness than other inner tubes. Therefore, to get the optimal parameters, the Non Surrogate Genetic Algorithm II (NSGA II) focuses on achieving the maximum total energy absorption (TEA) and the minimum peak crushing force (PCF). During the process of multi objective optimization design, it was found to be accurate enough for engineering design of structures with inner tube by octagon.

Keywords:- *Crashworthiness; Double Tube; Dynamic Axial Impact.*

I. INTRODUCTION

Transportation currently becomes one of the most important needs of the society not only on land, sea but also air transportation. Almost everyone in the world uses transportation if they want to travel to other place, even though the distance traveled is relatively close. Nevertheless, in the use of this transportation equipment, we cannot escape the risk of traffic accidents.According to the World Health Organization in a report entitled Global Status Report on Road Safety 2018 that there were around 1.35 million people in the world who died due to accidents during 2018 [1]. It stresses that accident victims are dominated by children and young people in the range of 5 -29 years. In addition, it reports that the main cause (first ranking) of the deaths of children and young people aged 5-29 years is traffic accidents.

In order to reduce the death rate caused by traffic crash, the researchers increasingly develop occupant safety by developing safety box. The function of safety box is to absorb the energy of crash in collision. The analysis of energy absorption characteristic by experimental testing and finite element has been studied by William Altenhof et al [3]. Liuyan Jie investigated the influence of material properties on automobile components to absorb the energy [4]. F. Djamaluddin conducted research about modeling of foam cylindrical double tubes with aluminum components under axial impact [5].

Basicly, the form of crashworthiness structures is circle, but it has been changed rapidly by researchers. R. Velmurugan and R. Muralikannan introduced the different shapes of structures in absorbing energy such as circle and rectangular [6]. Manmohan Dass Goel investigated the differences between single, double and stiffened circular tubes by crashing the structures on finite element analysis [7]. Annisa Jusuf et al developed crashworthiness of multi-cell prismatic structures, as the efficiency of energy-absorbing significantly increased by using internal ribs to the columns walled doubly [8]. S.A. Oshkovr researched about structures of energy-absorbing tubes made by silk/epoxy composite to know the crush force efficiency [9]. I. Vimal Kannan and Rajkumar monitored that multi cell thin walled tubes had influences to absorb the energy [10]. Jie song studied crashworthiness structures having square hole like windows along the surface of the tubes under oblique impact loading [11]. Some researchers also observed crashworthiness structures inspired by honeycomb material to get the values of the optimal energy absorption [12], [13].

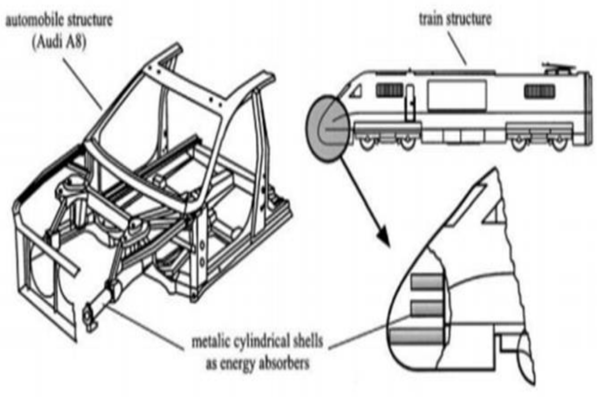

Fig 1:- Ilustration of transportation using energy absorber [2]

For the crushing behaviors, Xiong Zhang and Hui Zhang analyzed structures of circular multi-cell columns under axial crushing [14]. Xiong Zhang et al compared static and dynamic axial crushing of self-locking multi-cell structures on crashworthiness [15]. Fauzan Djamaluddin et al analyzed crashworthiness behavior of double tubes filled with foam under oblique crush [16] compared to axial impact loading [17]. Chang Qi also studied crashworthiness and lightweight optimization under oblique impact using thin-walled conical tubes [18]. Zhibin Li et al used the application of dynamic bending to analyze foam-filled thin-walled structures shaped circular compared to empty hollow circular tube [19].

