

Development of Impact Characteristics Response Model for Combined Tube Expansion Axial Splitting Module

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Abstract. Combined tube-expansion and axial splitting mechanism yields excellent force-displacement characteristic and high stroke efficiency. In this paper, a mathematical model to estimate and optimize impact response of such mechanism was developed, to correlate the impact response to the module dimensional parameters, i.e., diameter-to-thickness ratio, D_1/t and expansion ratio, D_2/D_1 and other design parameters such as material strength, expansion angle, and friction coefficient. Accurate finite element (FE) analysis, validated with experimental results were performed to generate results sufficient to form a response surface model (RSM). The current mathematical model successfully captured the effect of expansion ratio, thickness ratio, and initial diameter of the tube, with R^2 of 0.99 for specific energy absorbed and 0.81 for mean crushing force throughout 80 data points. A case study was also presented which shows the result comparison between numerical and the proposed model, yielding error below 1% difference for mean and peak crushing force, total energy absorbed, specific energy absorbed (SEA), stroke and crushing force efficiencies. The model has also been implemented in an optimization for railway vehicle case study using the proposed mathematical model. The current research found that the combined module could reach SEA and stroke efficiency values of 29.74 kJ/kg and 0.99 respectively, significantly better than most of the metallic-based impact energy absorbing mechanisms.

Keywords: *Crashworthiness, impact absorbers, tube expansion, axial splitting.*

1 Introduction

Since a group of early work by investigators to date, the search for effective and efficient impact energy absorber continues. Impact absorbers are used in many applications of vehicle crashworthiness to absorb as much kinetic energy as possible involved during collision so that minimizing the effect of collision to passengers or cargo. The performance of an impact absorption module can be observed from its force-displacement response under quasi-static as well as dynamic loading. This generates various impact characteristics, such as energy absorbed (EA), stroke efficiency, specific energy absorbed (SEA), mean crushing force (P_m), and crushing force efficiency (CFE) [1,2]. An ideal impact absorbing mechanism should have a constant force with the steady-state force reached instantaneously,

resembling rectangular shape in the force-displacement response, hence producing the maximum absorbed energy possible. This behaviour is important since the support structure will always have a maximum allowable crushing force value to limit the impact force received by the main structure, as well as limited space of the impact energy absorption module. To name a view, inversion mechanism [3], has a characteristic of relatively flat force vs displacement, however after the first phase of increasing and significant fluctuating force. Similar characteristic is also shown in the multiple splitting mechanism [4]. On the other hand, progressive buckling, multi-layer folded structure, and composite based modules have a more fluctuating force response [1,5–7]. Gel and fluid filled modules have a constantly increasing but with unfluctuating force characteristics [8].

Many geometries, materials, mechanisms have been proposed and exercised. The geometry may be categorized as drums, circular tubes, tubular rings, square tubes, corrugated tubes, multi-corner columns, frusta [9], struts, honeycomb cells, sandwich plates, circular thin-walled tubes, and top-hat thin-walled sections [10]. In more recent reports, light-weight material such as lattices [11], CFRP [6,12] and GFRP [13,14] composites, foams [5,7], fluids [8], or combinations of the mentioned [15,16] were investigated to attain impact absorption modules with high energy to weight ratio (SEA). For high-capacity loadings, however, metallic based materials are still preferred due to their superior energy absorption (EA) capabilities. Carbon steel and aluminium alloy tubes with various combination of mechanisms and improvements are amongst the most popular, notably in form of progressive buckling with multi-layered tubes [17,18] and various triggers [16,19], axial collapse with spherical and conch-shaped triggers [20], tube inversion [3], tube expansion [21], lateral buckling [22], axial splitting [4,23], perforated tubes buckling [24], adhesively bonded hat-shaped [25], and reinforced aluminium honeycombs [26,27].

The challenge of designing metal-based impact absorption module is to balance SEA and stroke efficiency. Some modules have excellent SEA with poor stroke efficiency [9,10,18,20,21], while the rest attain better stroke efficiency but with lower SEA [4,8,11,23]. Among various metal-based mechanisms, conch-triggered axial collapse [20] potentially gives the highest specific energy absorption (51.8 kJ/kg) followed by tube expansion [21] with 28.8 kJ/kg, whilst axial splitting (with either metallic or composite materials) gives the highest stroke efficiency of higher than 80% [4,13,23]. In order to answer this problem, attempts have been made to combine tube expansion and axial splitting [28–31]. Their advantages and disadvantages seem to complement each other: the expansion mechanism has high SEA but requires a long expander dies that is approximately as long as

the tube, hence requires larger space and poor stroke efficiency. On the other hand, axial splitting mechanism has an excellent stroke efficiency but lacks overall plastic deformation resulting in relatively lower crushing force response. In general, the combined mechanism is expected to have a force-displacement response as shown in Figure 1. The behaviour of the module can be predicted by looking at the curve. Directly after impact, the module will exert force as the result of expansion process. As the tube reaches the splitter die, the tube will split thus adding more force in the process.

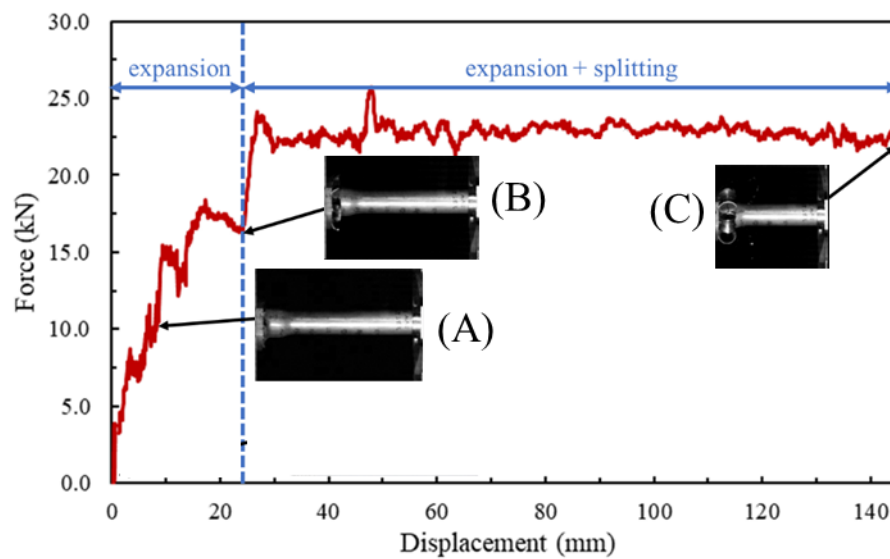


Figure 1 Force-displacement response of the combined module: (A) expansion process, (B) initiation of splitting, (C) curled final structure. Experimental pictures taken from [32].

Other groups of researchers [32–34] are also in agreement that the combined module provides good SEA and stroke efficiency. Li *et al.* [33] have conducted experimental and numerical studies to describe impact behaviour in terms of energy dissipation contribution of the combined module but has yet to propose discrete relations between dimensional parameters and its impact response. Moreno *et al.* [32,34] has also compared the mechanism with conventional axial splitting and tube expansion modules with variations in expansion ratio and load obliquity but just with a single tube diameter and thickness. However, its optimised performance has not been explored due to the absence of comprehensive study of the design parameters. In this study, the aim is to complete the understanding of such combined module by reviewing the design boundaries, how various design parameters affect the impact response, and finally establishing a discrete mathematical model which correlate between design parameters and impact response of the combined module. This research was conducted with finite element analysis, validated with experiments. The generated data were then processed with

response surface modelling (RSM) to extract correlation between parameters before finally, physical meanings of the mathematical model were interpreted.

2 Material and Design

The Tube Expansion-Axial Splitting mechanism consists of mainly three main components: a circular tube acting as the energy absorber, an expansion die, and a splitter die. For this study, tube is machined from standard API-5L Gr. B pipe for high manufacturability. The expansion die is a circular, machined component with a slope of α degree to ensure smooth tube expansion, whilst the splitter is conical in shape with a polygon cross-section to provide initial splitting to the tube into eight sections during the impact process. This polygon cone design with sharp edges removes the needs for initial cut, as used by the previous investigators, such as Huang *et al.* [23], Moreno *et al.* [32,34], and Li *et al.* [33]. Such a design increases the steady state force on the splitting mechanism compared to the above-mentioned pre-cutting design without sacrificing its repeatability. Figure 2 shows the configuration of tube (1) and dies (2) in the tube expansion-axial splitting mechanism. Point A is the initial point, B is the initiation of expansion, C is the start of fully expanded region, and D is the initiation of tube splitting.

