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NOVEL CFRP CRASH BOXES WITH HIGH ABSORPTION GEOMETRY REINFORCED WITH NANO GRAPHENE OXIDE

NOVI CFRP ODBOJNICI OJAČANI NANO GRAFEN OKSIDOM SA GEOMETRIJOM ZA VELIKE APSORPCIJE

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Keywords
- novel CFRP crash boxes
- nano graphene oxide (nGO)
- energy absorption
- buckling
- epoxy

Ključne reči
- novi CFRP odbojnici
- nano grafen oksid (nGO)
- apsorpcija energije
- izvijanje
- epoksi smola

Abstract

Due to the ever-increasing fuel cost, environmentally incompatible growth of Green House Gases (GHG) emissions, and evolving, progressively stringent environmental and safety regulations, the lightweight design of vehicle structures has attracted many researchers. The crash box is prepared with six layers of carbon fibre in 0-90, 45 orientation, with different nano graphene oxide (nGO) contents and two different fillets. The experimental procedure is completed, and the results show that geometry and nanostructure are measured as critical parameters, allowing us to understand the design weaknesses and reconsider or enhance the current concept. Also, the results find that the nGO has a significant impact on reinforcing the structures. Adding and reinforcing the carbon fibre plus epoxy with nGO, compared to the neat sample, improves the strength of the structure. Adding 0.1 % nGO to the epoxy fills the crystalline gaps and creates a great bonding structure with epoxy and carbon fibre. This property would cover the micro-cracks made during manufacture, cutting, or other machinery processes.

Izvod

Usled stalno rastućih cena goriva, ekološki nekompatibilnog porasta emisije gasova staklene bašte (GHG), kao i evoluirajućih, striktnih ekoloških i bezbednosnih propisa, dizajn lakih konstrukcija vozila privlači mnoge istraživače. Odbojnik je pripremljen sa šest slojeva ugljeničnih vlakana orijentacije 0-90, 45, sa različitim sastavom nano grafen oksida (nGO) i sa dva različite ispune. Izvedeni su eksperimenti i dobijeni rezultati pokazuju da su geometrija i nanostruktura ocenjeni kao kritični parametri, koji nam omogućavaju razumevanje manjkavosti u projektovanju, kao i ponovljeno razmatranje ili poboljšavanje tekućeg koncepta. Rezultati takođe pokazuju da nGO ima značajnog uticaja u ojačavanju konstrukcija. Dodavanjem i ojačavanjem ugljeničnih vlakana i epoksi smole sa nGO, u poređenju sa neojačanim uzorcima, postiže se veća čvrstoća konstrukcije. Dodavanjem 0,1 % nGO u epoksi smolu se popunjavaju šupljine u strukturi i formira se jača vezujuća struktura sa epoksi smolom i ugljeničnim vlaknima. Ovom ulogom nGO se pokrivaju mikroprsline nastale u toku proizvodnje, rezanjem, ili nekim od postupaka mašinske obrade.

INTRODUCTION

Due to ever-increasing fuel costs, environmentally incompatible growth of Green House Gas (GHG) emissions, and evolving, progressively stringent environmental and safety regulations, the lightweight design of vehicle structures has attracted many researchers. The open literature states that lightweight vehicle structures can be achieved through structural optimisation, advanced lightweight manufacturing technologies, and material replacement /1-3/. Structural optimisation can be classified into three groups: size, shape, and topology optimisation. The choice of optimisation method for each particular case in the automotive industry depends on the desired target for the subsystem that is supposed to be re-engineered: passive safety, static and dynamic stiffness, weight reduction, acoustic and riding comfort, service life, and serviceability /1/. Research shows that structural optimisation can give up to 7 % weight reduction and improve vehicle efficiency.