Although many scientists have conducted a series of researches about bi-tubular energy absorber, the primary focus was only the numerical simulation research. Only several researches have been performed on the optimization of the energy absorption on the structures for every shape. Therefore, the energy absorption capacity of thin-walled double structures is numerically studied and the tubes are optimized.

II. DEFINITION OF CRASHWORTHINESS

To get better comprehension of the crashworthiness of thin-walled structures, some parameters such as Total Energy Absorption (TEA), Specific Energy Absorption (SEA), Mean Crush Force (Fmean), Peak Crushing Force (Fpeak), Energy Absorption Efficiency (EAE), Crush Force Efficiency (CFE) and Energy Absorbing Effectiveness Factor (EAEF) are described with brief explanation

A. Total energy absorption (TEA)

$$TEA = \int_0^{\delta} F\, d\delta \qquad (1)$$

Where, F is the force crushing instantaneously and δ is the distance of crushing.

B. Specific energy absorption (SEA)

$$SEA = \frac{TEA}{m} \qquad (2)$$

Where, m is the mass of crash boxes.

C. Mean crushing force (F_{mean})

$$F_{mean} = \frac{TEA}{\delta} \qquad (3)$$

Mean force is the average of load during crush.

D. Peak crushing force(F_{peak})

This analysis presents the value of first force when the tubes are crushed.

E. Energy absorption efficiency (EAE)

EAE is characterised by the proportion of mean crush force of the multi-cell tube and single cell tube. EAE proposes the advancement of the normal crush force of the multi-cell tubes.

$$EAE = \frac{F_{mean\ multi\ cell\ tube}}{F_{mean\ single\ cell\ tube}} \qquad (4)$$

F. Crush force efficiency (CFE)

CFE is characterised as the portion between mean crush force an the peak crush force. The consistency of load-displacement curve is demonstrate by CFE.

$$CFE = \frac{F_{mean}}{F_{peak}} \times 100 \qquad (5)$$

III. FINITE ELEMENT MODELLING

The procedures are brief but sufficiently complete to permit a qualified reader to repeat the experiments and the methods. Only truly new procedures should be described in detail. Previously published procedures should be referenced. Modifications of previously published procedures should not be given in detail except where necessary to repeat the work. If the study characterizes the activity of new compounds, compound structures must be provided.

Dynamic axial crushing of the proposed configurations is carried out in ABAQUS explicit dynamics, a commercial FE package. FE's structural setups consist of two rigid plates and tubes sandwiched between the two plates. The top rigid plate can move in the axial path, while the opposite plate is restrained in all degrees of movement.

The S4R shell component, a 4-node doubly contoured dense or thin shell element, is used for meshing the tube setup while meshing the rigid plates using a separate rigid component. Following a series of convergence research, feasible mesh size of 2 mm is discovered to be ideal. For the interaction, a particular explicit interaction with frictional tangential behavior is described using a 0.2 frictional coefficient and hard contact. Tube and lower plates are connected together and a self-contact is also defined for all components of the configuration in order to avoid inter-penetration.

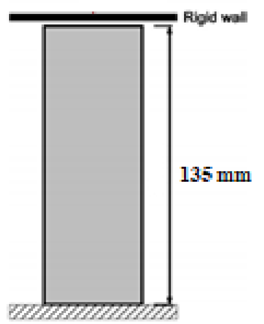

Fig 2: Schematic of the computational model

The tubes contain on an outer tube and an inner tube. The outer tube has circle form, while the inner tube has various shapes (triangle, square, hexagon, and octagon). This analyzing setup for assembly is shown in Figure 3.

