



Improvement of Force History Pattern in Composite Tubular Structures by Developed Trigger Mechanisms

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Abstract

This paper investigates the effect of various trigger mechanisms on the force history pattern, initial collapse load, mean force and specific energy absorption of CFRP composite tubular absorbers. These trigger mechanisms are bevel with angles of 15°, 30°, 45° and 60° and tulip with angles of 60° and 90° and tip numbers of 4 and 6. Experimental studies were performed for three trigger mechanisms of Bevel (B30° and B60°) and tulip with four tips and angle of 60°, 4T60. It was shown that tulip mechanisms significantly change the force–displacement pattern in comparison with bevel triggers. In this case, the initial collapse load decreases, which leads to improving the crush force efficiency (CFE) and progressive energy absorption. This analysis also contains numerical modelling, which investigates other designs of bevel and tulip trigger mechanisms with different angles. Finally, numerical results are validated against experimental results using advanced finite element techniques in LS-Dyna. The developed tulip trigger mechanisms indicated a significant change of crushing force history, which results in improvement of crashworthiness parameters.

Keywords Trigger · CFRP · Tulip · Force Pattern · Absorbed Energy

1 Introduction

In the past decades, different types of crashworthy polymer composite components have been investigated including various geometrical shapes, material systems and lay-ups, various fabrication methods and trigger mechanisms under oblique, axial, quasi-static and impact loading conditions [1–4]. These benefits rely on their high strength and low density which leads to high values of specific strength and stiffness of fibre reinforced polymer (FRP) composites [5]. This application produces a considerable weight reduction, which makes these materials very suitable for facing some of the challenges in the transportation sector nowadays [6–8]. In the case of crashworthy of composite tubular

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components, it has been proven that they can provide more efficient behaviour than equivalent metallic solutions [9, 10].

The crashworthiness of a structure or subcomponent is related to its crash resistance and involves its energy absorption capabilities during an impact scenario. Normally, kinetic energy is absorbed permanently by crash components, which are designed for this purpose. This energy absorption is produced employing both the device collapsing force and deformation. Therefore, the control of the accelerations is transmitted to the vehicle occupants (related with the crushing forces) as well as the component deformation which must ensure passengers' survivability zone. Moreover, these type of structures can be designed to fail progressively thus maximising their energy absorption capabilities. To obtain this sort of sustained failure and to avoid a low-efficiency sudden global failure, local geometrical modifications which are called trigger mechanisms are used in the structures [2, 9].

Different collapsing modes can take place within the axial crushing of tubular components. Several authors such as Hull [2] and Farley and Jones [3] identified three main crushing modes: transverse shear or fragmentation, lamina bending or splaying and local buckling. Fragmentation and lamina bending are the main mechanisms of high stiffness components and therefore of CFRP energy absorbers. The combination of two crushing modes of transverse shearing and lamina bending is called brittle fracture mode [3]. Within these modes, energy is absorbed using mode I and mode II crack formation and propagation, fibre breakage, interlaminar shear at the generated fronds, lamina bending and fracture, and the friction between the debris wedge with the fronds and impactor surface [2, 3]. Several factors alter these failure mechanisms, thus affecting the crashworthiness response of the energy absorbers. Among these factors, the geometry of tubes [1, 4, 9–13], laminate design [1, 10, 14–16] and material fracture toughness [14, 17–19] are widely reported.

Apart from these, trigger mechanisms are widely reported in the literature too. Czaplicki et al. [20] and Jiménez et al. [13] studied squared section tubes with chamfer and tulip triggers in E-glass composites. Czaplicki et al. [20] reported that tulip triggered tubes showed higher values of energy absorption than the chamfered ones. Moreover, tulip triggered tubes showed a smooth force response without initial peak when compared to the bevel ones [13, 20]. It was proven that the angle of chamfer has a strong effect on the crashworthiness response, with higher energy absorption at 60° in comparison with 30° and 45°. This angle dependence was less evident for the tulip triggered tubes. Palanivelu et al. [21] compared 45° bevel and tulip triggers in circular and squared E-glass tubes. For squared sections, the tulip absorbed higher energies than chamfer trigger mechanism. Contrary, for circular sections, chamfered tubes showed a better performance in comparison with the tulip trigger. Sivagurunathan et al. [22] explored the crushing behaviour of natural fibre tubes using four different initiators: no trigger, chamfer, double chamfer (steeple) and tulip. In the case of square tubes [13, 20], tulip triggered tubes did not exhibit an initial peak in load, however, they showed the highest specific energy absorption (SEA).

Tong et al. [23] tested a plug trigger with semi-circular shape which exhibited a stable crushing behaviour. Adding a notch trigger reduced initial loading instabilities with minimum effect in the SEA. Finally, Huang and Wang [24, 25] reported the use of two engineered triggers in CFRP components: crown trigger (a combination of bevel and notch) and the use of a Shape Memory Alloy (SMA). Similar mean forces and SAE but lower peak load were observed for the crown compared to the chamfer tubes. The SMA presented a significant increase in SAE compared to that of a ply-off triggered tube.

In this work, effect of various trigger mechanisms on energy absorption of CFRP composite tubes are studied experimentally and numerically. The developed trigger mechanisms

are tulip and bevel, which show a significant change in crashworthy performance of CFRP tubular absorbers.

2 Experimental Studies

2.1 Manufacturing of Specimens

A single tube was manufactured by hand layup with carbon/epoxy pre-impregnated plies with a stacking sequence of [45/-45/0/90]_s. Laminas were wrapped over a metallic mandrel with a machined OD of 65 mm. Once the CFRP tube was laminated, cured and de-moulded, it was cut to provide the tubular specimens of 150 mm long each. After that, triggers were machined on them. The outer diameter of the tubes was 70 mm with a wall thickness of 2.4 mm, providing a t/D ratio of 0.034 which according to Rabiee and Ghasemnejad [4] fits within the range of ratios providing stable axial crushing. Two different triggers and two different trigger configurations were analysed through those specimens. The triggers were 30° and 60° bevel (measured from the vertical axis) and 60° tulip (see Fig. 1).

2.2 Impact Testing

The specimens were tested at the Cranfield Impact Centre (CIC) in a drop tower test rig. Tubes were vertically loaded using a flat impactor of 80 kg at 5 m/s thus producing an impact kinetic energy of 1 kJ, which were simply supported at the bottom end. Samples were surrounded by a piece of foam (Fig. 2a) to protect the rig from a possible direct impact between the impactor and the load cell produced by a sudden failure of the specimens. Figure 2b is included to clarify how the tubes went all the way through the foam and show the support conditions. A 400 kN load cell and accelerometers were used to obtain the force–displacement response of the tubes from the test. The signal of the accelerometers was converted to obtain the impactor displacement.

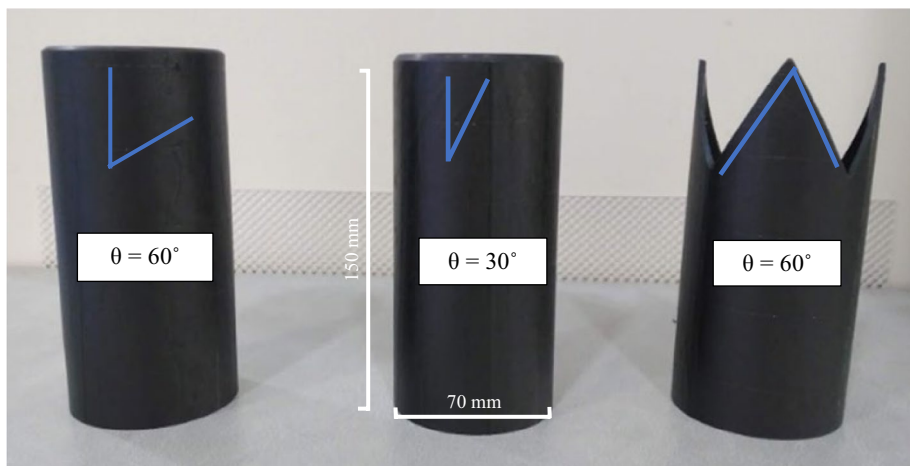


Fig. 1 Triggered specimens. 60° Bevel (left), 30° Bevel (middle) and 60° Tulip (right)

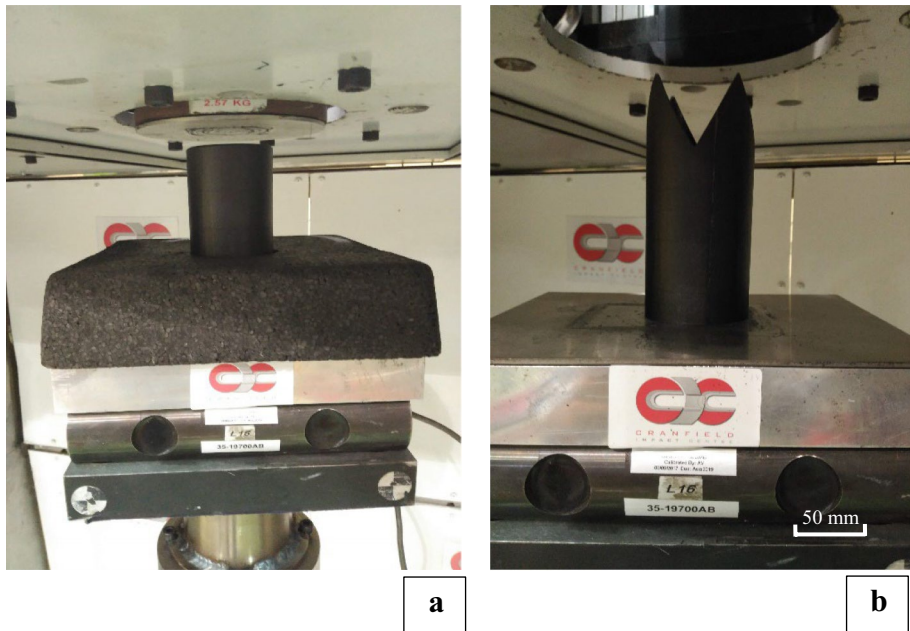


Fig. 2 **a** B60 specimen and safety foam and **b** 4T60 specimen under drop tower impact test