On the other hand, the advanced manufacturing process is gaining significant acceptance in the automotive sector in trimming the vehicle weight /4/. For instance, Ford Motor Co. has used an advanced forming technology known as hydroforming on the structural steel pillars of its 2013 Fusion body. The process cuts 18 pounds from each car /5/. General Motors (GM) has used resistance spot welding. Further, it reduces the weight of an already lightweight aluminium structure, thus eliminating the use of many rivets, which can cut up to 2 pounds in each hood, rear lift gets, and door /5/. However, the material replacement approach is the most effective way to achieve a lightweight vehicle structure. Material replacement, such as with an entire aluminium body, can lead to a weight reduction of up to 50 %. The ideal candidate materials are fibre-reinforced if further weight reduction is needed. Besides relevant weight reduction, fibre-reinforced materials have good corrosion resistance, impact cushion, and noise attenuation, allowing for relevant part consolidation /4, 6/. Vehicle crashworthiness can contribute to solving some of the occupant and pedestrian safety issues. Reports show that vehicle crashworthiness has improved significantly during the past three decades, as indicated, for example, by the reduction in the occupant death rate per million vehicle registrations of 1-3-year-old cars from 265 in 1979 to 98 in 2007. Despite these improvements, 28,869 vehicle occupants were killed in road crashes in the United States in 2007. Frontal crashes accounted for half of these fatal events even though new cars have mandatorily passed the frontal crash tests /7/. To mitigate this persistent problem, the design of the frontal crumple zone has played a significant role by managing crash energy, absorbing it within the frontal parts of the vehicle structure, and carefully avoiding its direct transfer to the vehicle occupants, the intrusion into, or the damage of the passenger compartment. In this regard, the bumper subsystem is one of the critical design spaces to tune the performance of the crumble zone /4, 8, 9/.

Vehicles are used extensively, and a large number of horrible accidents related to them occur widely. Increasing the safety of passengers is a valuable aim, and many investigations are carried out in this region /10, 11/. Using energy absorbers is an appropriate option for this purpose. These parts have different shapes and are made from low-density materials. In designing these parts, it is necessary to investigate their collapse behaviour and energy absorption capacity. Many studies have been done about these structures, especially thin-walled tubes. A thin-walled beam collapsing plastically in axial compression is considered one of the most efficient means of energy absorption /12, 13/. These tubes are light in volume and weight, easy to fabricate and cheap, and stable during crushing. Crashworthiness studies devote a great deal of attention to the behaviour of thin-walled structures which have been widely used as load-bearing structures and energy absorbers. One type of energy absorber is the crash box or crush tube, or energy absorbing beam connected to the bumpers and situated in the front and rear end of the body structure /14-17/. Figure 1 shows the crash box and bumper. The crash box is designed to absorb energy at low-speed impacts. Researchers and car manufacturers have implemented different types of composite materials, such as carbon fibre-reinforced plastic (CFRP), for the bumper beam to improve the bumper subsystem performance as it offers lightweight and reduces energy consumption /16, 18, 19/. After the development of SMC, mainly by Bayer AG, Germany, during the early 1960s, several automotive manufacturers showed their interest because this technology allowed composite materials to be manufactured in mass production for the first time. GM implemented the SMC bumper beam in Pontiac Bonneville, Cadillac Seville, and Cadillac Eldorado by replacing the conventional steel material.

On the other hand, it would be pretty easy to imagine how the level of complexity and the flow of the manufacturing process would change when composite materials are involved in lightweight vehicle structures /20/. A comprehensive literature is available regarding the energy absorption mechanisms of fibre-reinforced composite material tubes subjected to axial loading, and the failure mechanism is reasonably well understood and documented. In general, for axially loaded composite beams, the energy absorption is due to the concurrence of different failure mechanisms. These mechanisms include wall delamination, delamination penetration with axial crack formation, and petals bending followed by fibre fracture. These fibre fractures give place to fracture line formation across the tube wall. On the contrary, the energy absorption mechanisms for composite material tubes subjected to transverse loading, i.e., in bending and shear, which are usual loading conditions for bumper beams, have not been extensively investigated yet and the failure mechanism is not completely understood, on the other hand, when the material is subjected to any type of loading, failure starts at the point where there is a maximum stress concentration /16, 19, 21/. Therefore, we assume that introducing longitudinal stress concentration zones will lead to localised failure initiation followed by progressive failure development and collapse /22, 23/. The beam is thin-walled, and different section profiles are being considered. By introducing several adequately positioned stress concentration zones (longitudinal grooves), progressive tearing lines are generated, resulting in the expected progressive energy absorption /8/.

MATERIALS AND FABRICATION

Materials

The epoxy resin utilised in this study is EPR1080. Its epoxide equivalent weight is 185-192 g/eqiv, provided by Shell Chemicals Co. The curing agent is a nominally Aradur® 2973 supplied by Huntsman Co. nGO contents used in this study as nano reinforcement in the epoxy matrix are purchased from the Institute of Petroleum Industry (RIPI) of Iran with an outer diameter of 10-15 nm, purity of more than 95 % and maximum length of < 30 nm. The solvent is Tetrahydrofuran (THF) with purity (GC) of more than 99 % provided by Merck Co. (Germany). Carbon fibres are purchased from Toray Company.