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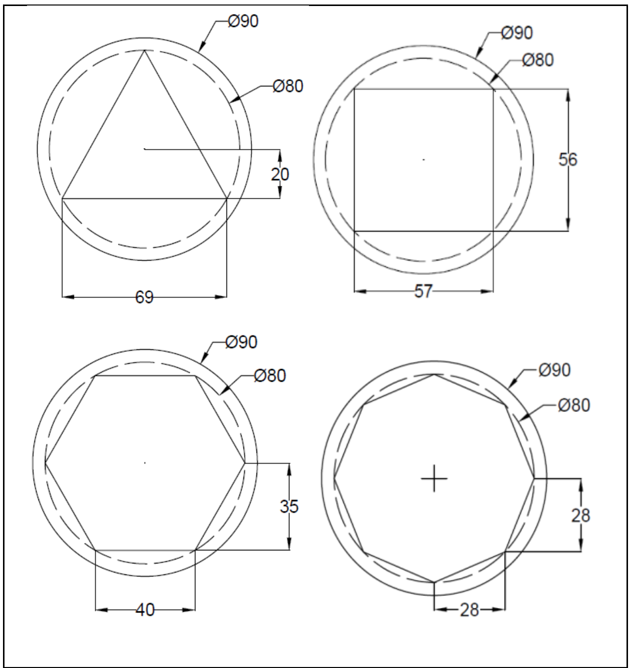


Fig 3: Section geometry and dimension of specimens

Representative geometry drawings of crash boxes that are used in this research are given in Fig 3. The crash boxes were selected with circular section as Ø90 mm an the height as 135 mm. In this study, it can be seen that there were 4 different shapes for inner tube which were analyzed, they were triangle (TR), square (SQ), hexagonal (HE), and octogonal (OC). Each inner tube had same circular sizes of Ø80 mm. every tube has different lenght of inner tube that is shown in Table 1.

Code	Inner Tube	Lenght of Side (mm)
TR	Triangle	69
SQ	Square	57
HE	Hexagon	40
OC	Octagon	31

Table 1: Code and specifications of bi-tubes

Table 2 shows mechanical properties of Aluminium Alloy 6060 T4 which is used in this study. The thicknees of material used is 4 mm for both outer tube and inner tube.