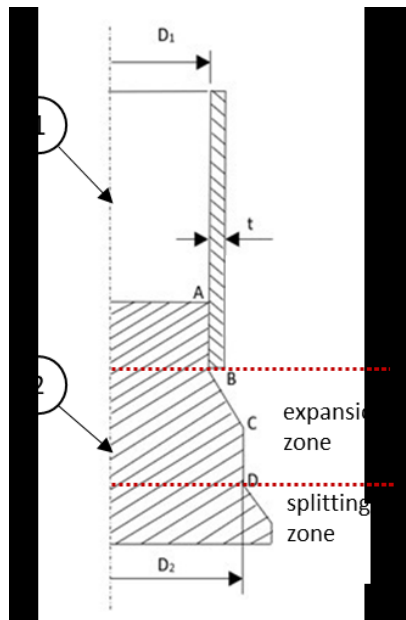


Figure 2 Schematic of the combined module.

The dimensional parameters to be varied in this research are expansion ratio and thickness ratio. The expansion ratio, D_2/D_1 , is described as the comparison of maximum tube expansion diameter to the

initial diameter. The thickness ratio, D_1/t , is the comparison of the tube initial diameter to its initial thickness. Other parameters such as splitting dies angle, friction coefficient, and strength of material are also of interest. Whilst theoretically higher D_2/D_1 and lower D_1/t will result in higher energy absorption, design boundaries must be established to prevent failure of the module which are premature splitting and progressive buckling [31,33].

3 Finite Element Simulation

Finite element analysis was performed with Abaqus/CAE dynamic with explicit mode. This method was chosen over experimental study to produce a lot of data points with low uncertainties required to establish a valid parametric study. The model was validated with lab-scale drop test experiments before the full numerical run was done.

3.1 Modelling Strategy

Geometry modelling was done in Solidworks for all components. The components are the tube, expansion die, splitter die, and impactor as shown in Figure 3. Later, only the tube and expansion die were modified for analysis purposes. Important geometry parameters, symbols, and values are explained in Table 1.

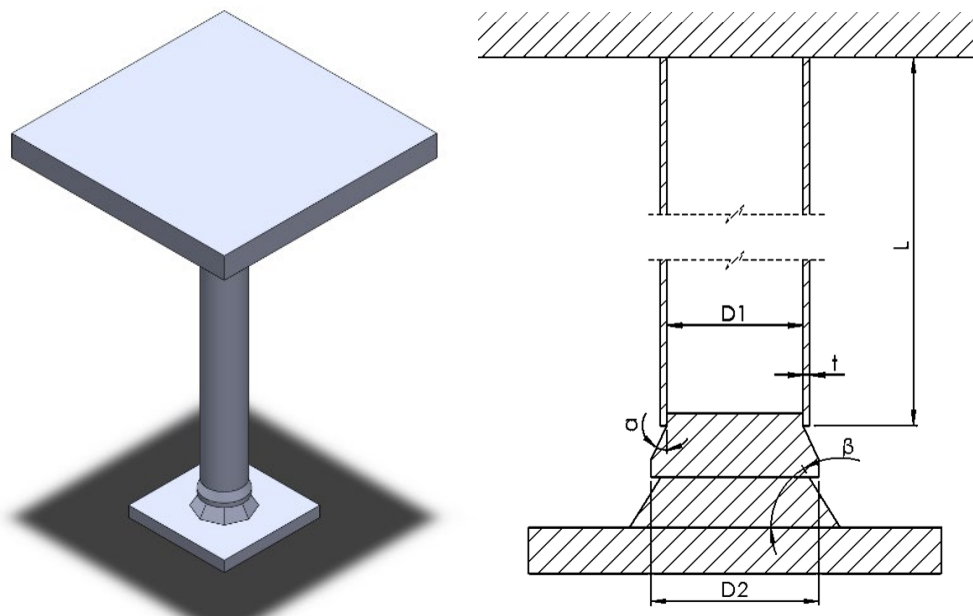


Figure 3 Generic CAD model of the present module.

Table 1 Geometric parameters of the present module.

Parameter	Symbol	Value	Unit
Initial Diameter	D_1	53	mm
Expanded Diameter	D_2	Varied	mm
Wall Thickness	t	Varied	mm
Tube Length / Stroke	L	150	mm
Expansion Angle	α	25	deg
Splitting Angle	β	60	deg

Johnson-Cook (J-C) material model [35] is used for the tube in this research to simulate plastic response in high strain rate application. Previous study also shows that it could adequately simulate steel tube with the combined mechanism [33]. The J-C material model could be expressed as:

$$\sigma = [A + B\varepsilon_p^n][1 + C \ln \dot{\varepsilon}^*][1 - T^{*m}] \quad (1)$$

In which σ is stress, ε_p is plastic strain, $\dot{\varepsilon}^*$ is strain rate, and T^* is normalized temperature.

J-C parameters for API-5L Grade B is taken from [36] and is shown in Table 2. Since stress triaxiality and influence of temperature are not of interest in this study, it is assumed the J-C thermal softening exponent, m , to be 1. The other components (impactor and dies) will be modelled as rigid bodies for computational efficiency. The tube is modelled using C3D8R element type, i.e. an 8-node linear hexagonal brick, with reduced integration to increase the efficiency of simulation.

Table 2 Johnson-Cook parameters of API-5L Grade B.

Parameter	Symbol	Value	Unit
True Yield Strength	A	387.9	MPa
Strain Hardening Constant	B	336	MPa
Strain Hardening Exponent	n	0.3327	-
Strain Rate Coefficient	C	0.03	s ⁻¹
Thermal Softening Exponent	m	1	-

Loading, supports, and other boundaries was modelled as close as possible to actual application. However, some assumptions were taken such as rigid bodies and constant friction coefficient for grease lubricated steel-to-steel contact ($\mu=0.16$) [37–39]. The load was modelled as initial velocity and mass of the impactor. The velocity normally is set to be 10 m/s but was varied along with its mass for validation purposes. Finally, a fixed support was assigned to the bottom surface of the dies. Force-displacement response would be generated with the axial reaction force of the support and the

displacement of the impactor. Other boundaries were also employed in the simulation to ensure the load obliquity of the analysis: lateral displacement and rotational restraints on the impactor.

3.2 Mesh Sizing

Convergence test was done to determine the optimum mesh size for the tube with energy absorbed (EA) and average force (P_m) as the parameters of interest. The output of the test in the form of force-displacement response is shown in Figure 4. The figure, especially for the larger element size, was post-processed with moving average method as a mean to reduce numerical fluctuations. As observed, the said fluctuation also decreases as force converges.

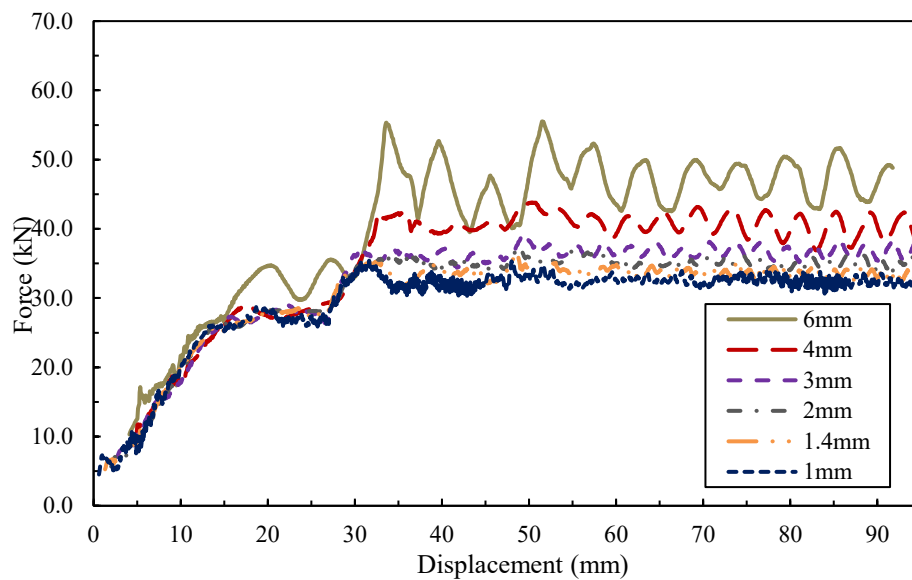


Figure 4 Force-displacement response for tube with various element size.