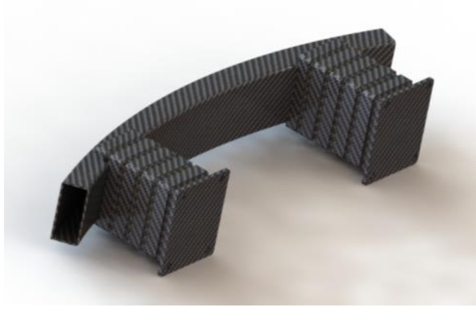


Figure 1. Bumper and crash box.

Fabrication

The crash box is prepared with six layers in 0-90, 45 orientation of carbon fibre and with different nano nGO contents and two different fillets according to Table 1 and Fig. 2. All specimens are prepared based on the vacuum resin transfer moulding method (VARTM). The resin is cured by Aradur® 2973 as the solvent for all mixture components. In order to prepare each sample, different contents of nGO are added to cured resin (see Table 1). The material is mixed well using a magnetic stirrer for at least two hours with 2000 rpm. The mixed matrix is set into the homogeniser ultrasonic device (ultrasonic SONOPLUS-HD3200 with 50 % amplitude, 20 kHz, and pulsation; On for 10 s and Off for 3 s). The process lasts eight minutes to the dispersion of the nGO particles into the epoxy matrix. In the next step, all prepared matrices are moulded into 6 carbon fibres, as shown in Fig. 2. All specimens are kept at room temperature for 24 hours. Then for final solidification, samples are post-cured in a hot oven at 80, 150, and 200 °C, respectively, each for 2 hours.

Table 1. Material design.

Sample No.	Fibre orientation (°)	Radius fillet (cm)	nGO content (wt.%)
1	0	5	0
2	0	10	0
3	0	5	0.1
4	0	10	0.1
5	0	5	0.25
6	0	10	0.25
7	0	5	0.5
8	0	10	0.5
7	0	5	0.75
8	0	10	0.75

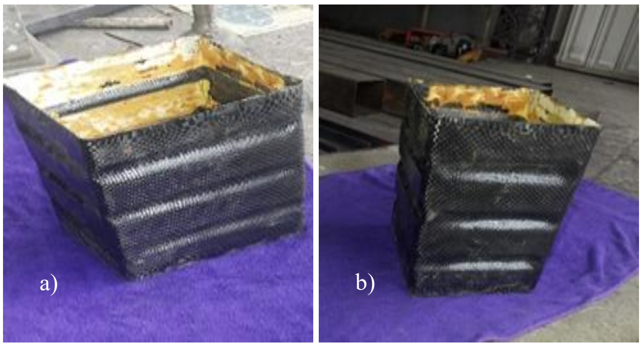


Figure 2. Two types of fillets: a) -2; b) -3 for manufactured crash box.

RESULT AND DISCUSSION

Compressive result for CFRP crash box

The experimental procedure is completed considering the effect of experimental and manufacturing parameters. The result shows that geometry and nanostructure are measured as critical parameters, allowing us to understand the design weaknesses and reconsider or enhance the current concept. Also, after surveying the test result we find the nGO has a significant impact on reinforcing the structure. As seen in Fig. 3, the effect of nGO is quite significant by adding and reinforcing carbon fibre plus epoxy with nGO. Compared to the neat sample the strength of the structure is improved. Adding 0.1 % nGO to the epoxy fills the crystalline gaps and creates a great bonding structure with epoxy and carbon fibre. This property covers the microcracks made during manufacture, cutting, or some other machinery process. The entire crash incident starts with two curves, the upper yield point and lower yield point, and the behaviour of these materials is obtained by analysing mentioned points. Micro and nanostructures of CFRP crash boxes can guarantee high durability and strain against crash incidents; also, high draw ability, good fatigue strength, and high energy absorption are noted as critical advantages of CFRP structures. As seen in Figs. 4 and 5, geometry in design plays an important role; for a 5 mm groove on the cubical structure, the ratios can be significant in crash box collapses, where the deformation of these materials is deeply dependent on shape modes. Cubical crash boxes can have pressure by unexpected or mean forces during the crash, during which initial compression undergoes elastic features in buckling loads; plastic features of materials can develop maximum forces to reach the highest values of strength. After that, in stable deformation mode, there is mostly energy absorption because the tube will continue to deform axially, creating microcracks and lobs that deform according to the mechanisms that will be discussed later. At this stage, called the permanent regime, the force developed by the cubical tube is a function of the formation of new lobs and cracks followed by the compaction of these. This force tends to vary less; the average force peaks between the

Figure 3. Delamination of crash box under a compressive test.