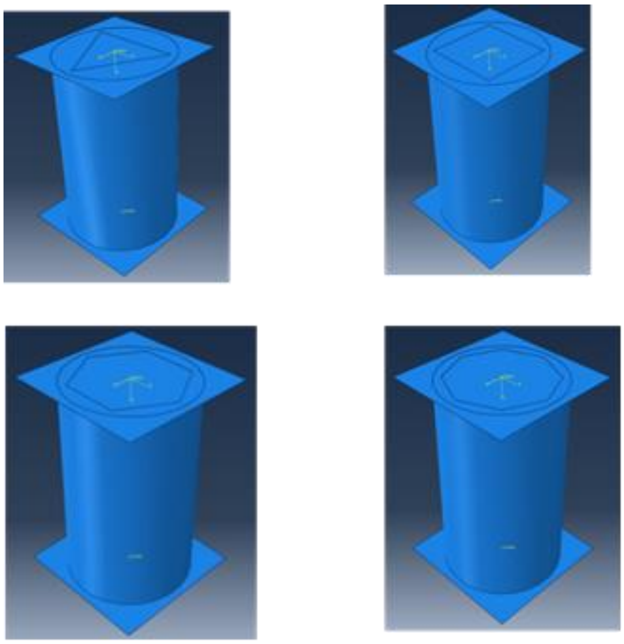


Fig:- 4 Assemblied specimens

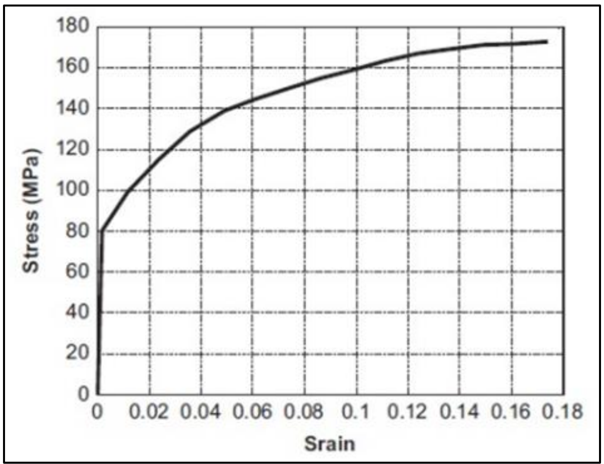


Fig 5:- Stress-strain curve for AA 6060 T4 [20]

Property	Value
Density	2700 kg/m³
Modulus Young	68900 MPa
Poisons Ratio	0.33
Yield Stress	83 MPa

Table 2: Mechanical properties of Aluminium Alloy 6060 T4 [20]

IV. OPTIMIZATION METHOD

Radial Base Functions (RBF) are a surrogate-based model that represents the relation between the individual objective functions and the vector of design variable. The technique for multi-objective optimization was created using NSGA II and Pareto front (Figure 6). The outcome of optimization is meant to define the connection between the parameters of crashworthiness; SEA and PCF.

V. RESULT AND DISCUSSION

A. Validation of FEA Model

Finite element models were distinguished with the work-based experimental data to guarantee that they were accurate enough to optimize design. Thin-walled tube was just a circular tube under dynamic impact loading. Table 3 shows the absorption of energy and the mean crushing force of the empty circular tubes that compare the outcome of the FE with the outcome of the experiment [5]. A great agreement is reached and the FE model has the potential to simulate each tube's numerical response under dynamic oblique impact.

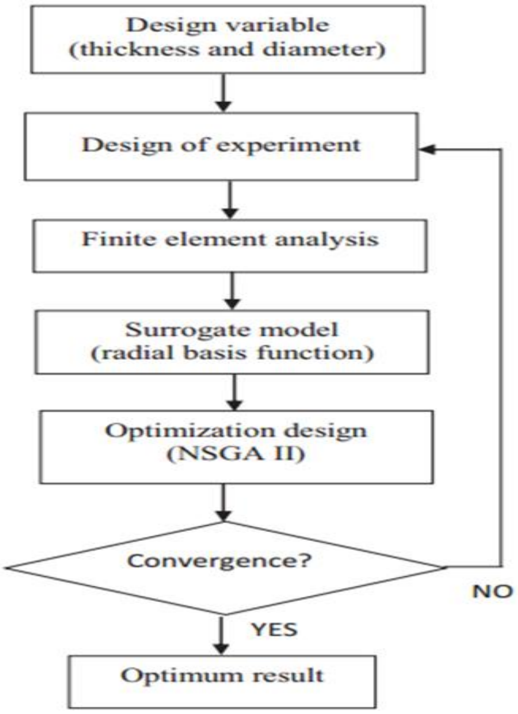


Fig 6: Methodologhy of optimization

B. Deformation Mode

Significant parameters of crashworthiness such as Peak Crushing Force (F_{peak}), Mean Crushing Force (F_{mean}), Specific Energy Absorption (SEA), Energy Absorption Efficiency (EAE), Crush Force Efficiency (CFE), and Total Energy Absorption (TEA) factor are calculated from the load–displacement curves of the specimens for each tube. The Figure 7 shows that the crushed specimens after loading. Diamond mode is observed in all specimens.