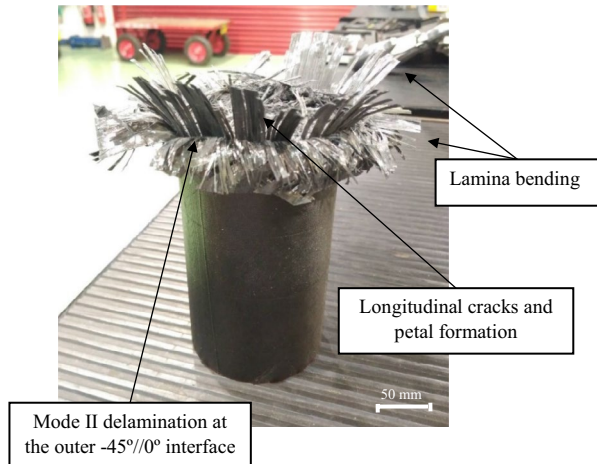
2.3 Analysis of Experimental Results

This section discusses the experimental results for the tested specimens in Sect. 2.2. Here, the failure modes which take place during the crushing process as well as their performance in terms of Peak Load or “Fmax”; Maximum displacement or “d”; Mean Force or “Fm” (Absorbed energy over maximum displacement); Specific Absorbed Energy or “SAE” (Absorbed energy over crushed mass); Crushing Force Efficiency or “CFE” (Fm over Fmax) and Stroke Efficiency or “SE” (crushed over initial length) are presented in detail.

2.3.1 Bevel at 60° (B60)

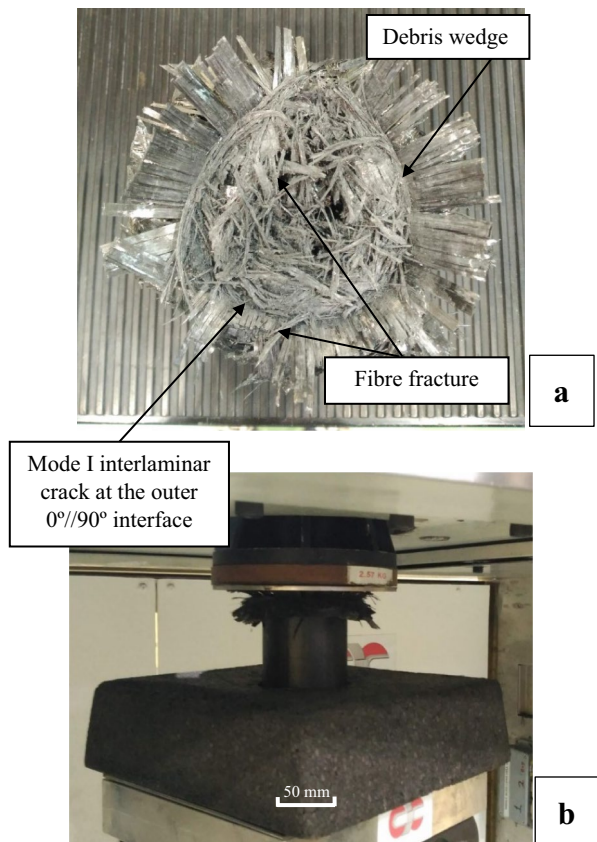
Figures 3 and 4 illustrate the B60 specimen after the impact test. Both figures depict that the tube failed progressively from the top (triggered) end throughout a brittle fracture mode but with a predominant lamina bending or splaying mode rather than a fragmentation one. Mode I circumferential main crack appeared in the outer 0°/90° interface therefore producing an inner bundle which is coarser than the outer. This specific failure might have been motivated because the UD 90°/90° laminate middle interface is stronger in terms of fracture toughness as reported in [15] than the 0°/90°. Crumpled 90° fibres produce a debris wedge along with the interface of this circumferential crack. While the outer bundle shows a clear bending and petal formation within the 0° fibres, the inner one depicts a larger amount of fibre fraction mode. Since the failure mode was not a pure lamina bending, certain failure modes appeared within the bundles too. The outer bundle shows a mode

Fig. 3 B60 specimen after impact testing



II delamination at the $-45^\circ/0^\circ$ interface, longitudinal intralaminar mode III cracks promoting the petals formation and some fibre fraction at the 0° lamina produced by bending. The strong bending interaction between the outer 0° lamina and the impactor can be observed

Fig. 4 B60 specimen after the impact testing, **a** plane view and **b** side view



in Fig. 4 which depicts how these fibres tended to support the impactor whereas the $\pm 45^\circ$ fibres tended to roll down the tube. On the other hand, the inner bundle presented mainly a brittle fracture mode with certain lamina bending which is produced by the accumulation of material in the inner section of the tube as well as the friction against the impactor.

2.3.2 Bevel at 30° (B30)

Results of a bevelled trigger mechanism at 30° are similar to the previous chamfered tube and exhibited the same brittle fracture failure mode involving lamina bending, mode I crack propagation ($0^\circ//90^\circ$ interface), debris wedge, mode II interlaminar cracking ($-45^\circ//0^\circ$ interface), fibre fracture, petal formation and longitudinal crack formations. A large amount of failure mechanisms is very positive for energy absorption purposes (see Fig. 5).

2.3.3 Tulip at 60° (4T60)

Figure 6 illustrates the crushing process of tulip trigger mechanism in brittle fracture mode with more fragmentation and less amount of mode II delamination compared to the bevelled tubes. This fewer delamination at the $0^\circ//45^\circ$ interface results in less longitudinal intralaminar cracks and less petal formation at the 0° fibres in this composite absorbers.

In general, the brittle fracture failure mode was observed similarly to other authors' who worked with similar materials, triggers, geometries and laminate designs [24, 25]. This

Fig. 5 B30 specimen after impact testing, **a** overall deformation and **b** plane view

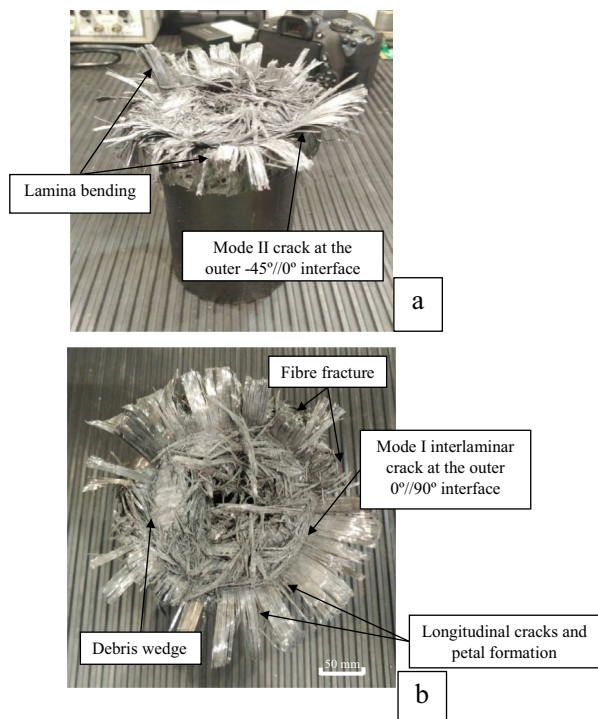
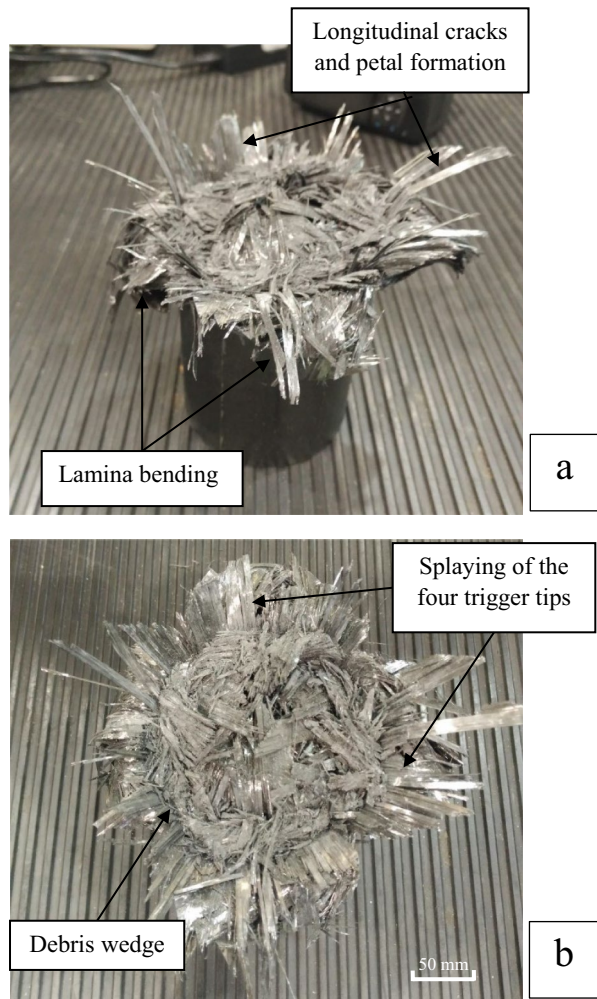