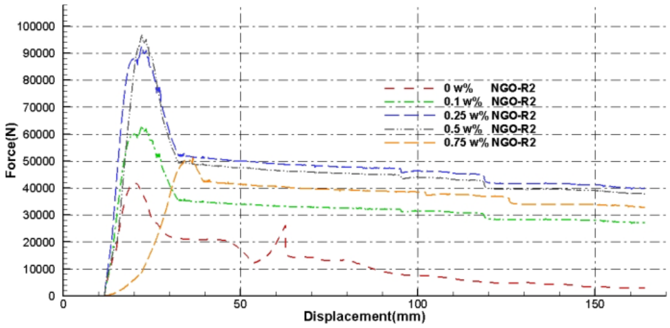


Figure 4. Compression test for crash box with 5 mm groove.

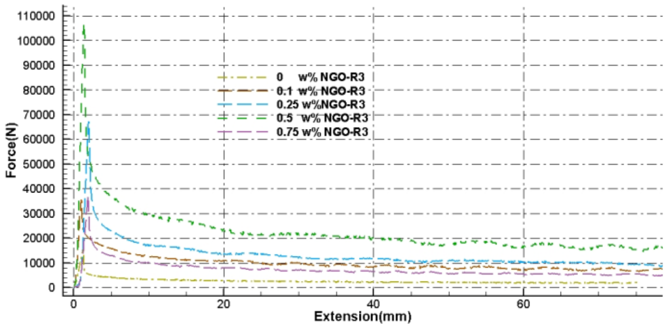


Figure 5. Compression test for crash box with 10 mm groove.

formation and compaction of a new lobe. The area below the curve is the energy absorbed that is easy to calculate by curve integral, so it is a valuable and quick tool for structural designers. Analysing other nGO contents would do better in understanding the nature of these materials. Adding more content of nGO, up to 0.5 wt.%, increases mechanical performances by 80 %, and the nGO completes the gaps in the crystal structure, creating a chain between matrix and fibre, consequently strengthening the entire structure. In the manufacture, some microcracks, gaps, and hollows can be created; nGOs fill these gaps and heal microcracks to make the whole structure more robust. nGO improves the energy absorption of the thin wall, changing the geometry and especially introducing geometric imperfections. So, it is easy to understand why impact and the crash bumper can harm and crush the crash boxes.

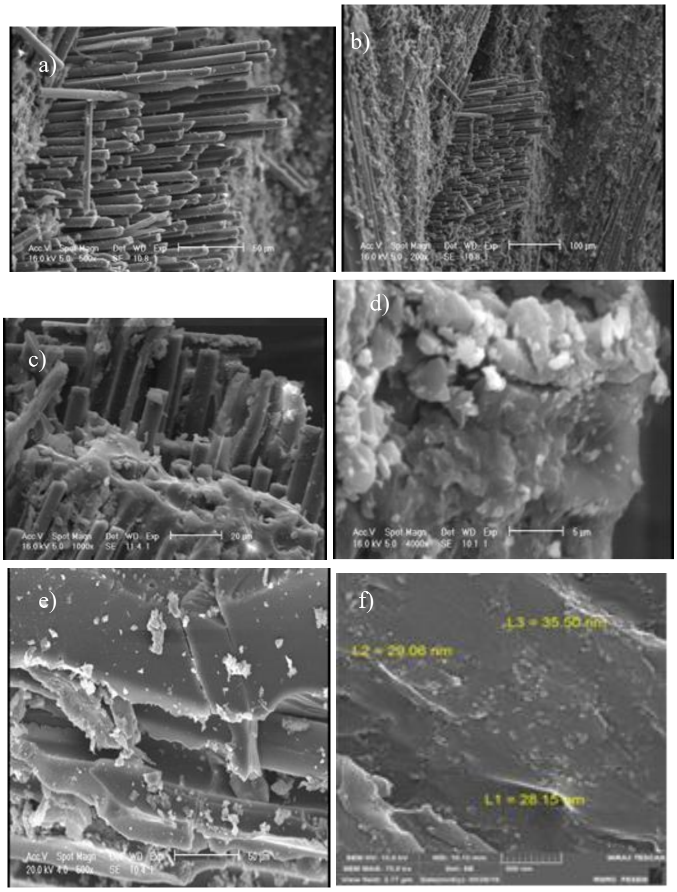


Figure 6. Crack growth mode shape and nGO in epoxy field: a), b) fibre delamination; c) fibre delamination and fracture form; d) nano graphene oxide and fracture form; e), f) fracture form and nGO distribution.

