International Journal of Engineering Materials and Manufacture (2023) 8(1) 13-20
https://doi.org/10.26776/ijemm.08.01.2023.02

Influence of Composite Skin on the Energy Absorption Characteristics of an Aircraft Fuselage

S. A. R. Sharifah Nadhirah, J. S. Mohamed Ali, M. S. I. Shaik Dawood, R. Adib Hamdani

Received: 08 January 2023
Accepted: 12 January 2023
Published: 20 January 2023
Publisher: Deer Hill Publications

ABSTRACT
In aviation history, accidents during landing are more frequent compared to other phases of flight and in most cases the aircraft is forced to make an emergency belly landing when landing gear malfunctions. This study aims to analyse the energy absorption of a typical composite aircraft fuselage section under such crash belly landing. A finite element model of this composite fuselage section was created and analyzed using LS-Dyna finite element software and the effects of different composite materials on the energy absorption of fuselage section were studied. Four different composite materials that are commonly used in aerospace application were selected for the purpose of the present study namely glass/epoxy, graphite/epoxy, Kevlar/epoxy, and boron/epoxy. An impact velocity of 7 m/s against rigid ground was considered. Results showed that frames and skin contribute the most in energy absorption while the passenger floor and strut contribute the least. Moreover, it was found that fuselage skin made of glass/epoxy absorbed more energy compared to other materials and it had the highest specific energy absorption.
Keywords: crashworthiness, belly landing, energy absorption, composite materials, LS-Dyna

1 INTRODUCTION

In the aircraft design, crashworthiness is a major concern, especially for civil aircraft. Crashworthiness is the ability of the aircraft structure to protect passengers from injury during a crash. In aviation history, belly landing crashes have been reported as one of the most frequent accidents. Belly landing mainly occurs due to landing gear failure or when pilots forget to deploy the landing gear. There are many risks in performing belly landing as the impact energy can be transferred to the passenger cabin and this can cause injuries or even fatalities.

Crash survivability of these types of events can be significantly improved by designing the aircraft structures for crashworthiness. Since it is expensive to do a full-scale drop test, Finite Element Analysis (FEA) is used to perform crash analysis. However, a real fuselage is a complex structure as it consists of many parts, so to ease analysis process, the fuselage model can be simplified according to the simplified principles proposed by Adams and Lankarini [1]. The most common materials used for fuselage is aluminium alloys while laminated composites are used in military aircraft [2]. The usage of composite materials has dramatically increased in commercial aircraft since 2005 [3]. Laminated composites such as glass/epoxy, graphite/epoxy, Kevlar/epoxy, and boron/epoxy are commonly used in aerospace applications. The current state of the art regarding the relationships between failure mode and energy absorption, the primary material, geometrical and physical parameters relevant to crashworthiness design, and methods for evaluating the energy absorption capacity of polymer composites have been reviewed by Carrythers et al. [4].

A study on the relationship between material property variables, geometrical variables and testing variables and energy absorbing characteristics of composite material was conducted in 1998 [5]. Another study was conducted to investigate the effect of lamination scheme and angle variations to the displacements and failure behavior of two most common composite laminated plates, which are glass/epoxy and graphite/epoxy laminates [6]. A study on the effects of high strain rate (HSR) loadings on the glass fiber failure process in epoxy matrix during tensile loading was carried out in 2019 [7]. Abdewi et al. examined the effect of corrugation geometry on the crushing behavior, energy absorption, failure mechanism and failure mode of woven roving glass fibre/epoxy laminated composite tube and found that there is no effect of corrugation geometry observed for lateral crushing [8].

In 2014, Xue et al. studied the crashworthiness characteristics of aluminium fuselage [9]. Mou Haolei et al. studied the influences of composite skin of a fuselage section and the results showed that the crashworthiness can be

S. A. R Sharifah Nadhirah, J. S. Mohamed Ali✉, M. S. I Shaik Dawood, R. Adib Hamdani
Department of Mechanical and Aerospace Engineering,
Kulliyyah of Engineering,
International Islamic University Malaysia.
Email: jaffar@iium.edu.my