Fig. 6 4T60 specimen after impact testing

collapsing mode produced the failure mechanisms and features which were introduced before and described by Hull [2] and Farley and Jones [3]. Results of SEA in the range of 27–40 kJ/kg are presented in Table 1. The main failure mechanism in Mode I circumferential crack took place in a weak interface such as the $0^\circ/90^\circ$. Figure 7 represents the force–displacement responses of the three tubes with three type of trigger mechanisms. The chamfered ones presented the typical sharp load rising with a triggered peak load

Table 1 Comparison of experimental crashworthiness performance of various triggers

	Fmax (kN)	Fm (kN)	Disp. (mm)	SAE (kJ/kg)	CFE (%)	SE (%)
B60	90	29	35	38	32	23
B30	72	31	33	40	43	22
4T60	33	17	58	37	52	39

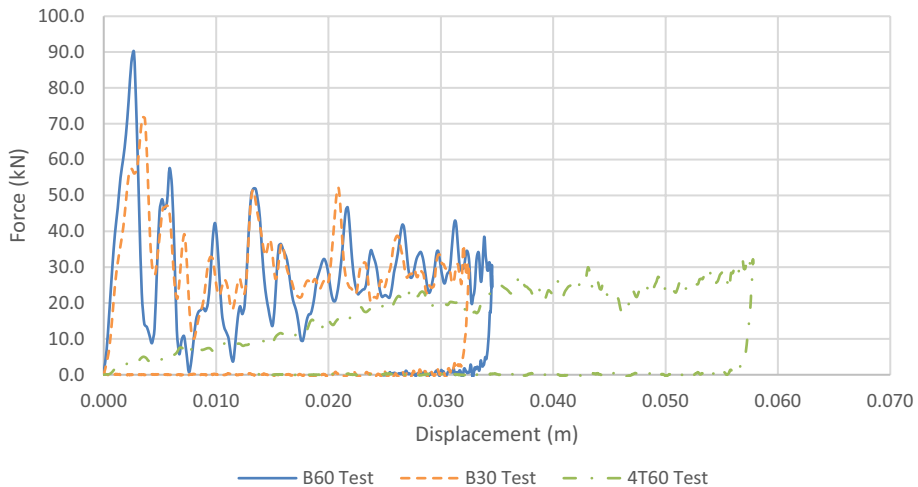


Fig. 7 Comparison of experimental force–displacement responses

followed by a drop and load stabilisation. However, the tulip trigger mechanism indicates a soft load rising during the trigger crushing followed by a constant load. This kind of response avoids the initial and high peak force. This conclusion agrees with the results presented by other authors [13, 21, 22] even taking into account the difference in materials, geometries and loadings. It can be observed that the sustained crushing force of three triggers is very similar and around 30 kN. This gives consistency to the results and validates the manufacturing process. In bevelled trigger mechanisms, it is clear that as the chamfer angle increases, the peak load becomes higher. Furthermore, the B30 sample presented not only the benefit of producing a lower peak load but also a higher mean force, which caused a shorter displacement. Also, between these two tubes, a difference in the loading slope can be observed. The B30 specimen presents a slightly softer slope compared to the B60 one. This behaviour makes the peak load duration of this tube to be longer than the B60's. This fact should be assessed in combination with the acceleration thresholds, since higher peaks can be as unsafe as shorter peaks but in longer periods.

The crashworthiness performance outputs of the specimens are shown in Table 1 and plotted in Fig. 8. Within the chamfered tubes, B60 produced a peak load which is 25% higher than the B30's. The 6% difference in mean force causes a 5.5% increase in SAE and 33.2% in CFE. The increase in mean force also causes an increase in CFE from the B60 specimen to the B30. Therefore, due to the reduction of initial peak load and consequently higher values of SAE and CFE, the B30 specimen was concluded to perform better than the B60. It is also shown that the bevelled tubes represent higher forces than the tulip tube. The maximum force and mean forces of 4T60 presented a 54% and 44% reduction respectively compared to B30. Also, the tulip specimen represented a 7.5% reduction of SEA in comparison with the B30, however, its SEA was close to B60 specimen. Nevertheless, the fact of having lower load levels produced an increase of 22% in CFE and 77% in SE from the B30 specimen to the 4T60. Therefore, the tulip type trigger appears to perform worse in terms of mean force and SEA. Nevertheless, the reduction in peak force causing the increase in CFE and SE, as well as the fact of avoiding the initial high peak load opens the

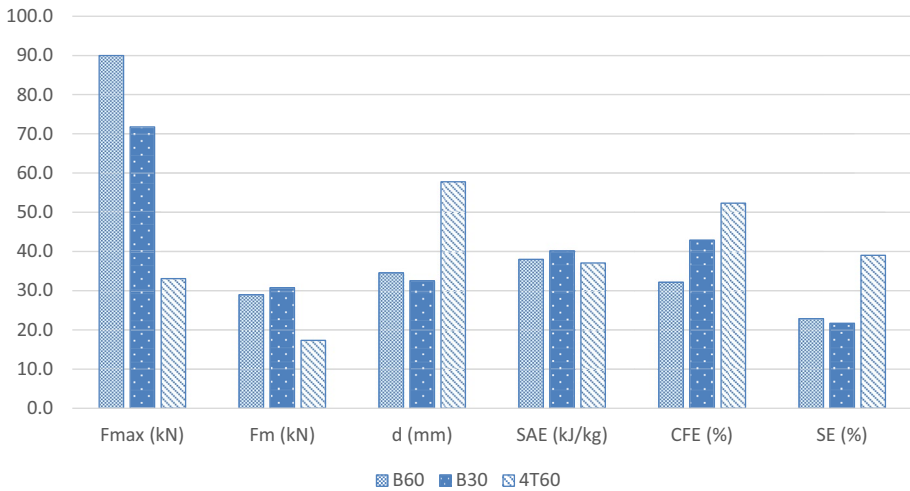


Fig. 8 Experimental crashworthiness parameters between three different trigger mechanisms

chance that, if the other parameters can be improved, find a compromise crashworthy solution within the tulip triggers.

3 Numerical Investigations

The tested CFRP triggered specimens were setup in a dynamic model in LS-Dyna with the same geometrical and impact inputs as per each test. Tubes were simplified through two cylindrical shells each of them representing one half of the wall's thickness. This method allows to represent the main longitudinal mode I delamination while reducing the modelling and running time. The shells were connected using an automatic one way surface to surface tie break contact which strength is linked to both normal and shear contact strengths. The contact between the impactor and the tube and, the self-contact of the tube were defined as automatic surface to surface and automatic general contact respectively. The two shells were implemented with 2×2 mm quadrilateral fully integrated multi-layered elements based on the Belytschko-Wong-Chiang shell formulation [29]. The material properties of the composite are presented in Table 2. The chamfers in the bevel triggers were implemented as a difference in the shells length at the top end whereas the tulip tubes didn't need from any sort of simplification. Within the LS-Dyna material cards, MAT_55 was selected, which implements the Tsai-Wu failure criteria and provided stable crushing. The output taken from the model was the impactor's force–displacement response. The force pulse was smoothened using an SAE filter @ 1000 Hz, which corrected the signal reducing high-frequency pulses that drove to high and sharpened force values. Figures 9, 10, and 11 show the force–displacement responses of the three tested and modelled specimens. Performance results, as well as numerical errors, are presented in Table 3.