FEM VERIFICATION FOR IMPACT TEST

Impact analysis on crash box specimens

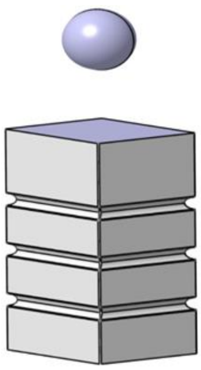


Figure 7 (right). Shape of bullets and crash box at speed of 40 m/s.

Geometry with Ansys® workbench software

The symmetry condition is used to simplify the problem and reduce the volume of processing calculations, and two pages of symmetry are defined. The calculation in the software is a quarter of fundamental geometry.

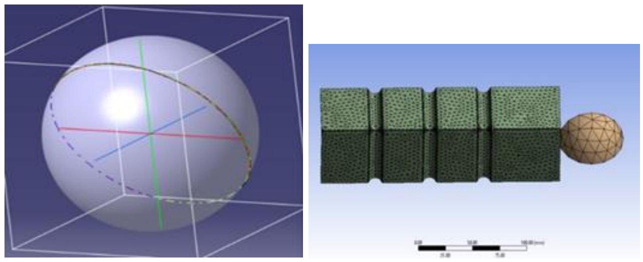


Figure 8. Geometry of cubic cross section crash structure. Bullet: d = 60 mm, 889 gr of steel is applied to the bullet.

First part: cubical crash box with aluminium material

The bullet hits the cross-section of the crash box with a constant velocity of 40 m/s; after the hit, the velocity drops to zero, then due to the elastic behaviour of this shape, 60 % of impact energy is absorbed, and the difference of impact reaction velocity is (40-15 = 25 m⁄s). The section profile is deeply impacted on tension distribution in three steps. In the first step, the number of grooves along the beam width can have an essential rule on tension distribution shape. Grooves are the primary crack initiation mechanism leading to transverse progressive tearing. In the analysis, the reaching force to each number of grooves continues until the strength of the beam begins to decrease, leading to direct impact of the rigid crash box and resulting in very high (not acceptable) load peaks. In this particular case, the acceptability limit is less than three grooves. We choose the last groove to understand the material behaviour as shown in Fig. 9. When material changes to CFRP, the impact on bumper beam behaviour changes from progressive to catastrophic failure, resulting in a high-peak reaction force. This implies that, at chosen impact velocity, the energy cannot be entirely absorbed by the beam, and the crash boxes and other nearby components must be involved in the energy absorption process.

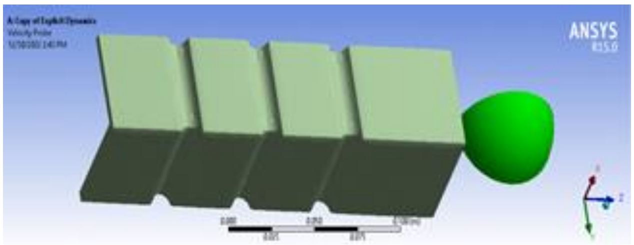


Figure 9. Analysis of the impact moment.

Impact result of cubical crash box with CFRP reinforced nGO

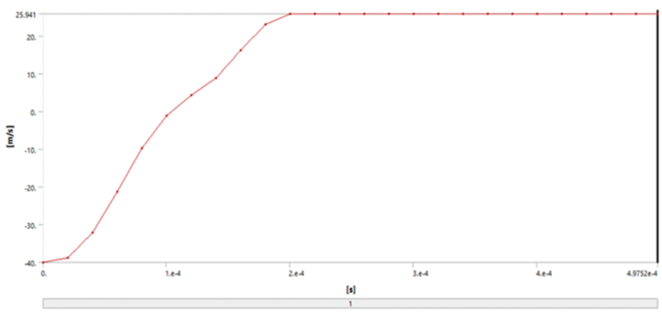


Figure 10. Diagramme of the impact moment analysis.

The zero moment is the moment of bullet collision. At this moment the bullet collides at 40 m/s with the crash box. Gradually, the speed of the bullet drops to zero and then returns at a speed of 26 m/s.

Second part: cylindrical crash box with aluminium material

The zero moment is the bullet collision instant. At this moment, the bullet collides at 40 m/s with the crash box. Gradually, the speed of the bullet drops to zero and then returns at a speed of 14 m/s. The absorbed energy is computed from the difference in velocity.