As demonstrated in Figure 5, both EA and P_m started to converge from element size of 2 mm onwards and reaching error of less than 5% with the element size of 1.4 mm, which is considered sufficient. Further validation was carried out by comparing the finite element simulation results with laboratorial experiments discussed in the subsequent section.

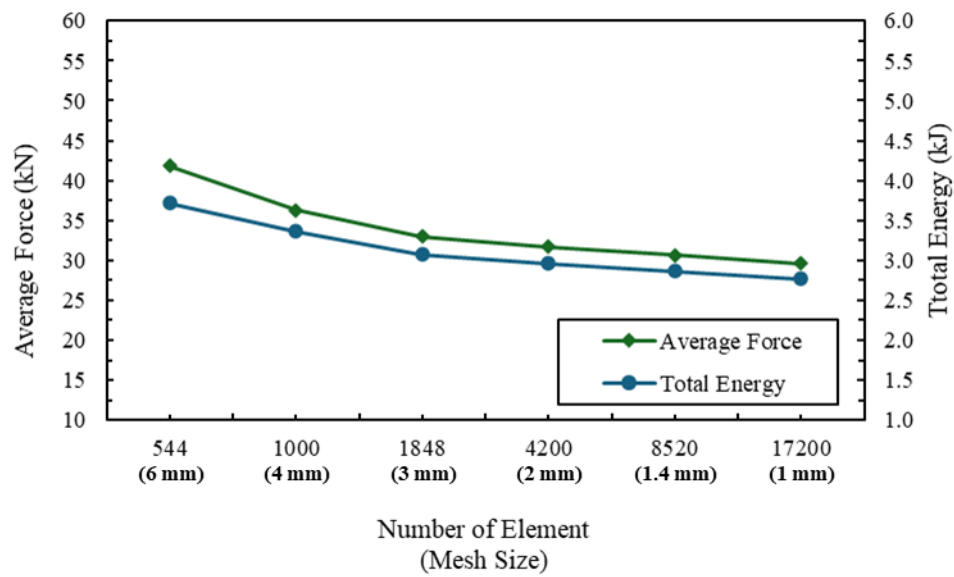


Figure 5 Convergence curve of the tube model.

3.3 Experimental Validation

Drop test loading conditions were selected to validate the finite element model. The components used in this experiment are impactor, the specimen, expansion and splitter dies manufactured from DIN 1623-2 Grade St 60-2G without heat treatment, TML load cell, and Keyence IL-600 digital laser proximity sensor. The impactor was dropped from the desired height, thus having potential energy. After impact, the load cell measured the reaction force of the module while the proximity sensor read the displacement. NI9237 with frequency of 450 kHz was also used as the data acquisition module. The drop test apparatus which was used is shown in Figure 6.

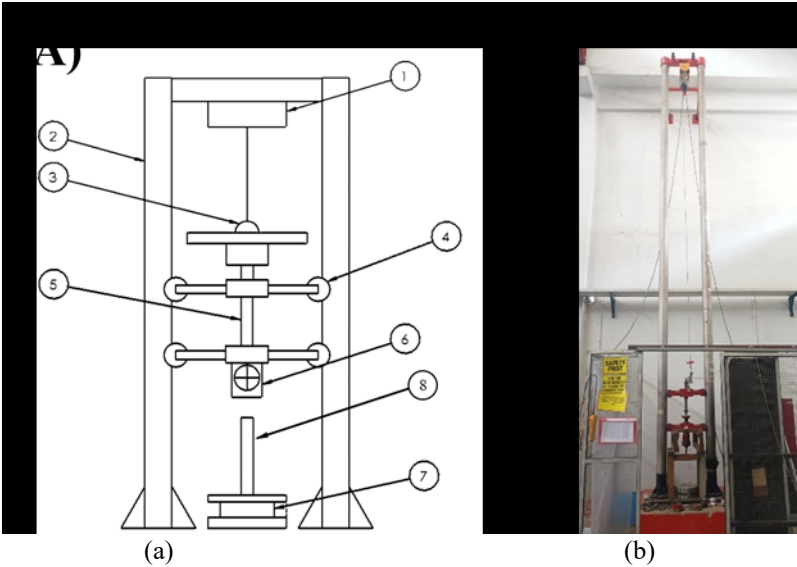


Figure 6 Drop test apparatus a) schematic diagram: (1) electric winch, (2) guide rail, (3) release pin, (4) guide wheel, (5) load plate mounting, (6) impactor head, (7) load cell & proximity sensor, and (8) specimen, and b) photo of the actual equipment.

Four tube specimens with two different thickness ratios were manufactured. Each pair of the tube was mounted to each die with two different expansion ratios, resulting in four impact absorption modules with different expansion ratio and thickness ratio combinations. The design parameters of the modules are shown in Table 3.

Table 3 Geometric parameters of the test specimens.

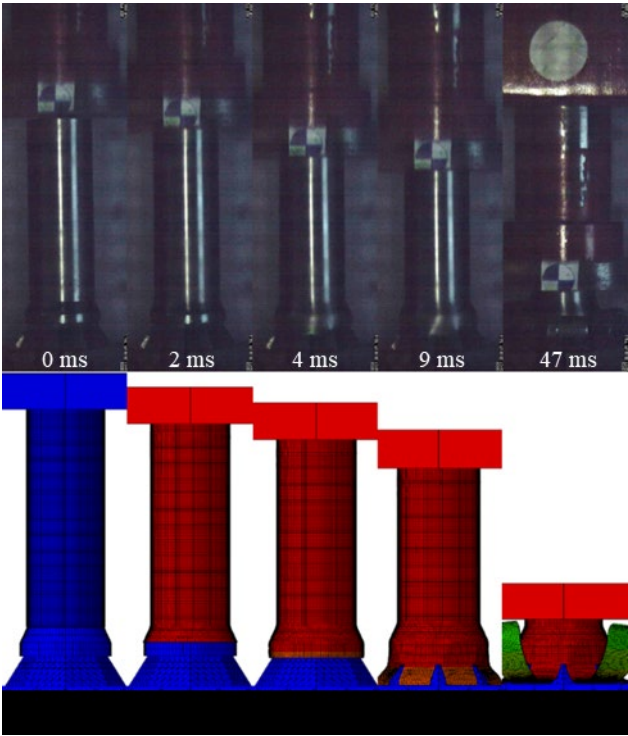
Module	D_1 (mm)	D_2 (mm)	t (mm)	L (mm)	D_1/t	D_2/D_1
1	53	60.95	1.4	150	37.86	1.15
2	53	60.95	0.7	150	75.71	1.15
3	53	63.07	1.4	150	37.86	1.19
4	53	63.07	0.7	150	75.71	1.19

The specimens are loaded until completely deformed or the drop test machine maximum potential energy is reached (4.3 kJ, dropped from 3 m above specimen). Table 4 shows the loading conditions for each specimen. For specimen 1 & 3, maximum potential energy was reached thus not allowing them to deform until full stroke. However, the deformations are enough for validation purposes since past studies has shown that the module has flat force-displacement response [28–30,32–34]. It is also worth noting that the kinetic energy (KE) values (calculated from real impact velocity) shown in the table is lower than the potential energy (PE) due to losses such as guide wheel-rail friction and misalignment. The KE values were taken as reference for the simulations.

190 **Table 4** Drop test loading conditions.