As mentioned, not only the values of the performance parameters were important to be matched, but also the behaviour of the absorbers. That would ensure that the model represents the same mechanisms as the experiments. As it was observed in the test, the

Table 2 Summary of composite laminate material properties

Material parameters			Numerical parameters		
Parameter	Value	Description	Parameter	Value	Description
RO (kg/m ³)	1500	Mass density	TFAIL	0.65	Time step size criteria for element deletion
EA (GPa)	119.3	Young's modulus – longitudinal direction	SOFT	0.7	Softening reduction factor for material strength
EB (GPa)	8.2	Young's modulus – transverse direction	FBRT	0	Softening for fibre tensile strength
PRBA	0.01	Poisson's ratio ba	CRIT	55	Failure criterion
GAB (GPa)	3.6	Shear modulus, AB	FS	0.05	Static factor of friction (Impactor/tube contact)
XC (GPa)	0.8	Longitudinal compressive strength	FD	0.05	Dynamic factor of friction (Impactor/tube contact)
XT (GPa)	1.71	Longitudinal tensile strength	FS	0.23	Static factor of friction (Tube self-contact)
YC (MPa)	150	Transverse compressive strength	FD	0.23	Dynamic factor of friction (Shell self-contact)
YT (MPa)	40.5	Transverse tensile strength	FS	0.23	Static factor of friction (Shell/shell contact)
DFAILM	0.016	Maximum strain for matrix	FD	0.23	Dynamic factor of friction (Shell/shell contact)
DFAILS	0.021	Maximum tensorial shear strain	NFLS (MPa)	42.4	Normal Failure Stress (Shell/shell contact)
DFAILT	0.014	Maximum strain for fibre tension	SFLS (MPa)	42.4	Shear Failure Stress (Shell/shell contact)
DFAILC	-0.005	Maximum strain for fibre compression			

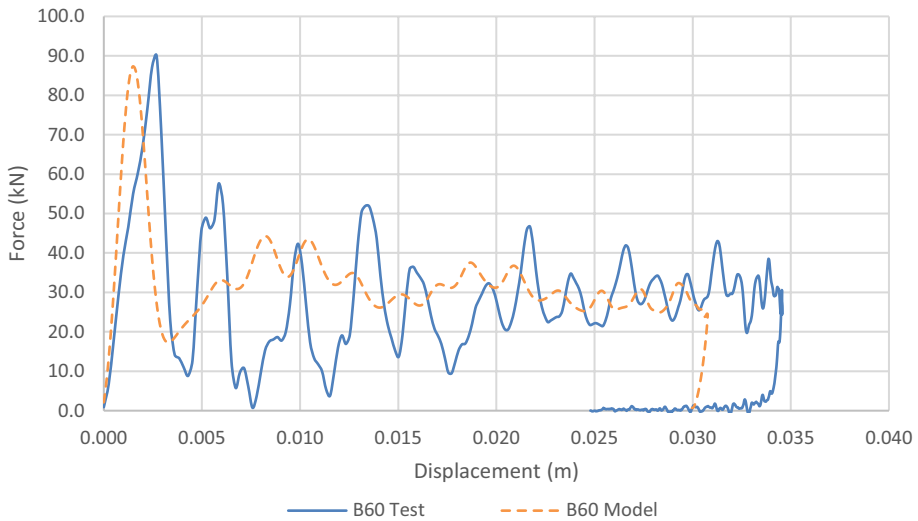


Fig. 9 Experimental and numerical comparison for force–displacement results – B60 Specimen

tubes effectively failed by a mode I central delamination and certain fracture, which is represented by the element deletions. These Longitudinal cracks leading to petal formation did not visually happen leading to a perimeter crack progression. However, it seems that petal formation is prevented by element distortion instead of deletion at the points where these longitudinal cracks are initiated. The physical differences between the numerical and experimental results come from the lack of debris, the element deletion which removes the failed elements, and an excessive curling of the two shells in the numerical results which reduces the shape of bent laminas. Nevertheless, the response of the simulation showed good correlation with experimental data, and tubes' crushing process and failure mechanisms as shown in Figs. 12, 13, and 14.

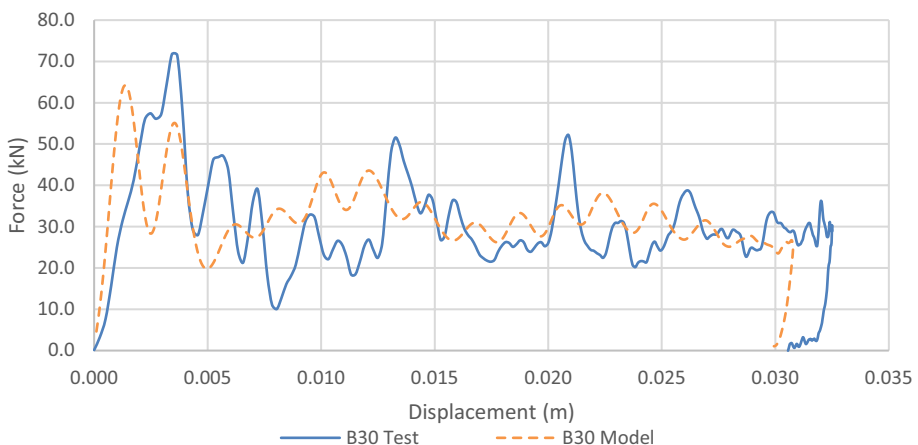


Fig. 10 Experimental and numerical comparison for force–displacement results – B30 Specimen

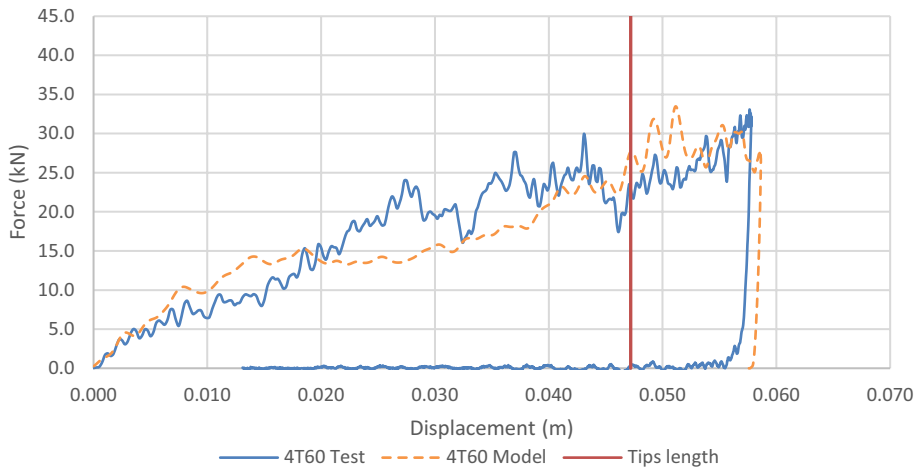


Fig. 11 Experimental and numerical comparison for force–displacement results – 4T60 Specimen

4 Development of Trigger Mechanisms

4.1 Bevelled Trigger

Once the accuracy of the model is examined, it was used to numerically assess new designs based on the tested specimens but with modified geometries. Two different tubes with chamfers at 15° and 45° were modelled and simulated (models B15 and B45 respectively). Figure 15 includes the range of all the studied bevelled tubes.

Figures 16 and 17 indicate the visual results of the crushing tubes. These are very similar to previous simulations, being the B45 failure the most rounded and symmetrical bevelled result so far. Regarding the force response, the trend across the four different bevelled tubes is quite stable, and the biggest difference appears in the peak force duration and shape produced by the mentioned initial contact gap effect. Because the bevel trigger was represented by a height offset between the two shells, there is a contact lag at the early stages of the impact event. This explains the difference in the loading stage. Nevertheless, the root of the trend in F_{max} is different. The flatter angles represent a hard surface for the impactor to impact against, hence the increase in F_{max} from B30 to B45 and B60. However, it is thought that because the B15 was too sharp,

Table 3 Summary of experimental and numerical results

	F_{max} (kN)	F_m (kN)	Disp. (mm)	SAE (kJ/kg)	CFE (%)	SE (%)
B60 Test	89	29	35	38	32	23
B60 Model	87	32	31	42	37	21
B30 Test	72	31	32	40	43	22
B30 Model	64	32	31	43	50	20
4T60 Test	33	17	58	37	52	38
4T60 Model	33	17	58	36	51	39



Fig. 12 B60 specimen. Comparison between macroscopic experimental (top view (a), overview (c)) and numerical results (top view (b), overview (d))

the initial response was weaker leading to its failure and resulting in a flatter surface (hence high F_{max}). Results are stable in crushing force too, revealing that all the tubes failed similarly. Table 4 together with Fig. 18 compares the performance of numerical results. Again, it is clear that all the mean forces are very similar, which produces also similar results in a maximum displacement. However, already in these two parameters, model B45 presents slightly improved results compared to B30 (best specimen from the experimental stage). Further comparisons depict how both SAE and CFE present higher results for the intermediate values of the chamfer angle (30° and 45°). This trend is opposite to the maximum force results, as the highest values belong to the 15° and 60° bevels. Thus, the results point towards B45 as an optimal solution within the bevel trigger. This model exhibited the highest SEA and CFE as well as the lowest peak load. Compared to the numerical results from the B30 model, B45 presented a 2.1% improvement in SEA and a 7.6% reduction in peak force.



Fig. 13 B30 specimen. Comparison between macroscopic experimental (top view (a), overview (c)) and numerical results (top view (b), overview (d))

4.2 Tulip Trigger

To further investigate the tulip trigger, two techniques were numerically assessed aiming to rise the loading stage of the force response; therefore increasing mean force. From the 4T60 model as a baseline, firstly, tip angle was increased from 60° to 90° (model 4T90). Secondly, the number of tips was incremented from four to six (model 6T60). Finally, a model combining these two solutions was tested to see the interaction (model 6T90). Figure 19 collects the trigger detail of all four tulip models investigated.