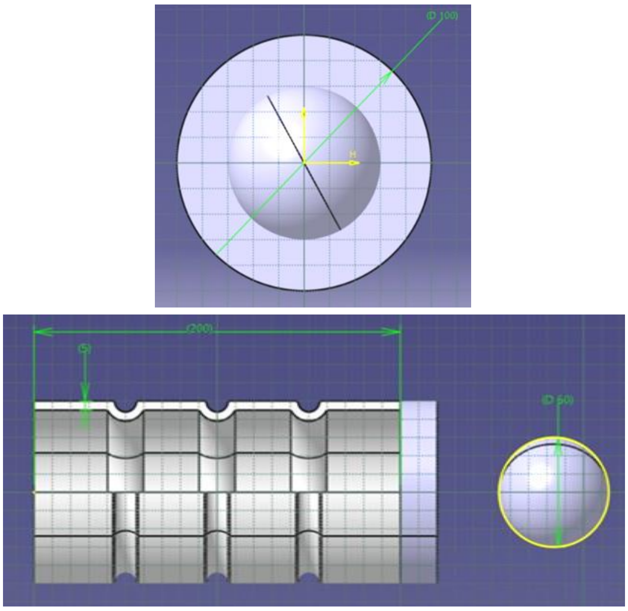


Figure 11. Geometry design of cylindrical crash box with 3 grooves.

In this analysis, a bullet of 889 g mass and chosen velocity of 40 m/s collides in all modes. absolute velocity can be calculated in different modes. From this point of view, the kinetic energy is under second order. The difference in absolute velocity value is under determination, and the difference in velocity vector must be included in further calculations.

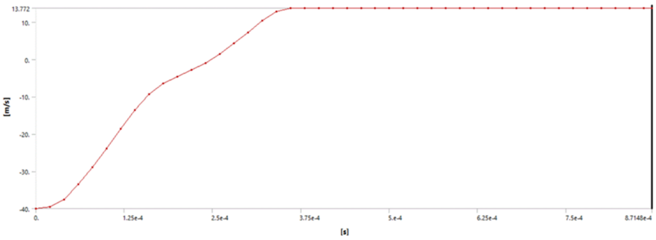


Figure 13. Bullet velocity in cylindrical aluminium crash box.

Cylindrical crash box with CFRP material

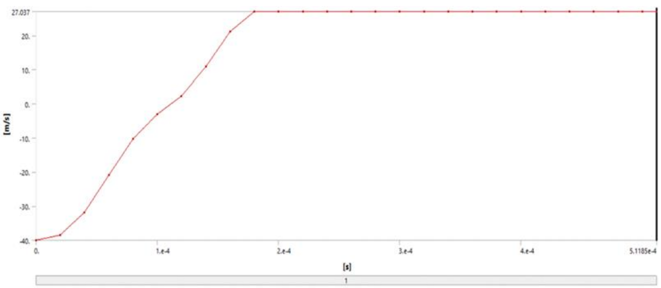


Figure 14. Bullet velocity in cylindrical CFRP material crash box.

Energy absorption in different modes

The higher the rate change, the more energy the crash box absorbs.

Crash box with cubical cross section with aluminium material: the change of bullet velocity is 25 m/s.

Crash box with cubical cross section with CFRP material: the change of bullet velocity is 14 m/s.

Crash box with cylindrical cross section with aluminium material: the change of bullet velocity is 26 m/s.

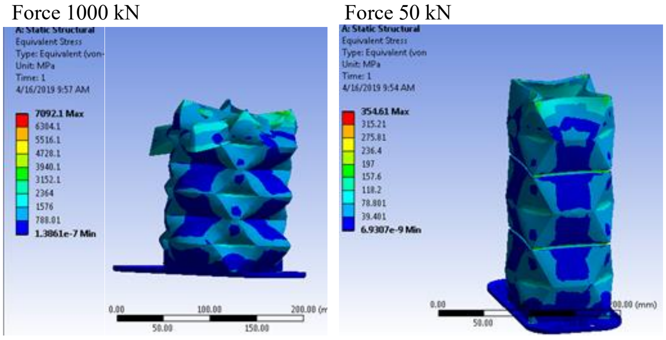
Crash box with cylindrical cross section with aluminium material: the change of bullet velocity is 13 m/s.