Reference: Sharifah Nadhirah, S. A. R., Mohamed Ali, J. S., Shaik Dawood, M. S. I., Adib Hamdani, R. (2023) Influence of Composite Skin on the Energy Absorption Characteristics of an Aircraft Fuselage. *International Journal of Engineering Materials and Manufacture*, 8(1), 13-20.

effectively improved by selecting appropriate composite ply numbers and ply angles [10]. Yidris et. al performed a quasi-static crash analysis of a woven c-glass/epoxy fuselage section of an unmanned aerial vehicle (UAV) to investigate energy absorbing capability [11]. With a wide-bodied aircraft made primarily of composites, Yu and Xue simulate drop tests and compared the responses of T800/QY8911 composite and GLARE [12]. In 2017, Crash analysis of a metallic fuselage on land and water was investigated [13]. In a recent study, Riccio et al. investigated the influence of material toughness on the capability of a composite fuselage barrel to tolerate an impact on a rigid surface [14]. A comparative study by experimental, numerical, and analytical methods on oblique lateral crashworthy characteristics of thin-walled circular tubes with aluminium, GFRP and CFRP materials was carried out [15]. From the literature survey, no work has been reported on the effects of different composite materials on the energy absorption characteristics of a fuselage. Thus, this paper aims to investigate the effects of different composite materials on energy absorption of a fuselage section using LS-Dyna.

2 FINITE ELEMENT MODELLING

2.1 Fuselage Modelling

In this study, LS-Prepost was used to model a typical fuselage section while the finite element analysis was done using LS-Dyna explicit finite element code. The geometry of the fuselage was kept simple which consists of five parts; skin, Z-shaped frames, U-shaped stringers, passenger floor and U-shaped struts. The length and the diameter of the fuselage are 1 m and 2 m, respectively. The thickness of the skin is 0.5 cm and the thickness for the rest of the fuselage components is 0.2 cm.

All the fuselage components were meshed using shell elements. Based on the conducted convergence study, the finite element model consists of 42945 nodes and 39736 elements. The impact velocity used is 7 m/s and the rigid ground was modelled using RIGIDWALL_PLANAR. The total simulation time was set to 150 ms.