The numerical force–displacement responses (Fig. 20), clearly indicate that the increase in angle is translated in a stiffer loading phase for the fact of having a larger amount of material against the impactor. Furthermore, as the tips get shorter, the tube full-section crushing occurs earlier, which increases the mean force thus reducing the maximum

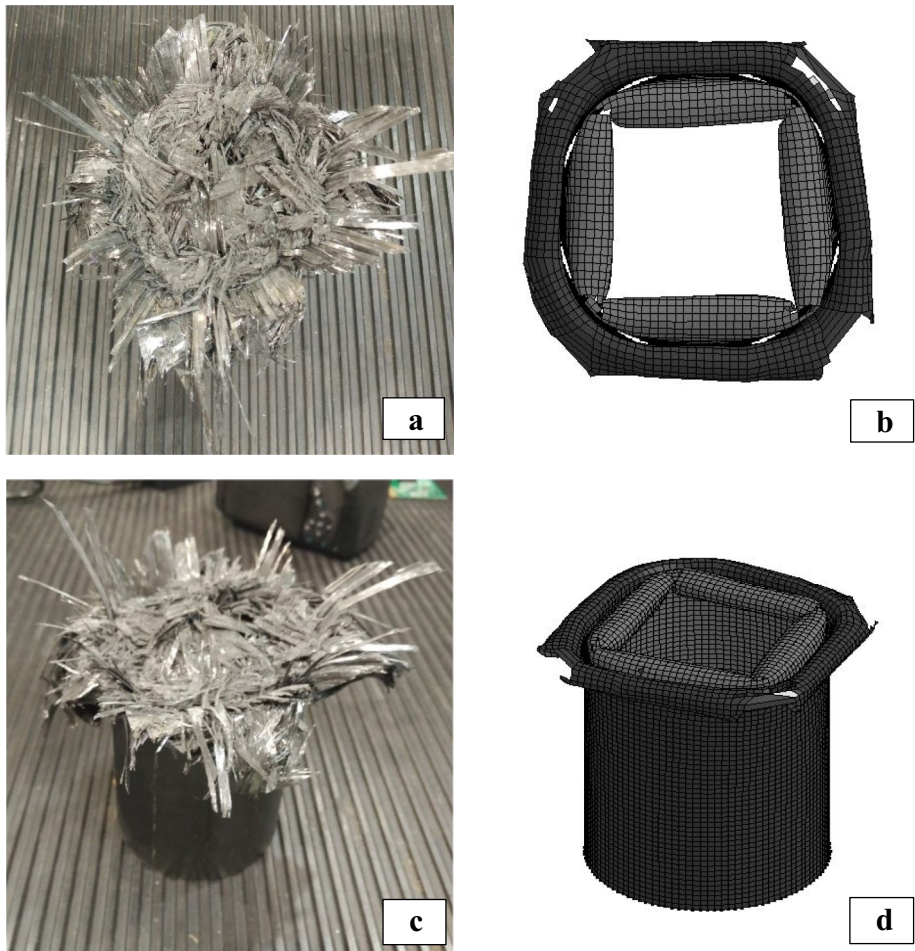
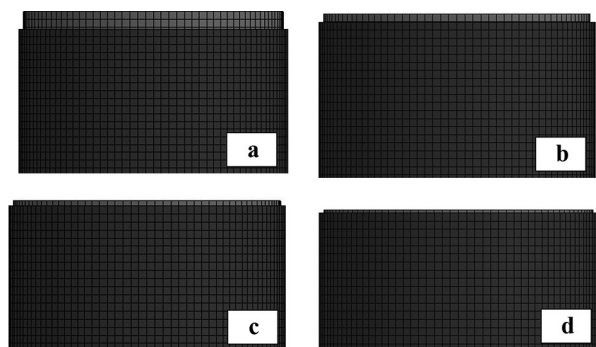


Fig. 14 4T60 specimen. Comparison between macroscopic experimental (top view (a), overview (c)) and numerical results (top view (b), overview (d))

Fig. 15 Bevel tube models. Side view. B15 (a), B30 (b), B45 (c) and B60 (d)



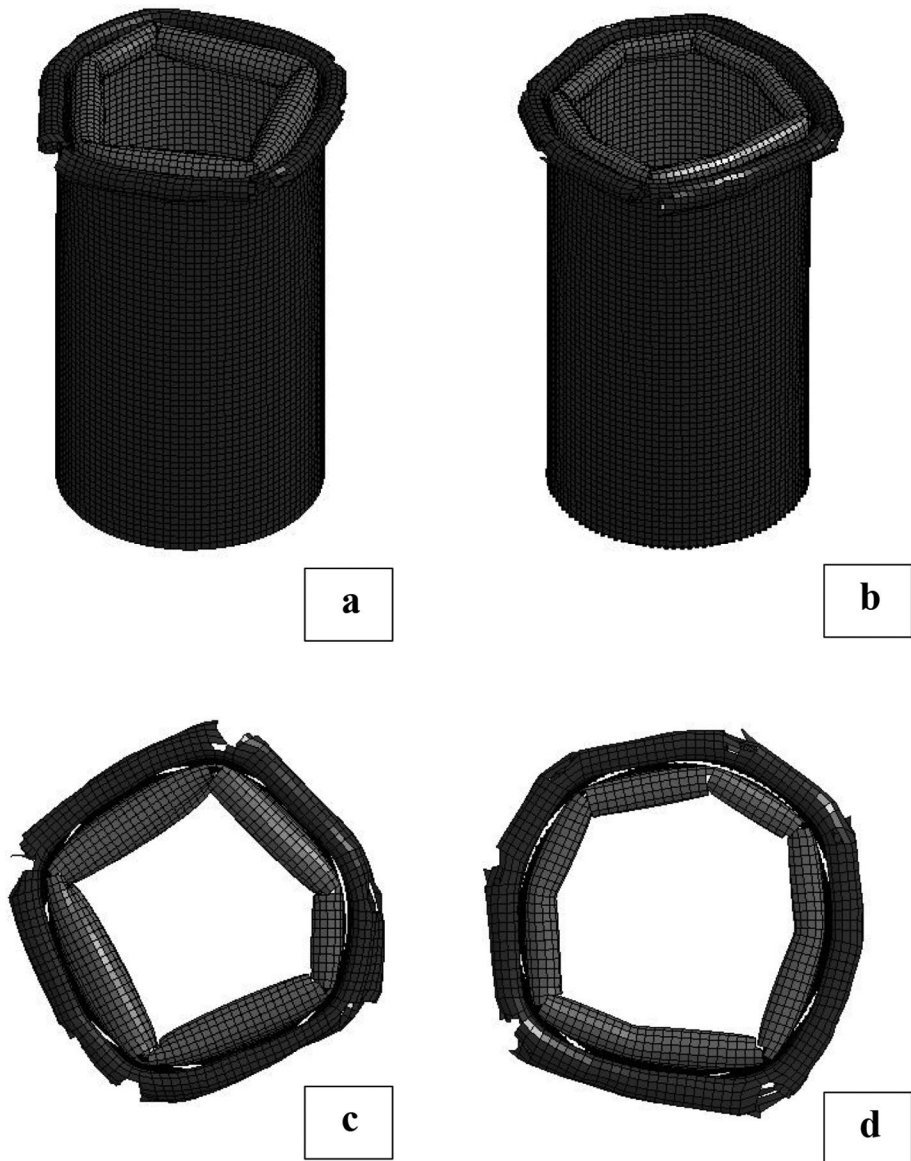


Fig. 16 Macroscopic results of B15 (overview (a) and top view (c)) and B45 (overview (b) and top view (d)) models

displacement. These two effects were the ones aimed in order to enhance performance of these triggered tubes. However, during crushing process, the outer tips torn off and folded inwards so results might be affected by this difference in the progressive crushing process (see Fig. 22).

Figure 21 shows the effect of the number of tips. The improvement is clear and can be observed in the shorter displacement, which is interpreted in a higher mean force.

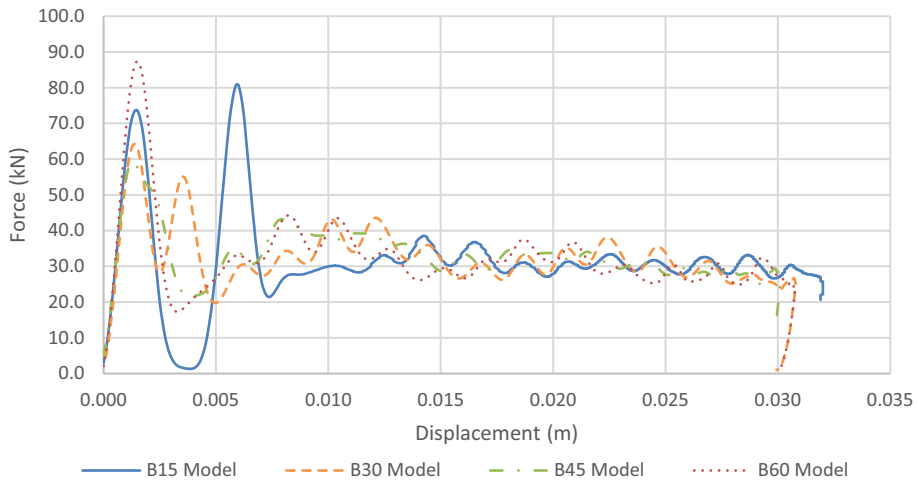


Fig. 17 Numerical comparison of Bevel trigger mechanisms

Table 4 Performance results of bevel trigger models

	Fmax (kN)	Fm (kN)	Disp. (mm)	SAE (kJ/kg)	CFE (%)	CE (%)
B15 Model	81	31	32	41	39	21
B30 Model	64	32	31	43	51	21
B45 Model	59	33	31	44	56	20
B60 Model	87	33	31	43	37	21