The two principal responses of the materials to external forces of interest for the present study are deformation and fracture. Depending on the material type, deformation may be elastic, visco-elastic (time-dependent elastic deformation), or elastoplastic. Eventually, with creep effect (time-dependent plastic deformation), strain-rate sensitivity (dependence on the loading velocity), and fracture may occur catastrophically or after repeated application of loads (fatigue). Material engineering characteristic parameters are the base input for numerical analyses. For isotropic materials, i.e., materials whose mechanical property does not depend on the particular loading direction, only three independent engineering constants (E, G, or ν, and α) are needed, sufficient to describe the elastic response of the material during loading. On the contrary, for advanced composite materials (i.e., materials having a directional dependant mechanical behaviour), more constants are needed to describe their elastic behaviour. For most composite materials, 12 engineering constants (E_1, E_2, E_3, G_{12}, G_{13}, G_{23}, ν_{12}, ν_{13}, ν_{23}, α_1, α_2, and α_3) are required for the elastic regime, where 1, 2, and 3 are the material axes. Measuring these values requires testing numerous samples with several different test procedures. These procedures are designed to generate a constant or nearly constant state of stress throughout the material, reducing the number of elastic constants needed to describe the deformation for the given loading condition to the smallest possible number. This is usually done by using simple geometries, usually planar samples, to measure 1-3 engineering constants simultaneously (as in the longitudinal modulus test - E_1, ν_{12}, and ν_{13} can be measured simultaneously). In an ideal situation, with the proper test matrix and procedures, all the material constants can be obtained, given enough tests and sample materials.

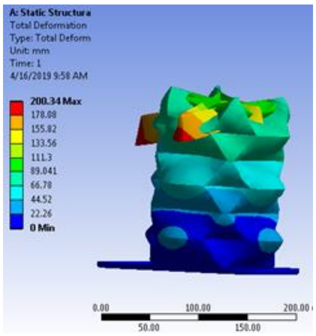
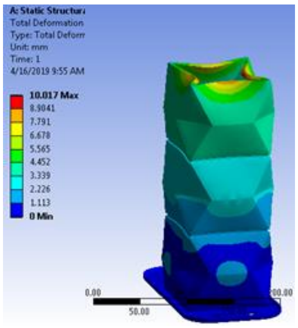
Comparing ideas in terms of energy, deformation, stress

Shape 1

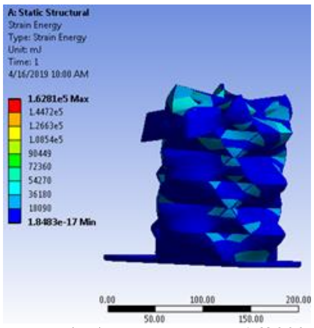
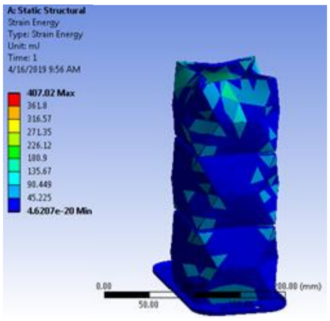
Force 1000 kN — Force 50 kN



stress (MPa) 7092 354

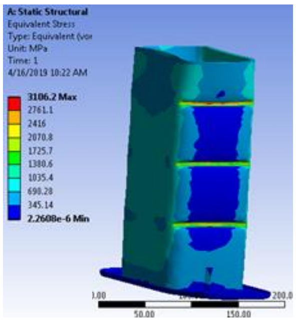
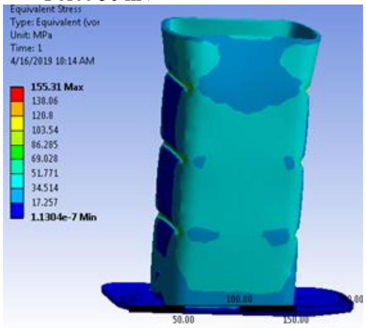
deformation (mm) 200 10

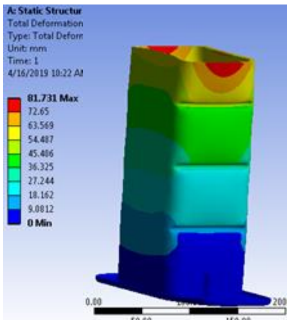
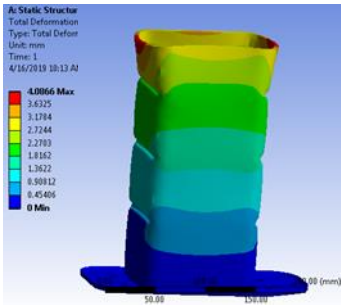
energy (mJ) 162000 407