Impactor			Geometry Parameters				Experiment			FE			Error	
velocity	mass		length	diameter	thickness		*EA*	F^{d}_{avg}		*EA*	F^{d}_{avg}		*EA*	F^{d}_{avg}
v (m/s)	M (kg)		*L* (mm)	*d* (mm)	*t* (mm)		(J)	(kN)		(J)	(kN)		(l%l)	(l%l)
6.6	104.5		180	40	2		2326	45.6		2278	43.76		2.107	4.2
6.6	104.5		180	40	2.5		2260	42.3		2176	41.68		3.86	1.49
10.7	91		180	50	3		5081	86		4947	83.45		2.709	3.06

Table 3: Finite Element simulation and experimental solution of empty circular tubes [5]

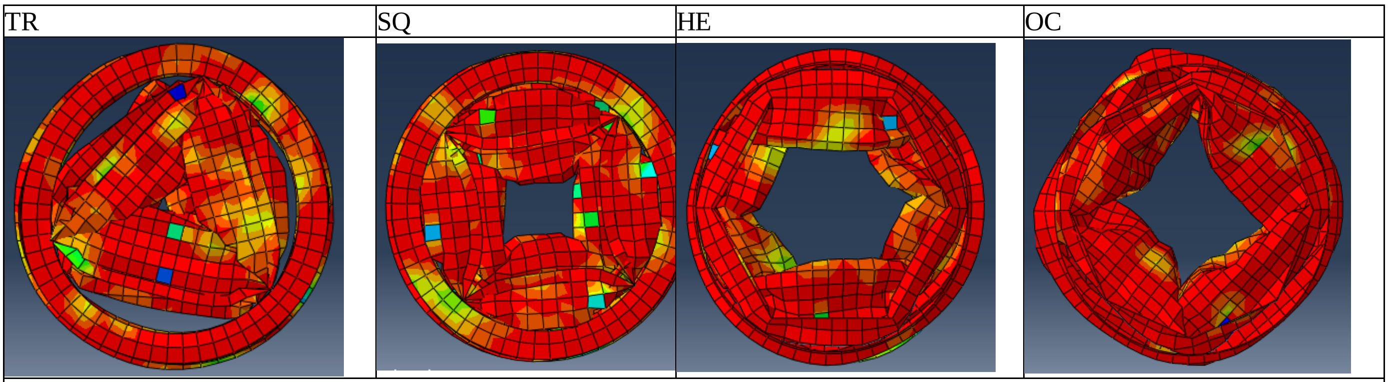


Fig 7 Deformation mode of models

Table 4: Crashworthiness indicator of double tube

Tubes	Parameter				
	Weight (kg)	**Crush Distance (mm)**	**TEA (J)**	**SEA (kJ/kg)**	**Fmean (kN)**
TR	0.255	134.57	2104.225	8.27	15.64
SQ	0.266	133.261	2458.894	9.25	18.45
HE	0.274	134.821	3010.848	10.97	22.33
OC	0.268	133.885	3481.032	12.97	26.00

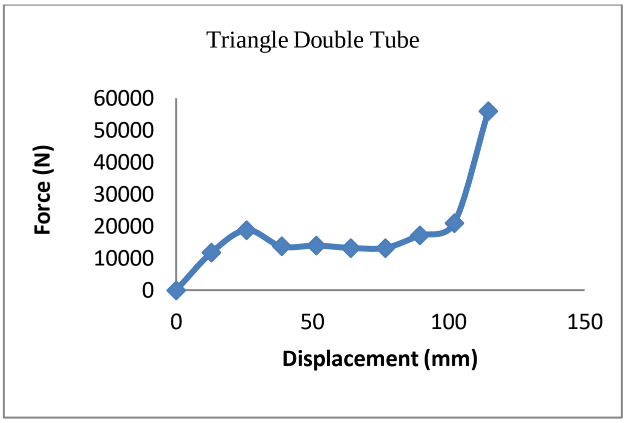
C. Comparison of Energy Absorption

The crashworthiness performance of the bi-tubes was compared on the basis of numerical results and the load-displacement curves of the bi-tubal tubes model obtained from simulation are shown in Figure 8.