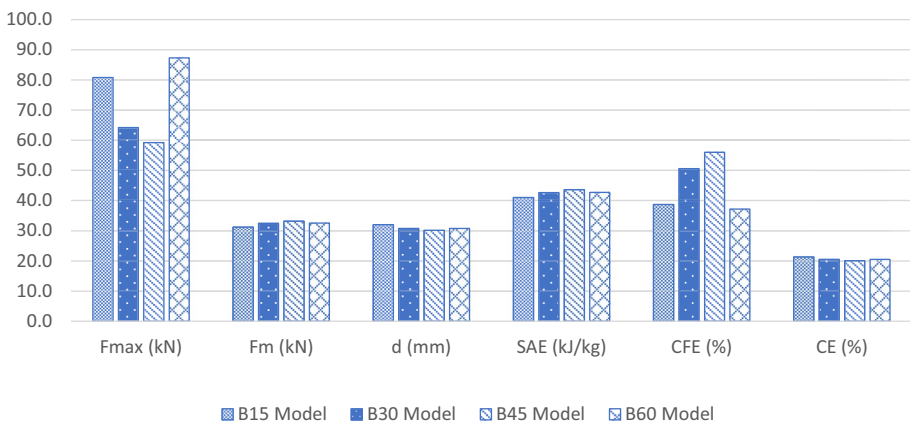


Fig. 18 Comparison of the results of bevel trigger models

The curve depicts that there is a small effect on the loading stage; therefore, the impact of the number of tips is mainly reflected in the anticipation of the tubes full section crushing process. Also, Fig. 22 demonstrates that the tube failed in a very stable way,

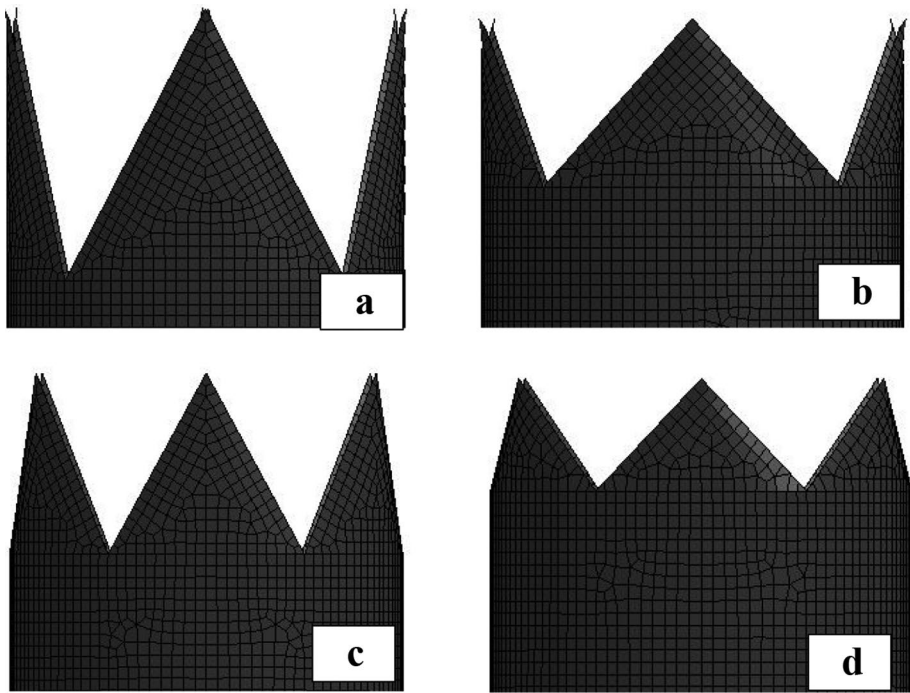


Fig. 19 Tulip tube models. Side view. 4T60 (a), 4T90 (b), 6T60 (c) and 6T90 (d)

which caused the most rounded and symmetrical post-failure section. This can reveal that increasing the number of tips produces an improvement in the stability of the failure.

The results from the 6T90 model confirm that the effect of increasing the number of tips affects mainly to the tube's full-section crushing starting point and not to the slope at

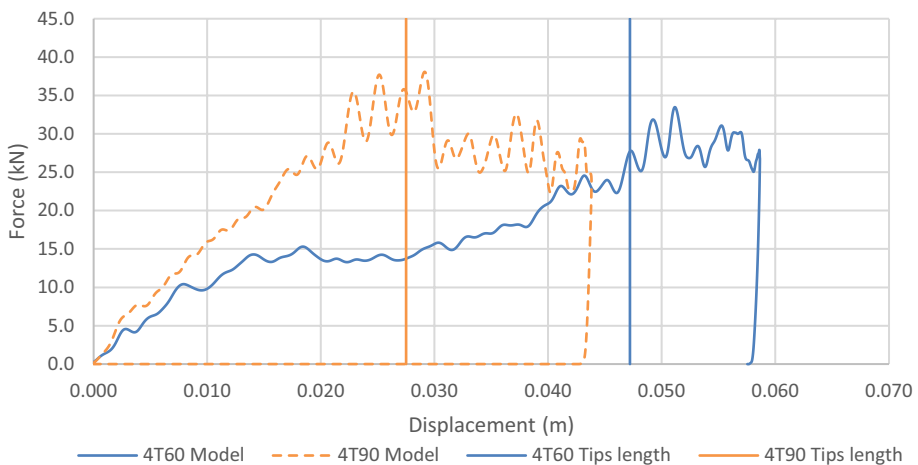


Fig. 20 Force–displacement responses of 4T60 and 4T90 models – Tulip angle effect

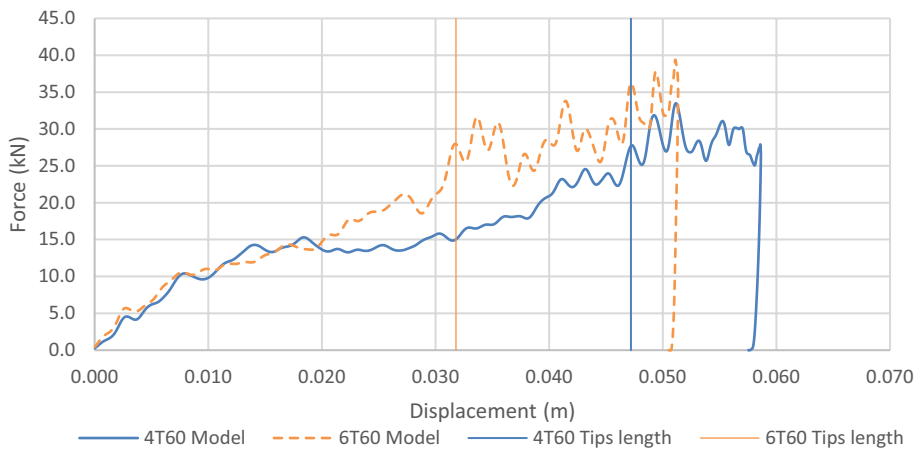


Fig. 21 Effect of tip numbers on force–displacement responses of 6T60 and 6T60 models

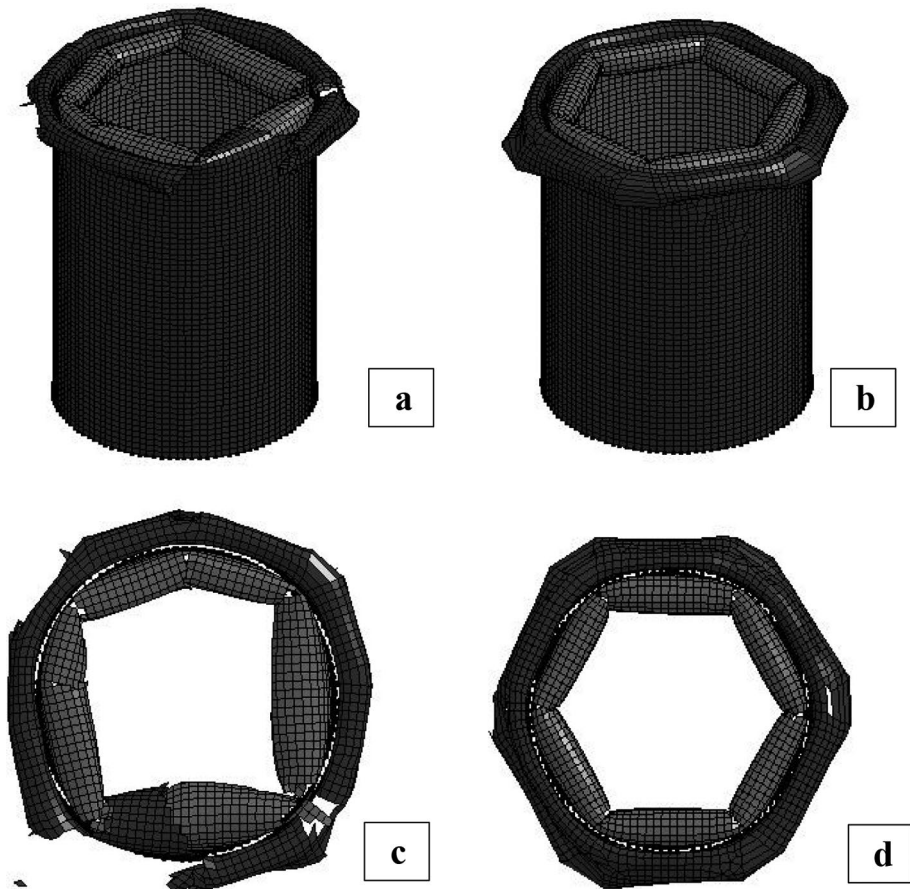


Fig. 22 Macroscopic results of 4T90 (overview (a) and top view (c)) and 6T60 (overview (b) and top view (d)) models