Module	Impactor Mass (kg)	Drop Height (m)	Impact Velocity (m/s)	PE (kJ)	KE (kJ)
1	142.806	3	5.503	4.199	2.162
2	142.806	2	5.565	2.798	2.279
3	142.806	3	6.773	4.199	3.275
4	171.627	2	5.651	2.904	2.740

191 The step-by-step deformation of both the experimental and numerical specimen is given in Figure 7.
192 Figure 8 shows the final deformation of specimens after impact tests. As can be seen, all test
193 specimens behave as expected, with no trace of unwanted failure modes occurred.



194 **Figure 7** Comparison on deformation step of the present module between experimental and FE
195 simulation: (1) initial state, (2) expansion phase, (3) fully expanded state, (4) splitting phase, (5) end state.
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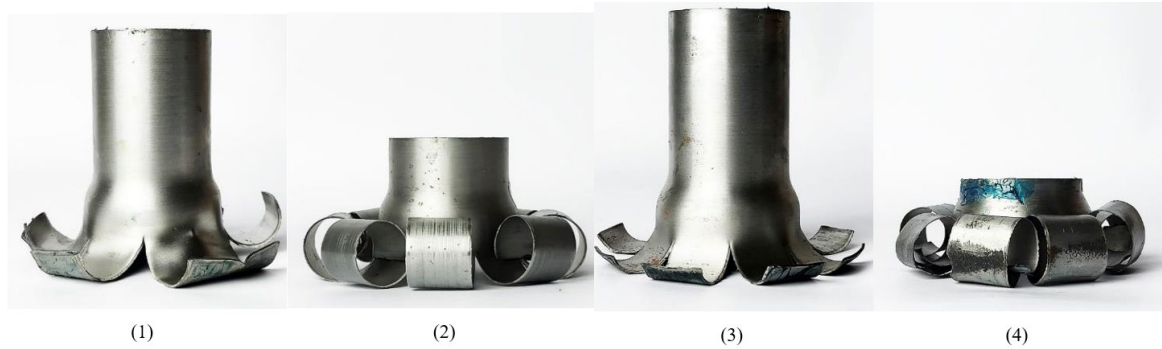


Figure 8 Deformed shape after drop test for Specimen number 1, 2, 3, and 4.

The comparison of the force-displacement responses and impact characteristics results between finite element analysis and experiment are shown respectively in Figure 9 and Table 5. Even though there are differences in the force-displacement response, the numerical results of the mean crushing force, peak force, and specific energy absorption from the FE simulation results agree well with those of the experimental results as shown in Table 5. From trials, the best approximation of the coefficient of friction for FE simulation is 0.16, to simulate greased contact between tube and dies. This agrees with a number of tribology investigations [37–39]. The error values are reasonable [15,18,32–34,40] with uncertainties present during the drop test, namely friction, dies wear, and geometry tolerance. This validation also shows that modelling assumptions and strategies i.e., the J-C material model, rigid dies, and meshing are adequate to capture the impact response of the combined module.

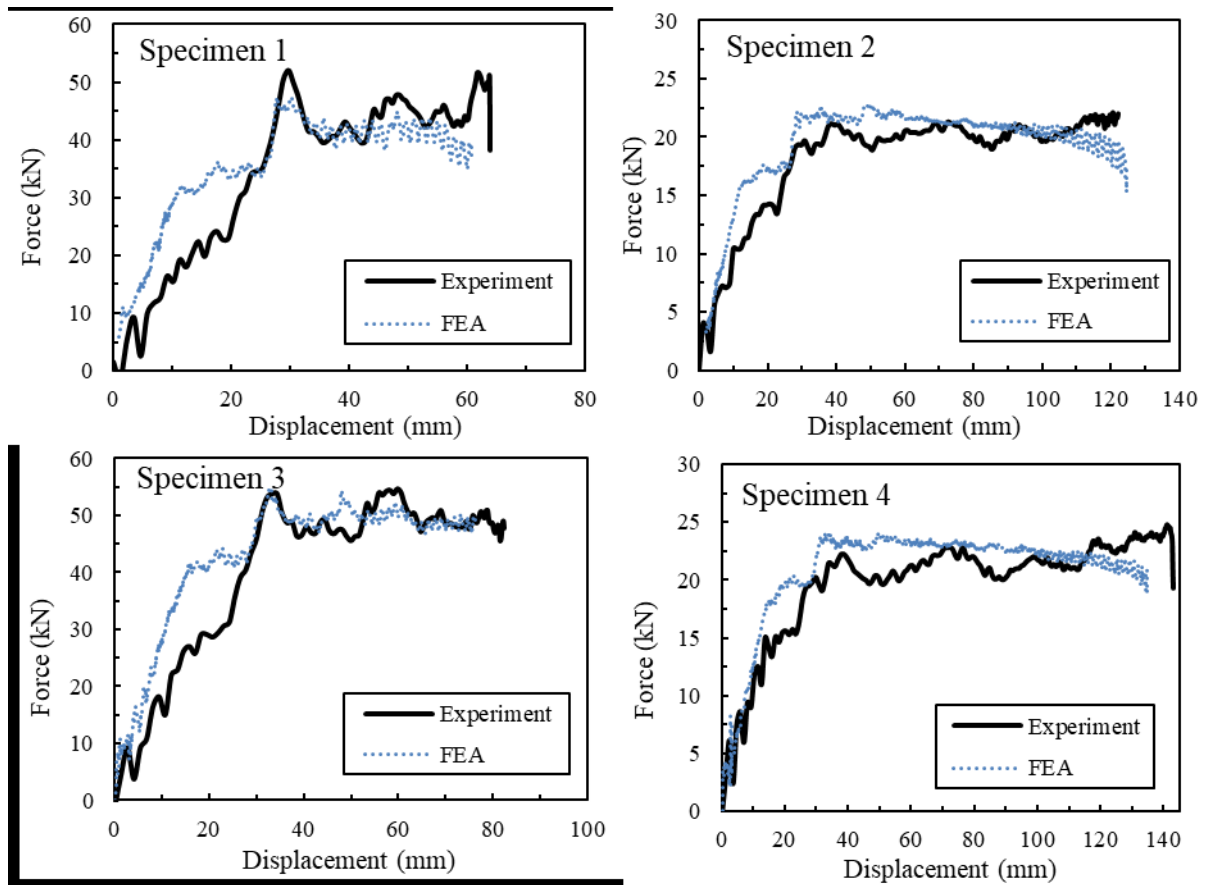


Figure 9 Comparison of force-displacement response for specimen number 1, 2, 3, and 4.

Table 5 Comparison of impact characteristics between FEA results and experiment results.

Module	Mean Force (kN)			Peak Force (kN)			SEA (kJ/kg)		
	FEA	EXP	%Diff.	FEA	EXP	%Diff.	FEA	EXP	%Diff.
1	37.37	39.19	4.66%	48.80	51.98	6.52%	19.03	18.12	4.81%
2	19.34	19.64	1.86%	23.10	22.06	4.49%	19.28	19.64	1.89%
3	44.29	44.17	2.58%	55.10	54.61	0.89%	22.99	21.09	8.99%
4	21.09	21.00	0.43%	24.10	24.77	2.76%	26.60	25.05	5.84%

4 Parametric Study

This chapter is divided into two sections: the first section is intended to give a clear overview of the impact response of the combined module by using evenly spaced data points. The second section will demonstrate how the proposed mathematical model was derived by using a larger, normally distributed data set.

4.1 Effect of Geometry Parameters

In order to study the impact characteristics of the present impact absorption module, 30 evenly spaced finite element models were used. The expansion ratio ranges from 1.135 to 1.235 whilst the thickness ratio ranges from 25 to 75 based on the feasibility criteria for the present module which has been discussed elsewhere [31,41] .

All the FE models successfully underwent tube expansion and axial splitting until full stroke. The force-displacement responses were then generated as shown in Figure 10. The force characteristics of this module resembles that of an ideal module, flat steady state force with high crushing force efficiency (CFE). With the current scale, a notable amount of stroke was required to attain the steady state force due to expansion process. However, as most applications would have bigger stroke to expansion ratio, the stroke needed to reach steady state force would be notably low compared to the total stroke.