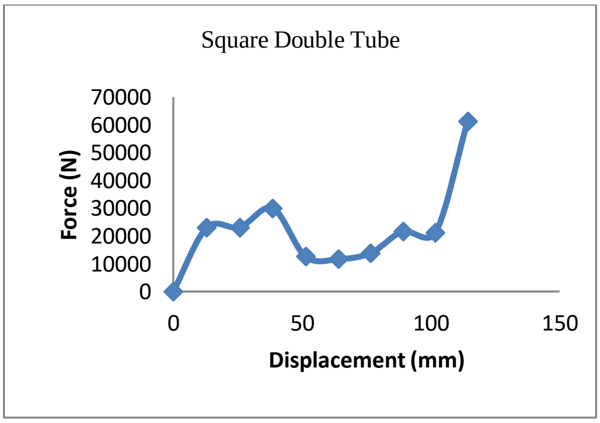
The total absorbed energy (TEA) of the bi-tube with an octagonal shape of the inner tube was higher than that of the hexagon and the hexagonal inner tube was better than the square followed by the triangle. For the same inscribed polygonal diameter, the more the number of sides, the higher the energy absorbed. The two-tubular designs with an octagonal arrangement of the inner tube have more eak crush force (PCF) than the other segments as shown in Figure 9. Also Figure 10 presents the comparison among double tubes for indicator of total energy absorption in percentage. It has been clearly shown that octagonal inner double tube is higher than other structures about 32%.

D. Optimization Result

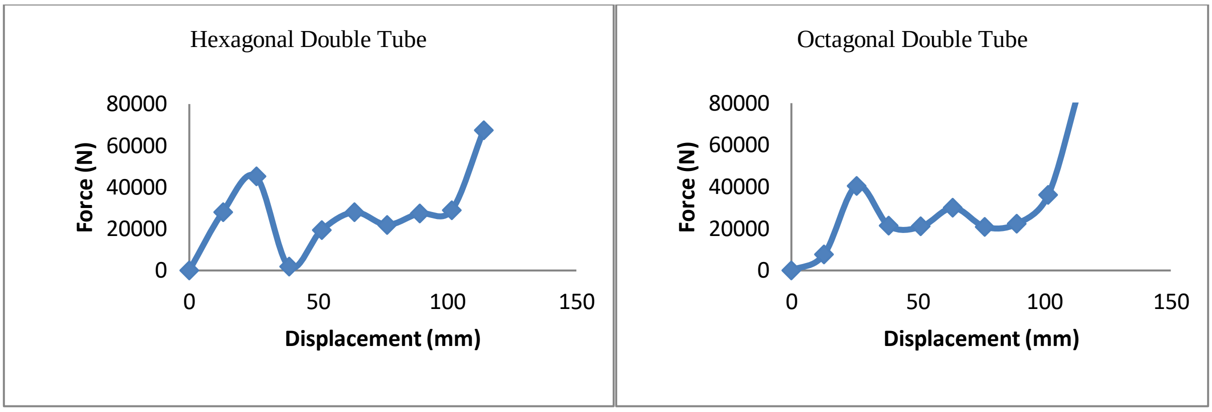
Figure 11 shows the result of this optimization. The Pareto optimum solutions represent 42 circular points, explaining the trade-off between the energy absorbed and the force peak. The two crashworthiness criteria are shown to compete heavily with each other: hugely absorbed energy values go hand in hand with tiny TEA values. Therefore, as long as the decision-maker wants to highlight more on the TEA or energy absorber weight, the energy absorption must be compromised and lowered, and vice versa. Keep in mind that the Pareto front spreads across a broad range and with a distinctive set of design parameters every point provides a feasible ideal solution. The points with lower TEA values favor the increased PCF target and the points with lower energy absorption values favor weight minimization, while the midpoints tend to favor the PCF to TEA proportion.