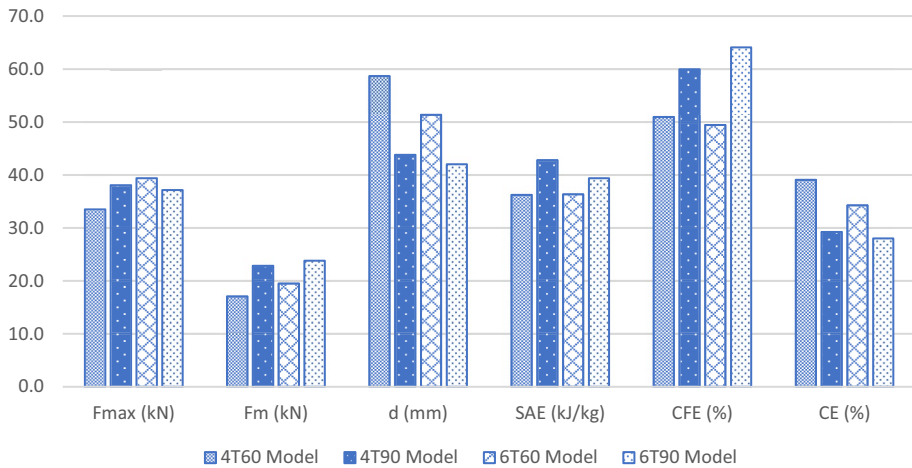


Fig. 23 Performance comparison of the tulip trigger mechanisms

the loading stage. The post-failure shape is shown in Fig. 25 and it is confirmed that the failure becomes more stable when the number of tips increases. The performance parameters of all the tulip models are collected in Fig. 23 and Table 5. For the comparisons, the baseline model 4T60 has been used as a reference. It is important to remark that, since the 4T90 design involved a certain failure instability, results might be affected and were not considered as comparable for the analysis. Therefore, the angle effect was assessed through the models 6T60 and 6T90 whereas the number of tips effect was analysed using the models 4T60 and 6T60. The performance parameters confirmed that enlarging the tip angle produces higher benefits than increasing the number of tips in the tube. In this regard, the increase of angle provides a 22% increase in mean force whereas this improvement is 14% due to the increase of tip numbers. The SEA is only sensitive to the tip angle, which represents an increase of 8.5% from 6T60 to 6T90 model.

Overall, numerical results showed that the 6T90 configuration effectively produced an improvement of crashworthy parameters compared to all previous tulip tubes. This solution leads to a SEA of 39 kJ/kg, close the results exhibited from the bevelled triggers, 43 kJ/kg, but bringing the soft loading benefit and producing an improvement of 8.8% compared to the baseline, 4T60 tulip model (Fig. 24). Moreover, 4T90 model showed certain instability leading to tearing of one of the tips while 6T90 presented a rounded and symmetrical crushed shape (see Figs. 22 and 25).

Table 5 Performance results of Tulip trigger models

	Fmax (kN)	Fm (kN)	Disp. (mm)	SAE (kJ/kg)	CFE (%)	CE (%)
4T60 Model	34	17	58	36	51	39
4T90 Model	38	23	44	43	60	29
6T60 Model	39	20	51	36	49	34
6T90 Model	37	24	42	39	64	28

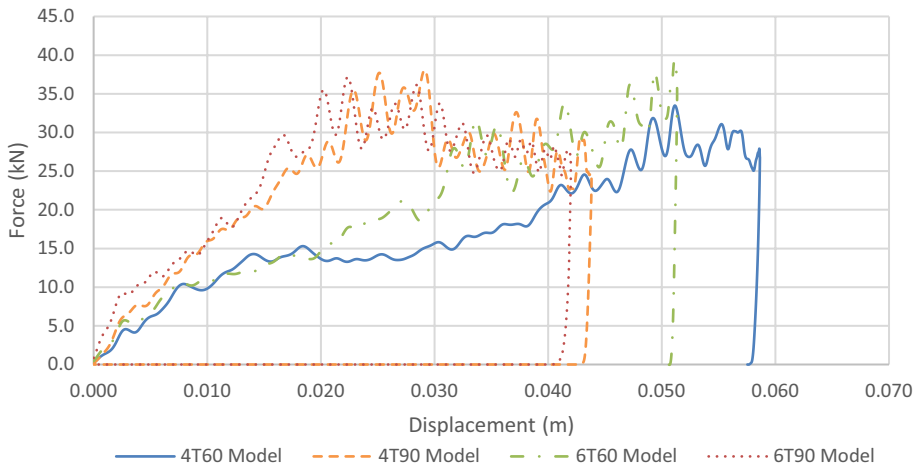
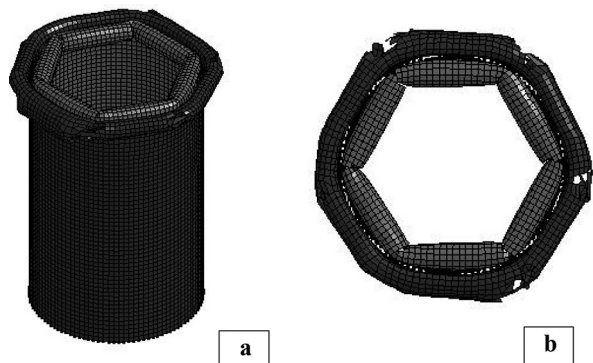


Fig. 24 Comparison of force–displacement of tulip trigger mechanisms

Fig. 25 Numerical results of 6T90 model **a** overview and **b** top view



5 Conclusions

All the results provided in Fig. 26 give an overview of the main differences between the bevel and tulip trigger mechanisms. Our results show that, in some cases bevelled tubes produced peak loads double in value compared to tulip type tubes. Also, despite all crushing forces were similar, tulip tubes decreased the mean crushing force for 36% compared to the bevel trigger models, which is remarkably resulted in higher values of displacement for the tulip ended tubes. Both the CFE and SE are higher for the tulip triggers whereas the SEA from the bevels and particularly at 45° showed the highest values in all cases in this paper. Finally, Fig. 27 includes all the force–displacement responses, which are obtained from numerical study. The developed tulip trigger mechanisms indicated a significant change of crushing force history, which results in improvement of crashworthiness parameters. Among these, it was seen how increasing the tips angle is more effective than increasing the number of tips in order to enhance the crushing mean force. However, tubes with a larger amount of tips failed in a more stable way. Therefore, a solution combining these two upgrades was proposed as an optimum solution with a SAE close to the bevel tubes and the benefit of avoiding high initial peak loads during a crash event.

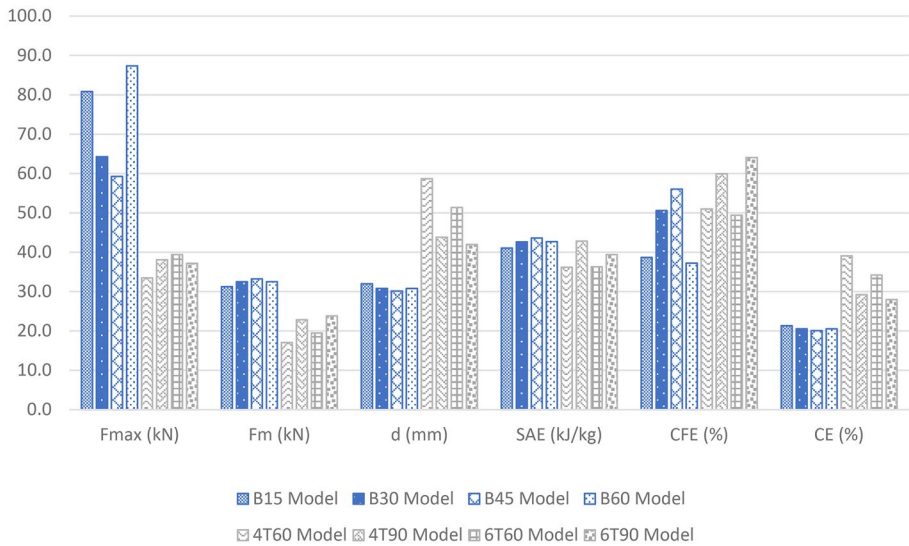


Fig. 26 Overall numerical results comparison of all trigger mechanisms

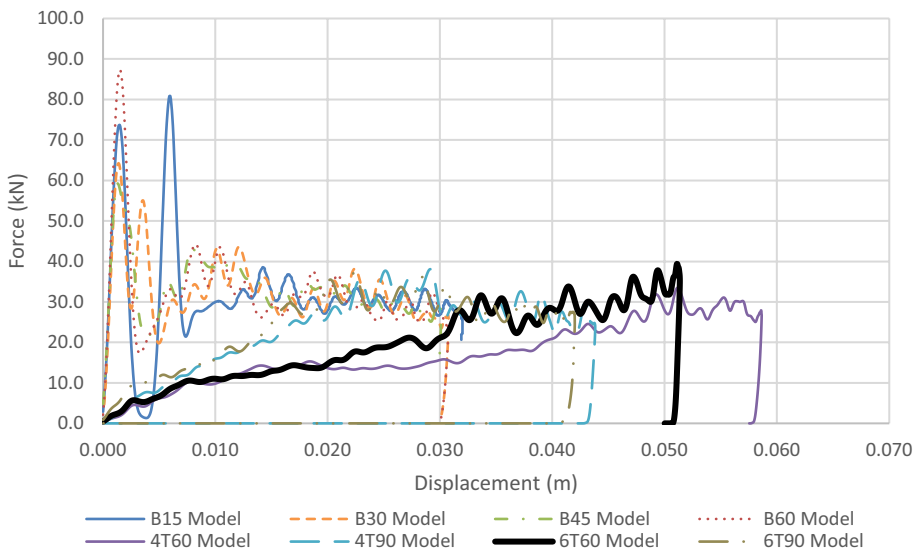


Fig. 27 Overall numerical comparison of all trigger mechanisms

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Data Availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Submission of this article implies that the work described has not been published previously, that it is not under consideration for publication elsewhere.