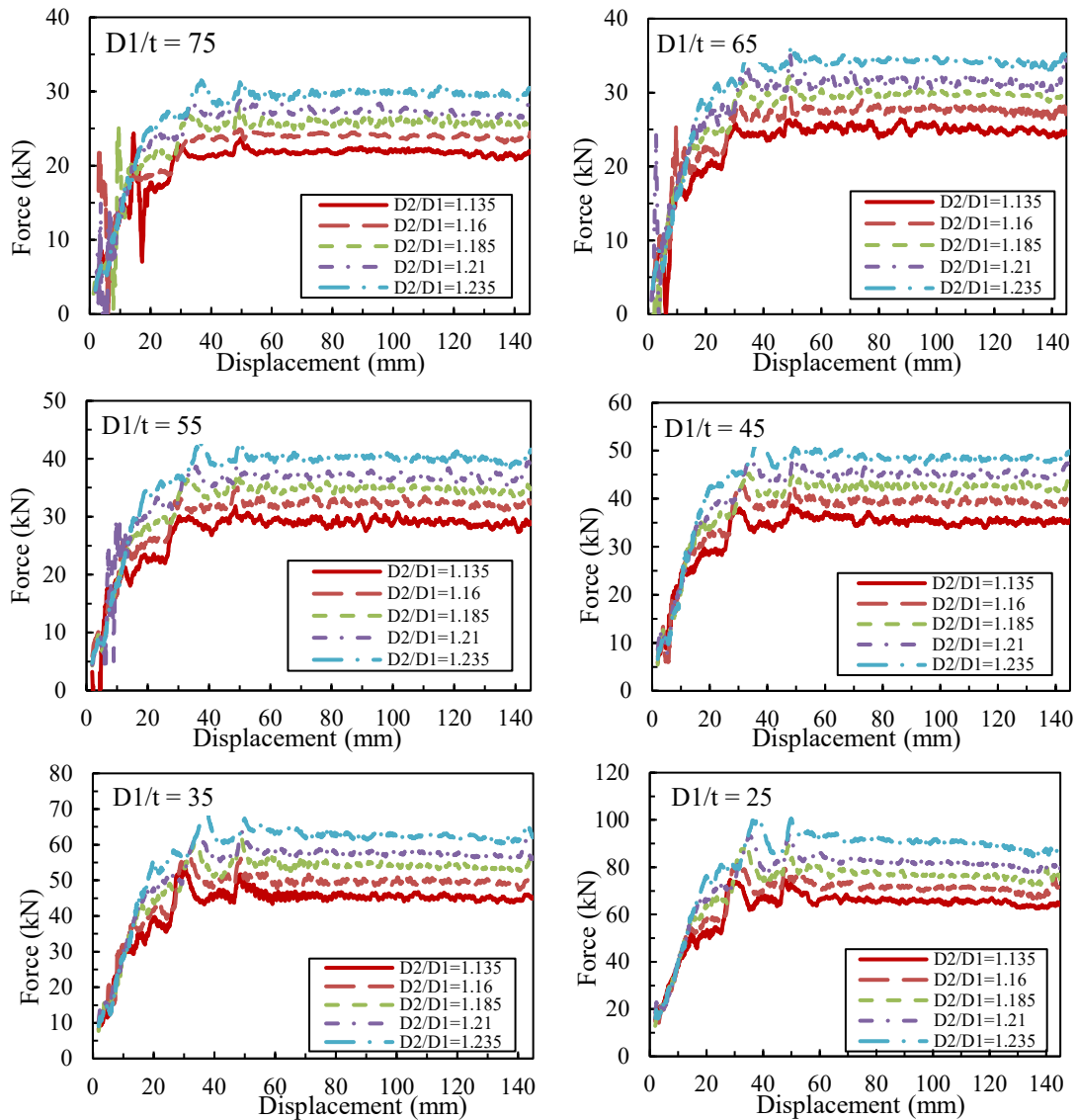


Figure 10 Force-displacement responses of the preliminary models.

The comparison of mean crushing force of the models was plotted in Figure 11. The average crushing force tends to increase as expansion ratio increases and diameter-to-thickness ratio decreases. Lower diameter-to-thickness ratio means larger tube cross-sectional area while higher expansion ratio means greater plastic deformation resulting in higher amount of force. The specific energy absorbed, however, is only sensitive due to change of expansion ratio, indicating that the addition of deformed mass in the form of thickness is directly proportional with the ability of the module to absorb impact energy (Figure 12).

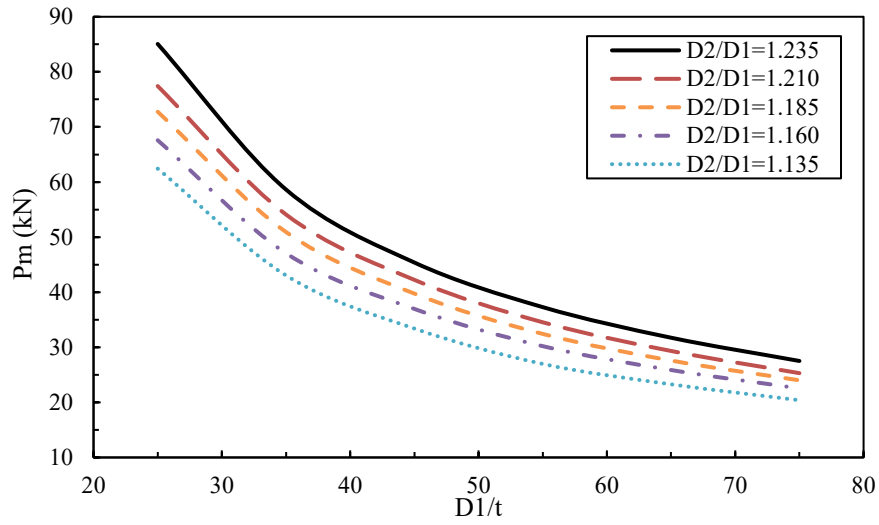


Figure 11 Mean crushing force comparison of the preliminary finite element models.

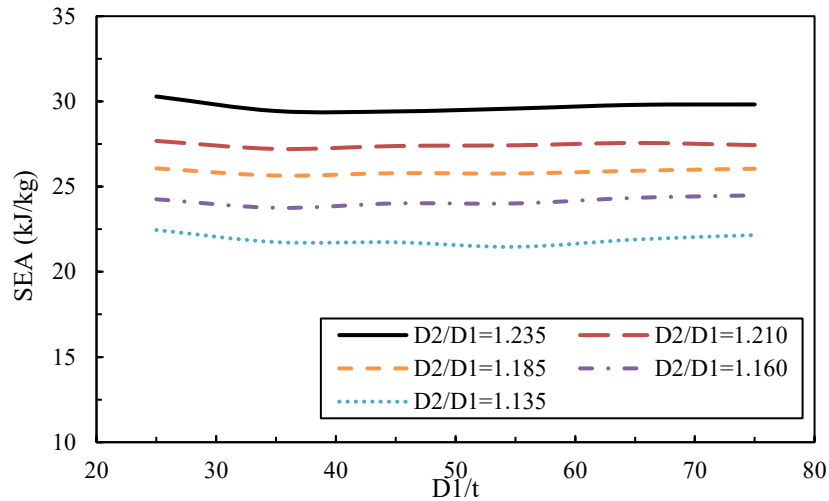


Figure 12 SEA comparison of the preliminary finite element models.

Additionally, the effect of friction was also assessed numerically by comparing three conditions: unlubricated, lubricated with light mineral oil (LMO), and lubricated with grease resulting in friction coefficients of 0.5, 0.23, and 0.16 respectively [38]. The output parameter of interest was the non-dimensional force since it is insensitive to diameter-to-thickness ratio [23]. As shown in Figure 13, the non-dimensional force increases with the increase of friction coefficient as energy dissipation through friction intensifies. However, such module is prone to an unwanted failure mode which is premature splitting during expansion process [28]. Thus, a suitable lubrication is still needed to eliminate friction coefficient value uncertainty for steel-to-steel contact.