(a) TR



(b) SQ



(c) HE (d) OC

Fig 8: Curves of force-displacement for all samples

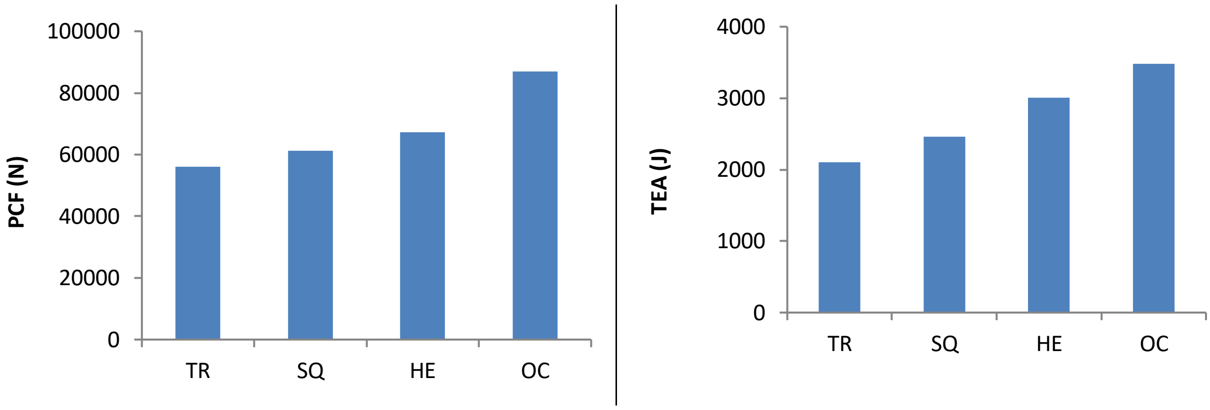


Fig 9: PCF and TEA for all samples

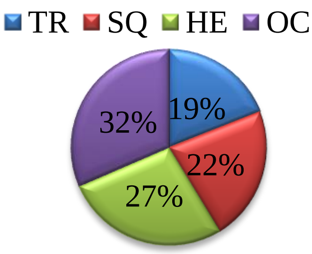


Fig 10 Curve the comparison of inner double tubes in TEA

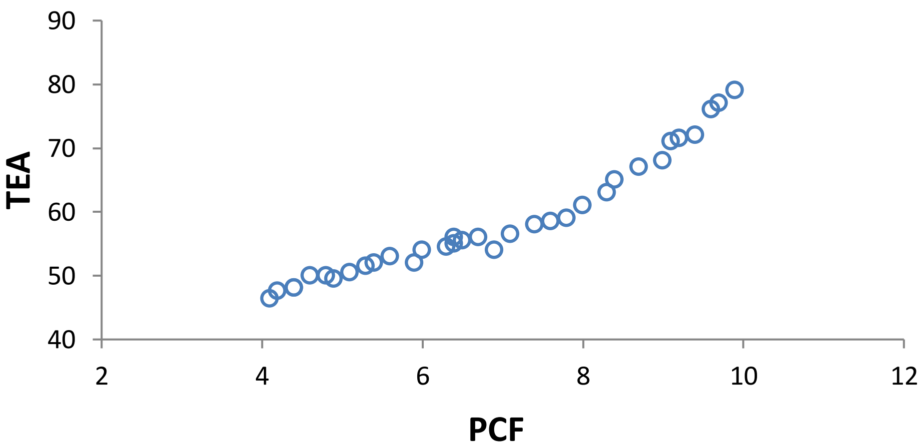


Fig 11:- Curves of force-displacement for octagonal

VI. CONCLUSION

To sum up, the behaviour of crashworthiness of double bi-tubular thin walled structures with different shapes of inner tubes was studied under dynamic axial impact. Based on the simulation of finite element, among four speciments analyzed double tube with octagonal inner tube had better TEA than other combination with 32% compared to all three tubes of triangle, square, and hexagonal section. To demonstrate the minimum PCF and maximum TEA for each model, the optimization equation was developed. Based on the study, the optimum findings showed that double bi-tubular octagonal internal tube's crashworthiness capacity was higher than other bi-tubular internal tubes.

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