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References

1. Mamalis, A.G., Manolacos, D.E., Demosthenous, G.A., Ioannidis, M.B.: *Crashworthiness of Composite Thin-Walled Structural Components*, 1st edn. Technomic Publishing Co., Inc., Lancaster (1998)
2. Hull, D.: A Unified Approach to Progressive Crushing of Fiber-Reinforced Composite Tubes. *Compos. Sci. Technol.* **40**(4), 377–421 (1991). [https://doi.org/10.1016/0266-3538\(91\)90031-J](https://doi.org/10.1016/0266-3538(91)90031-J)
3. Farley, G.L., Jones, R.M.: Crushing Characteristics of Continuous Fiber-Reinforced Composite Tubes. *J. Compos. Mater.* **26**(1), 37–50 (1992). <https://doi.org/10.1177/002199839202600103>
4. Rabiee, A., Ghasemnejad, H.: Progressive Crushing of Polymer Matrix Composite Tubular Structures: Review. *Open. J. Compos. Mater.* **7**(1), 14–48 (2017). <https://doi.org/10.4236/ojcm.2017.71002>
5. Barbero, E.J.: *Introduction to Composite Materials Design*, 2nd edn. CRC Press, Boca Raton, FL (2011)
6. Hosseini, S.M., Shariati, M.: Experimental analysis of energy absorption capability of thin-walled composite cylindrical shells by quasi-static axial crushing test. *Thin-Walled. Struct.* **125**, 259–268 (2018). <https://doi.org/10.1016/j.tws.2018.01.026>
7. Chiu, L.N.S., Falzon, B.G., Boman, R., Chen, B., Yan, W.: Finite element modelling of composite structures under crushing load. *Compos. Struct.* **131**, 215–228 (2015). <https://doi.org/10.1016/j.compstruct.2015.05.008>
8. Yan, L., Chouw, N.: Crashworthiness characteristics of flax fibre reinforced epoxy tubes for energy absorption application. *Mater. Des.* **51**, 629–640 (2013). <https://doi.org/10.1016/j.matdes.2013.04.014>
9. Athapreyangkul, A., Gangadhara, P.B.: Experimental and numerical analysis on the geometrical parameters towards the maximum SEA of CFRP components. *Compos. Struct.* **164**, 229–236 (2017). <https://doi.org/10.1016/j.compstruct.2016.12.078>
10. Farley, G.L.: Energy Absorption of Composite Materials. *J. Compos. Mater.* **17**, 267–279 (1983). <https://doi.org/10.1177/002199838301700307>
11. Zhang, Z., Sun, W., Zhao, Y., Hou, S.: Crashworthiness of different composite tubes by experiments and simulations. *Compos. B.* **143**, 86–95 (2018). <https://doi.org/10.1016/j.compositesb.2018.01.021>
12. Palanivelu, S., Van Paepegem, W., Degrieck, J., Kakogiannis, D., Van Ackeren, J., Van Hemelrijck, D., et al.: Comparative study of the quasi-static energy absorption of small-scale composite tubes with different geometrical shapes for use in sacrificial cladding structures. *Compos. Struct.* **29**, 1–22 (2010). <https://doi.org/10.1016/j.polymertesting.2010.01.003>
13. Jiménez, M.A., Miravete, A., Larrodé, E., Revuelta, D.: Effect of trigger geometry on energy absorption in composite profiles. *Compos. Struct.* **48**(1), 107–111 (2000). [https://doi.org/10.1016/S0263-8223\(99\)00081-1](https://doi.org/10.1016/S0263-8223(99)00081-1)
14. Ghasemnejad, H., Blackman, B.R.K., Hadavinia, H., Sudall, B.: Experimental studies on fracture characterisation and energy absorption of GFRP composite box structures. *Compos. Struct.* **88**(2), 253–261 (2008). <https://doi.org/10.1016/j.compstruct.2008.04.006>
15. Rehan, M.S.B.M., Rousseau, J., Fontaine, S., Gong, X.J.: Experimental study of the influence of ply orientation on DCB mode-I delamination behavior by using multidirectional fully isotropic carbon/epoxy laminates. *Compos. Struct.* **161**, 1–7 (2017). <https://doi.org/10.1016/j.compstruct.2016.11.036>
16. Tao, J., Sun, C.T.: Influence of ply orientation on delamination in composite laminates. *J. Compos. Mater.* **32**, 1933–1947 (1998). <https://doi.org/10.1177/002199839803202103>

17. Ghasemnejad, H., Hadavinia, H., Aboutorabi, A.: Effect of delamination failure in crashworthiness analysis of hybrid composite box structures. *Mater. Des.* **31**(3), 1105–1116 (2010). <https://doi.org/10.1016/j.matdes.2009.09.043>
18. Warrior, N.A., Turner, T.A., Robitaille, F., Rudd, C.D.: The effect of interlaminar toughening strategies on the energy absorption of composite tubes. *Compos. A Appl. Sci. Manuf.* **35**(4), 431–437 (2004). <https://doi.org/10.1016/j.compositesa.2003.11.001>
19. Rabiee, A., Ghasemnejad, H.: Effect of multi stitched locations on high speed crushing of composite tubular structures. *Compos. B. Eng.* **100**, 164–175 (2016). <https://doi.org/10.1016/j.compositesb.2016.06.068>
20. Czaplicki, M.J., Robertson, R.E., Thornton, P.H.: Comparison of bevel and tulip triggered pultruded tubes for energy absorption. *Compos. Sci. Technol.* **40**(1), 31–46 (1991). [https://doi.org/10.1016/0266-3538\(91\)90041-M](https://doi.org/10.1016/0266-3538(91)90041-M)
21. Palanivelu, S., Van Paepegem, W., Degrieck, J., Van Ackeren, J., Kakogiannis, D., Van Hemelrijck, D., et al.: Experimental study on the axial crushing behaviour of pultruded composite tubes. *Polym. Testing*. **29**(2), 224–234 (2009). <https://doi.org/10.1016/j.polymertesting.2009.11.005>
22. Sivagurunathan, R., Lau Tze Way, S., Sivagurunathan, L., Yaakob, M.Y.: The Effects of Triggering Mechanisms on the Energy Absorption Capability of Circular Jute/Epoxy Composite Tubes under Quasi-Static Axial Loading. *Appl. Compos. Mater.* **25**, 1401–1417 (2018). <https://doi.org/10.1007/s10443-018-9673-5>
23. Tong, Y., Xu, Y., Wang, J., Suman, B.: Energy absorption capability of carbon fiber reinforced plastic tubes with semi-circle grooved external trigger. *J. Reinf. Plast. Compos.* **35**(20), 1460–1476 (2016). <https://doi.org/10.1177/0731684416654579>
24. Huang, J., Wang, X.: On a new crush trigger for energy absorption of composite tubes. *Int. J. Crashworthiness*. **15**(6), 625–634 (2010). <https://doi.org/10.1080/13588265.2010.484194>
25. Huang, J.C., Wang, X.W.: Effect of the SMA trigger on the energy absorption characteristics of CFRP circular tubes. *J. Compos. Mater.* **44**(5), 639–651 (2010). <https://doi.org/10.1177/0021998309347572>
29. Rabiee, A., Ghasemnejad, H.: Laminate Tailoring of Composite Tubular Structures to Improve Crashworthiness Design at Off-Axis Loading. *Open. J. Compos. Mater.* **08**(03), 84–109 (2018). <https://doi.org/10.4236/ojcm.2018.83008>

Further Reading

26. Hussain, N.N., Prakash, S., Daseswara, Y.V.: Comparative Study of Trigger Configuration for Enhancement of Crashworthiness of Automobile Crash Box Subjected to Axial Impact Loading. *Procedia. Eng.* **173**, 1390–1398 (2017). <https://doi.org/10.1016/j.proeng.2016.12.198>
27. Bisagni, C., Di Pietro, G., Frascini, L., Terletti, D.: Progressive crushing of fiber-reinforced composite structural components of a Formula One racing car. *Compos. Struct.* **68**(4), 491–503 (2005). <https://doi.org/10.1016/j.compstruct.2004.04.015>
28. Obradovic, J., Boria, S., Belingardi, G.: Lightweight design and crash analysis of composite frontal impact energy absorbing structures. *Compos. Struct.* **94**(2), 423–430 (2012). <https://doi.org/10.1016/j.compstruct.2011.08.005>

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