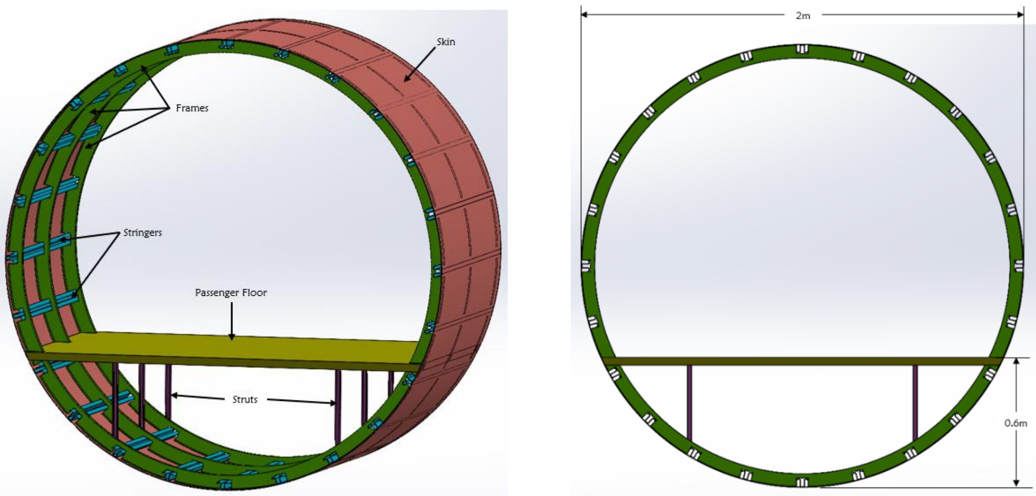

Figure 1a: Fuselage components **Figure 1b:** Fuselage dimension

Figure 1: Fuselage components with dimension

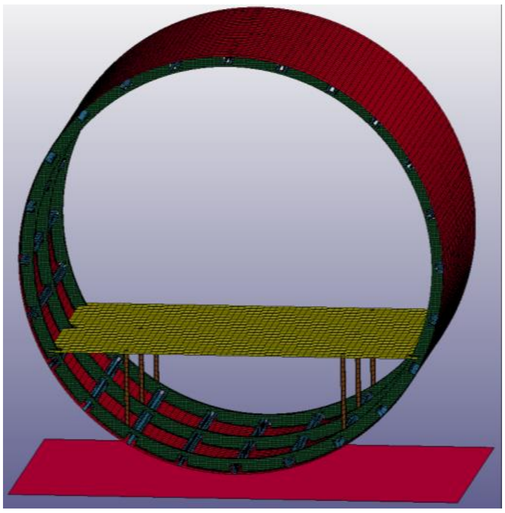

Figure 2: FE model of the fuselage and ground

2.2 Materials Selection

All the five parts were modelled with aluminium, and for the parametric study, only the skin material was changed to composite. In modelling the parts made of aluminium, MAT_098 (Simplified Johnson Cook) were used while in modelling the part made of composite materials – which is the skin, MAT_054 (Enhance Composite Damage) was used. The skin when replaced by composite laminates, consists of 40 layers with each lamina having a thickness of 0.125mm. The laminate fibre angle is measured with respect to the axis of the fuselage. Tables 1 and 2 show the material properties of the aluminium and composite respectively used in the analysis.

Table 1: Aluminium material properties [16]

	Density [kg/m³]	Elastic Modulus [GPa]	Poisson's ratio
AL 7075	2796	71	0.34

Table 2: Composite materials properties [17, 18]

Properties	Glass/Epoxy	Graphite/Epoxy	Kevlar/Epoxy	Boron/Epoxy
Density [kg/m³]	1900	1600	1380	2000
Young's Modulus (longitudinal), E_1 [GPa]	38.6	181	80	204
Young's Modulus (transverse), E_2 [GPa]	8.27	10.3	5.5	18.5
Poisson's ratio, μ_{12}	0.26	0.28	0.34	0.23
Shear Modulus of elasticity, G_{12} [GPa]	4.14	7.17	2.2	5.59
Longitudinal Tensile Strength, X_t [GPa]	1.062	1.5	1.4	1.26
Longitudinal Compressive Strength, X_c [GPa]	0.61	1.5	0.335	2.5
Transverse Tensile Strength, Y_t [GPa]	0.031	0.04	0.03	0.061
Transverse Compressive Strength, Y_c [GPa]	0.118	0.246	0.158	0.202
Shear Strength, S_{12} [GPa]	0.072	0.068	0.049	0.067

3 RESULTS AND DISCUSSIONS

3.1 Validation on Aluminium Fuselage Crash Test

Since experimental benchmark results are not available in the literature, only a qualitative validation was carried out. For the validation, the work of Xue et al. [9] was used in which an aluminium fuselage crash on ground at an impact velocity of 9 m/s was studied and the energy absorption of each element of a fuselage is reported. Comparing the internal energy graph of the present study (Fig 3.) with that of [9] shown in Fig 4., it is observed that the trend is similar where frames absorbed the most of impact energy followed by the skin, struts, stringers, and the passenger floor.