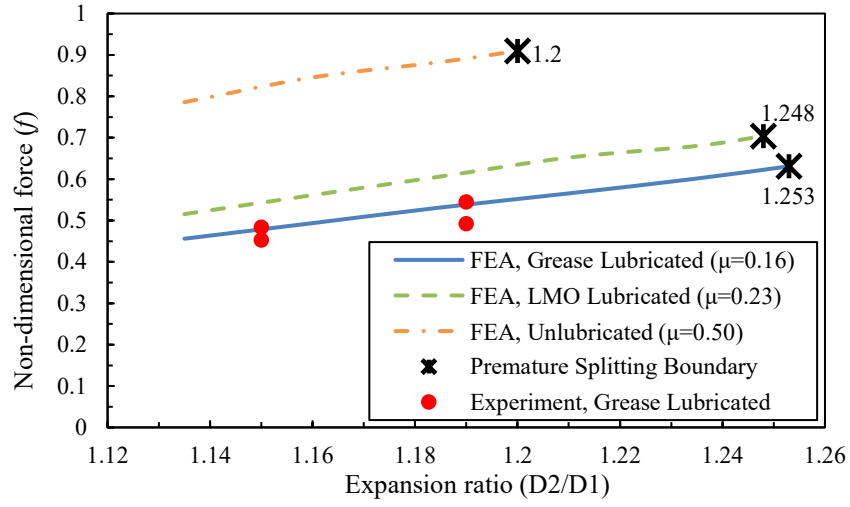


Figure 13 Effect of friction on the present mechanism.

4.2 Response Surface Modelling

To derive the impact characteristics of the module to a mathematical formula, response surface modelling was conducted. Input data sampling was done with Latin Hypercube Sampling method which is amongst the most popular for numerical study. The method ensures the generated sample points are normally distributed. The selected number of points was 40 to study the effect of expansion ratio and diameter-to-thickness ratio with the minimum sample size in mind which is at least ten times the number of parameters of interest [42]. Boundaries shown in Eq. (2) and Eq. (3) are used to prevent unwanted failures [41]. 10 other samples were generated with the same method with varying initial diameter. These samples were intended to study the effect of scaling the size of the module and will be used for cross validation of the regression model. The upper and lower boundary of the initial diameter was 30 mm to 380 mm. The generated 50 data points are shown in Figure 14.

$$20 \leq \frac{D_1}{t} \leq \min \left(120, \left(\frac{V_{imp}}{60.23} \right)^{-3.31} \right) \quad (2)$$

$$1.09 \leq \frac{D_2}{D_1} \leq 1.235 \quad (3)$$

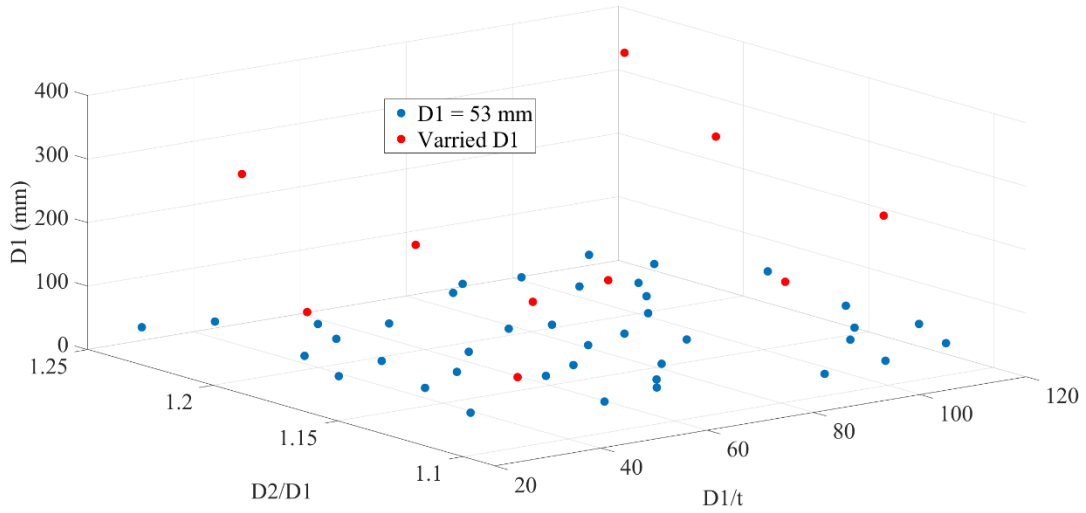


Figure 14 Normally distributed sample points of the present module.

After finite element analyses have been conducted, the resulting P_m and SEA values were calculated. The SEA value alongside the input parameters were then imported to MATLAB for 3-dimensional regression then processed using regression tool. SEA was chosen as the primary parameter since Figure 11 and Figure 12 show that the behaviour of SEA is more predictable compared to P_m : linear regression was adequate to regress the SEA. The regression shows that the gradient for the diameter-to-thickness ratio is very small as also shown in Figure 12. Thus, assumption could be made that SEA is independent of diameter-to-thickness ratio, allowing regression model of SEA to be written as solely a function of expansion ratio (Eq. (4)). This model produced an R-squared value of 0.990.

$$SEA = -57.61 + 69.57 \left(\frac{D_2}{D_1} \right) \quad (4)$$

Mean crushing force equation was obtained through theoretical correlation between P_m and SEA (Eq. (5)). Thus, the formula for mean crushing force could be stated as Eq. (6) which yielded an R-squared value of 0.998.

$$SEA \approx \frac{P_m \cdot L_{def}}{m_{def}} \quad (5)$$

$$P_m = 57.61 \rho \pi D_1^2 \left(\frac{D_1}{t} \right)^{-1} \left(1.208 \left(\frac{D_2}{D_1} \right) - 1 \right) \quad (6)$$

Even though the response surface model is proved to be usable, Eq. (5) and Eq. (6) still lacks some crucial properties such as effect of material strength, tube-to-dies friction, and expansion angle, all of which contribute to the overall energy absorption [32,33]. Since the crushing force of the combined module is mostly contributed by the tube expansion process rather than axial splitting due to plastic deformation and friction dissipation, as suggested by Li *et al.* [33], the theoretical equation of tube expansion module [43] (Eq. (7)) may be used as the basis of incorporating the said parameters.

$$P_m = [(1 + \mu \cot(\alpha)) \cos(\alpha)] \left[\pi \int_{D_1}^{D_2} t \sigma_0 dD \right] \quad (7)$$

By solving the equation, it was found that the constant of 57.61ρ in Eq. (6) could be replaced with the first term of Eq. (7) and would results in Eq. (8) in which, σ_0 is material yield strength, μ is friction coefficient, α is expansion angle, D_1 is tube initial diameter, D_1/t is diameter-to-thickness ratio, and D_2/D_1 is expansion ratio. Here, the constant of 1.208 was interpreted as the correction factor for adding splitting into the mechanism. Subsequently, formula for SEA was derived from the correlation shown in Eq. (5) to form Eq. (9) in which ρ is material density.

$$P_m = \sigma_0 (1 + \mu \cot \alpha) \cos(\alpha) \pi D_1^2 \left(\frac{D_1}{t} \right)^{-1} \left(1.208 \left(\frac{D_2}{D_1} \right) - 1 \right) \quad (8)$$

$$SEA = \frac{\sigma_0}{\rho} (1 + \mu \cot \alpha) \cos(\alpha) \left(1.208 \left(\frac{D_2}{D_1} \right) - 1 \right) \quad (9)$$

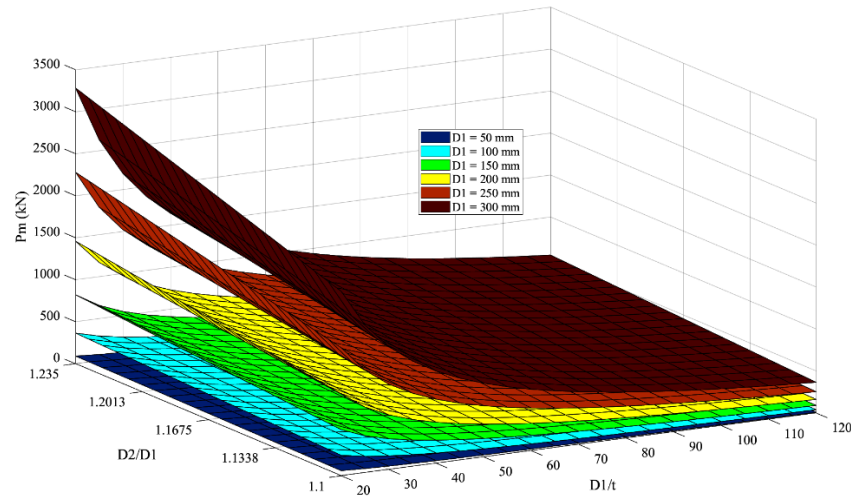
5 Results and Discussion

To demonstrate the predictive power of Eq. (8) and Eq. (9), cross-validation was conducted with numerical model and previous research and performed a case study. The parameters that are present in both equations; tube material, friction coefficient, expansion angle, tube diameter, expansion ratio, and thickness ratio, were to be discussed in this section. Comparison and discussion were also made on the impact performance of present module with optimized dimensional parameters to other popular mechanisms.