Shape 2

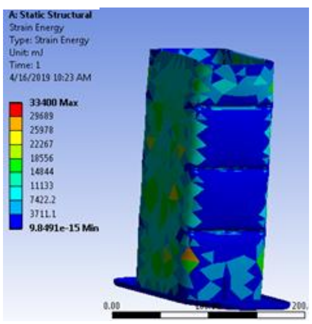
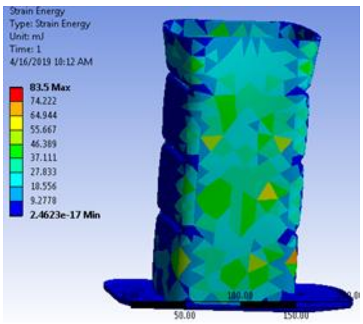
Force 1000 kN Force 50 kN

stress (MPa) 3107 155

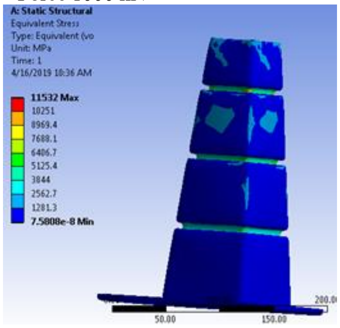
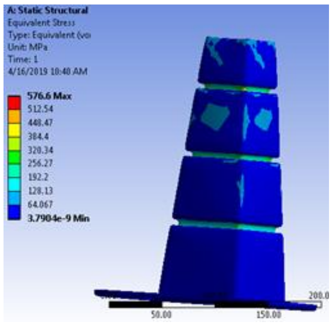
deformation (mm) 81 4

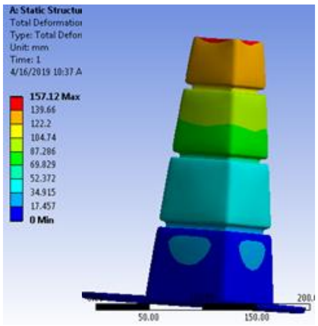
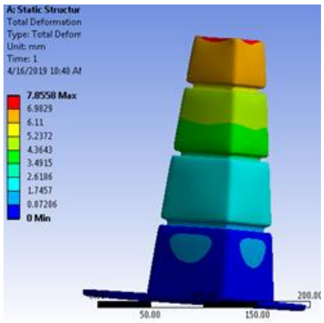
energy (mJ) 33400 83.5

Shape 3

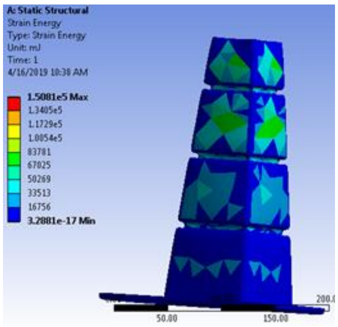
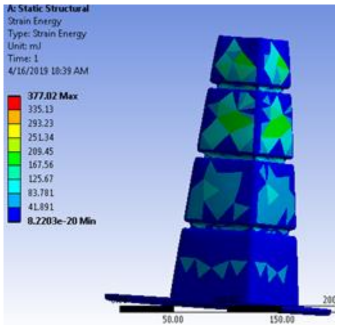
Force 1000 kN Force 50 kN

stress (MPa) 11532 576

deformation (mm) 157 7.8

energy (mJ) 150000 377

CONCLUSION

Adding more content of nGO up to 0.5 wt.%, the mechanical performances increase 80 %, and the nGO completes the gaps between the crystal structure which creates a chain between matrix and fibre, consequently strengthening the entire structure. In manufacture, some microcracks, gaps, and hollows can be created. nGO fill these gaps and heal microcracks to strengthen the whole structure. After this briefing on the cubical crash box, nGO improve the thin wall energy absorption, changing the geometry and especially introducing geometric imperfections. So, it is easy to understand why an impact and crash bumper can harm and crush the crash boxes. Adding and reinforcing carbon fibre plus epoxy with nGO in the neat sample improves the strength of the structure. Adding 0.1 % nGO to the epoxy fills the crystalline gaps and creates a great bonding structure with epoxy and carbon fibre. It would even cover the microcracks from manufacture or other machinery cutting process. The cross-section has the most negligible impact on energy absorption. That is how other parameters, such as groove size and material design, can impact the absorption rate even more. It is also concluded that CFRP absorbs more energy than the aluminium base crash box. More of the elastic behaviour and higher Young's modulus can cause more absorption rate. If the velocity or weight of the bullet are chosen to be over 40 m/s and 889 g, a collision can cause massive deformation on the crash box, and CFRP can play a critical role in this deformation.

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