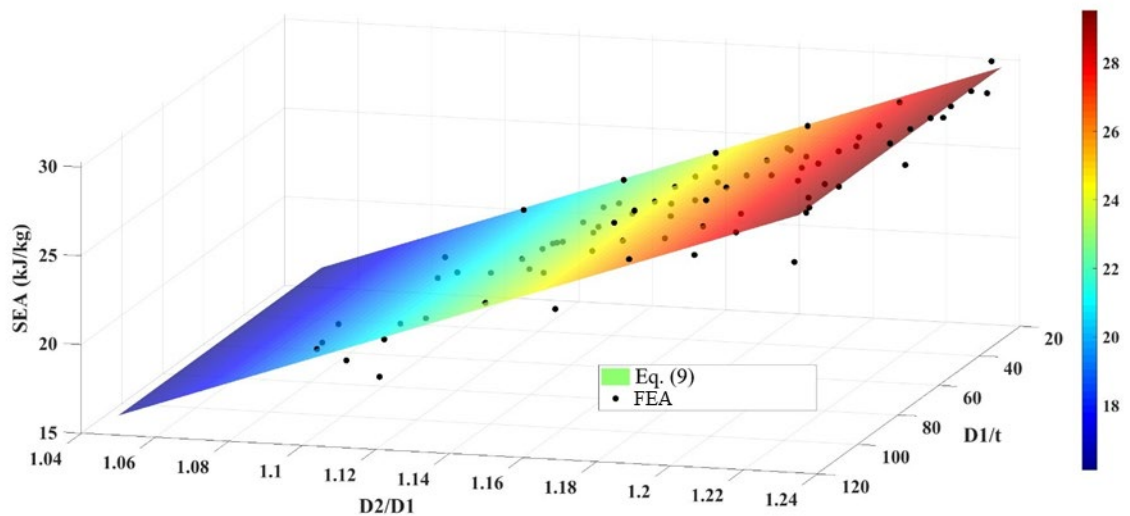
5.1 Cross-validation of Mathematical Model

Eq. (8) and Eq. (9) were used to fit 80 finite element analysis different models (30 evenly distributed data, 40 normally distributed data, and 10 data with various initial diameter). Both equations

303 successfully predicted the P_m and SEA values with R-squared of 0.99 and 0.81 respectively. The
304 surface plots of the equations are shown in Figure 15.



305



306

307 **Figure 15** Surface characteristics of the present mechanism: mean crushing force (top) and specific
308 energy absorbed (bottom).

309 Additionally, to test the effects of material yield strength, friction coefficient, and expansion angle,
310 impact performance of 7 new models were generated and compared in which the first one being the
311 control (Table 6). The initial diameter, expansion ratio, and diameter-to-thickness ratio of all models
312 are 53 mm, 1.176, and 64.62 respectively. Both Eq. (8) and Eq. (9) successfully predict the mean

crushing force and specific energy absorbed of the finite element models with average difference of 4.03% and 4.26% respectively.

Table 6 Models with variation of yield strength, friction coefficient, and expansion angle.

No.	Material	σ_0 (MPa)	μ	α (deg)	P_m (kN)			SEA (kJ/kg)		
					FEA	Eq. (8)	(%)	FEA	Eq. (9)	(%)
1	API 5L	387.90	0.16	25	27.24	27.14	0.35	24.88	25.27	1.60
2	SS400	478.67	0.16	25	31.91	33.50	4.98	29.30	31.19	6.44
3	ST37	268.74	0.16	25	19.06	18.81	1.33	17.43	17.51	0.46
4	API 5L	387.90	0.05	25	21.71	22.38	3.06	19.84	20.83	5.01
5	API 5L	387.90	0.25	25	31.97	31.04	2.91	29.18	28.90	0.96
6	API 5L	387.90	0.16	30	27.06	24.66	8.85	24.71	22.96	7.06
7	API 5L	387.90	0.16	20	28.26	30.17	6.73	25.94	28.09	8.29

The results from previous studies were then taken and exercised on the mathematical model. For the tube, Li *et al.* [33] used 20 Steel with fixed diameter, thickness, and expansion ratio (100 mm, 2 mm, and 1.06 respectively). They classified the energy absorption as plastic deformation (expansion), friction, and splitting thus having crushing force values for various friction coefficient. Moreno *et al.* [32] utilized mild steel E355 with tube diameter of 30 mm and thickness of 2 mm. They used 2 different expansion ratios: 1.10 and 1.25. Both studies essentially utilized similar combined mechanisms to ours apart from the splitter in which, they used curved continuous die with pre-manufactured notch on the tube. However, as shown in Figure 16, Eq. (8) still managed to capture the mean crushing force from both studies as tube expansion and friction are the main source of energy dissipation in this module.

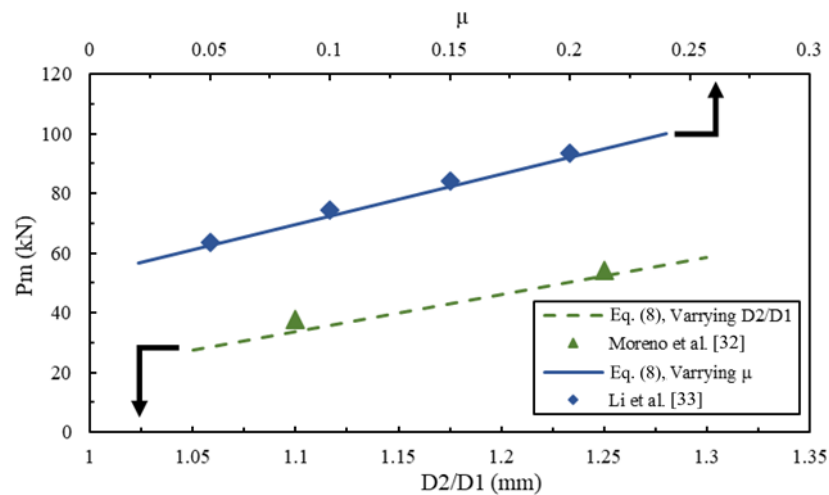


Figure 16 Proposed equation in comparison with previous numerical and experimental studies.

5.2 Case Study

Eq. (8) and Eq. (9) could be employed for engineering and optimization purposes without the needs of experimental and numerical studies in the early design stages. In this section, demonstration in the form of a case study was made to assess the performance of the mathematical model compared to finite element analysis. The deformed module shown in Figure 17 is an optimized module for light rail transport (LRT) application with an initial diameter of 104.76 mm and tube length of 670 mm. The force-displacement response comparison is shown in Figure 18. Table 7 further shows the comparison of impact characteristics comparison generated from FEA and forecasted by the mathematical model. The difference is 0.6% at most for all variables.

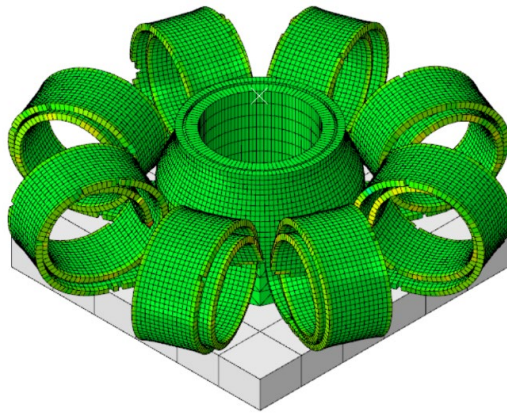


Figure 17 Fully deformed optimized tube expansion-axial splitting module.

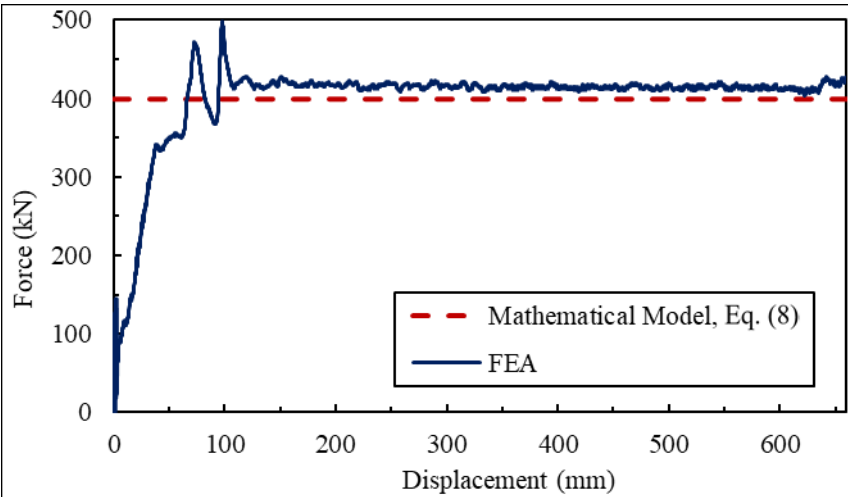


Figure 18 Force-displacement response of the optimized tube expansion-axial splitting module.

Table 7 Impact performance of the optimized module for the case study.

Parameter	Mat. Model	FEA	Error
P_m (kN)	399.30	401.72	0.60%
P_{peak} (kN)	499.12	499.70	0.12%
EA (kJ)	263.58	264.69	0.42%
SEA (kJ/kg)	29.74	29.87	0.44%
Stroke Efficiency	0.99	0.99	0.02%
CFE	0.80	0.80	0.49%

5.3 Impact Performance Comparison

Based on the response surface modelling on the parametric study, the impact characteristics of the present module may be found. Diameter-to-thickness ratio lightly affects the specific energy absorption, whilst expansion ratio provides linear effects on the specific energy absorption. The mean crushing force is proportional to expansion whilst inversely proportional to diameter-to-thickness ratio. The highest specific energy absorption may be obtained in relatively higher expansion until the limit of feasibility is reached that is 1.235, below which premature splitting would happen [31,41]. Furthermore, using the above equations, the best combination of geometric parameters of the present module could be determined based on the specific energy absorption or stroke efficiency. The module would have diameter-to-thickness ratio of 20 and expansion ratio of 1.235. The undeformed length of the tube would be 11% of the dies length, resulting in overall stroke efficiency of 98.8%, higher than any other studied mechanism, including that of composites due to metal higher resistance to detrimental buckling.

Figure 19 shows that the present module performs better compared to the other modules, only behind composite-based modules and aluminium-based axial collapse in terms of specific energy absorption, which density is much less than that of carbon steel. However, as demonstrated before, the present mechanism provides a relatively constant crushing force and is more suitable for high-capacity loadings such as railway applications. It would be interesting to consider applying such mechanism in different metallic materials with lower density such as aluminium alloys to increase SEA, potentially surpassing that of axial collapse or even composite-based modules. This would be beneficial particularly for applications that sensitive to weight.

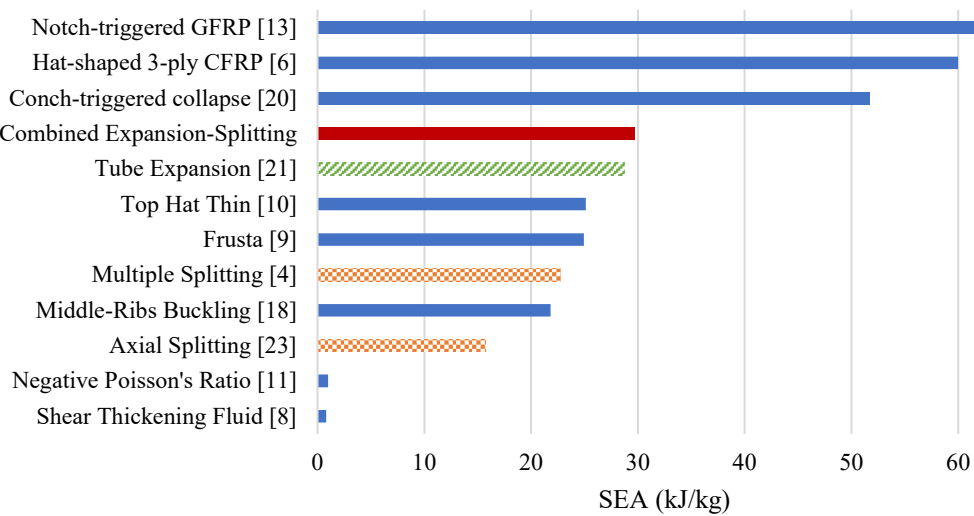
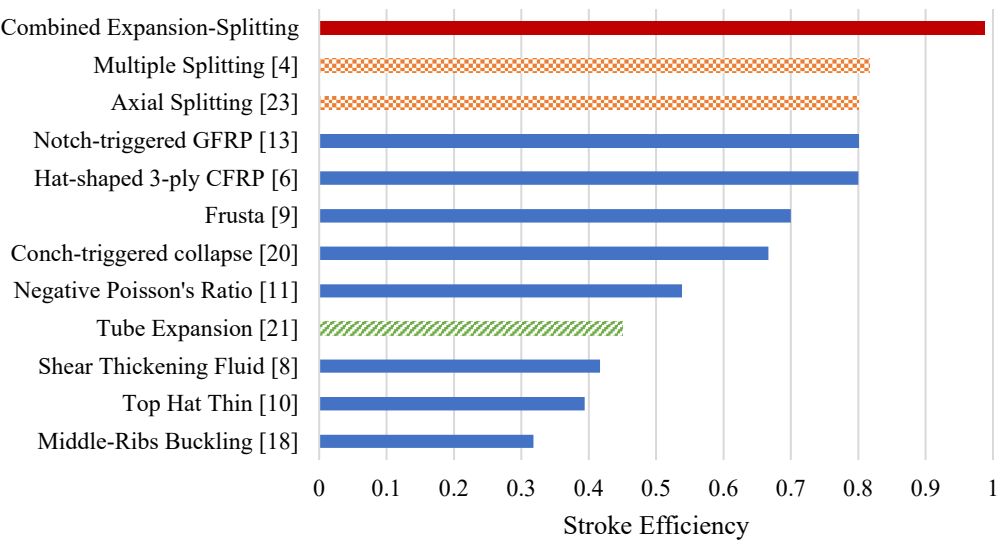


Figure 19 Impact performance of present mechanism (in red) compared with other notable impact absorption module (axial splitting modules are chequered in orange and tube expansion is hatched in green).

6 Conclusion

In this research, a mathematical model which correlates between the impact performance and design parameters of combined tube expansion-axial splitting energy absorption module was proposed. Based on numerical aided parametric study, the results successfully captured the effects of expansion ratio, diameter-to-thickness ratio, initial diameter, material strength, expansion angle, and friction coefficient of the combined module. As for the dimensional parameters, conclusion was drawn that only

expansion ratio affects the specific energy absorbed while crushing force is affected by all the parameters. The proposed mathematical model yielded R^2 values of 0.99 for specific energy absorbed and 0.81 for mean crushing force. A case study was also presented to compare results between numerical and the proposed model which yielded difference of less than 1% for all impact performance values. Furthermore, a combined module optimized with the proposed mathematical model proved to perform better in terms of specific energy absorbed and stroke efficiency compared to other popular mechanisms with carbon steel material (29.74 kJ/kg and 0.99 respectively). The present mechanism with carbon steel material is potentially suitable for high load capacity such as in railway applications. It is interesting to investigate the present mechanism for lower density metallic materials such as aluminium alloys, in order to increase the specific energy absorption.

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Development of impact characteristics response model for combined tube expansion axial splitting module

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