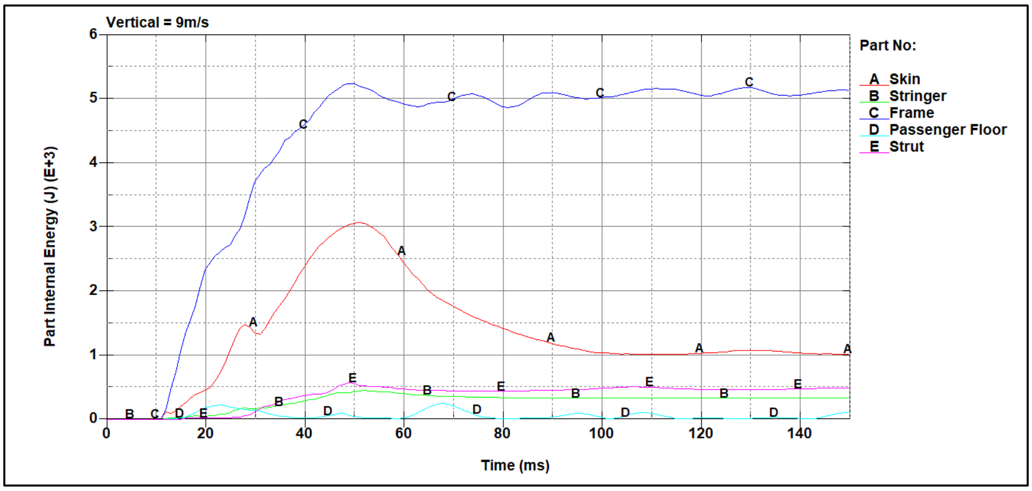

Figure 3: Internal energy absorbed by each component of aluminium fuselage

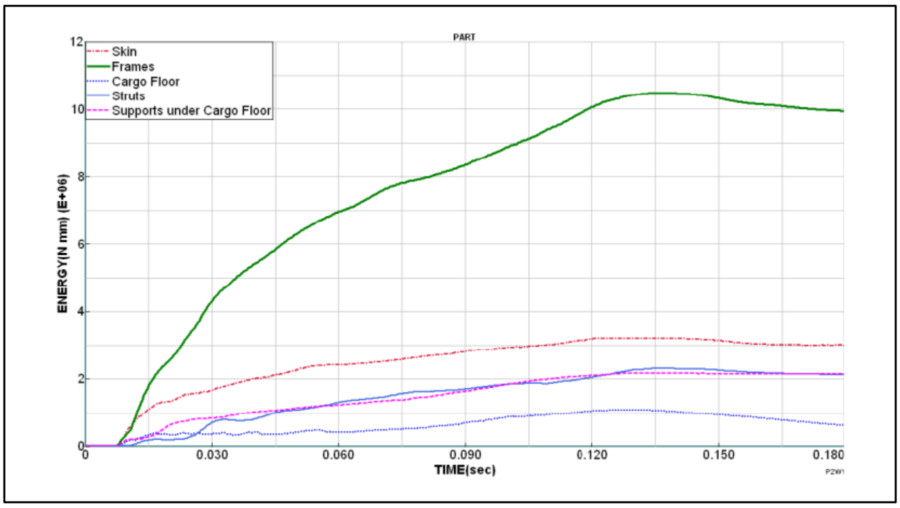

Figure 4: Energy vs time curve of each component (P. Xue et al., 2014)[9]

3.2 Energy Absorption of Different Composite Materials

The structural behaviour of each part during impact is depicted in the Figure 6-10 below. It can be seen in Figure 6-10 that upon impact, lower part of the fuselage sustained damage. In all the cases studied, the frames absorbed more energy than other elements. Comparing the damage pattern of various materials, aluminium fuselage has less damage compared to other materials as aluminium is less brittle than composite. It is known that aluminium material absorb energy in plastic and elastic region while composite materials mostly absorb energy in elastic deformation, making it more brittle than aluminium. Hence, the damages on composite fuselage are greater than the aluminium ones.

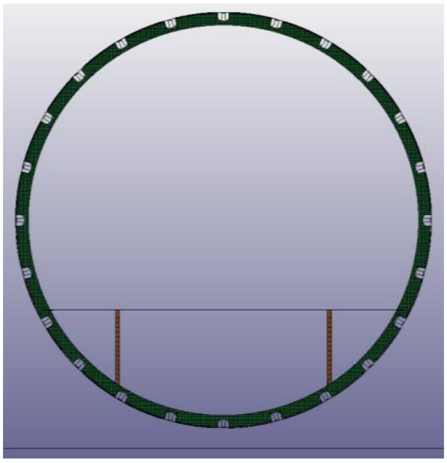

Figure 5: Before the impact

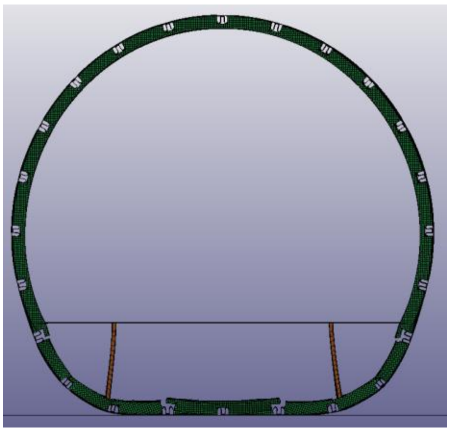

Figure 6: Aluminium fuselage after impact

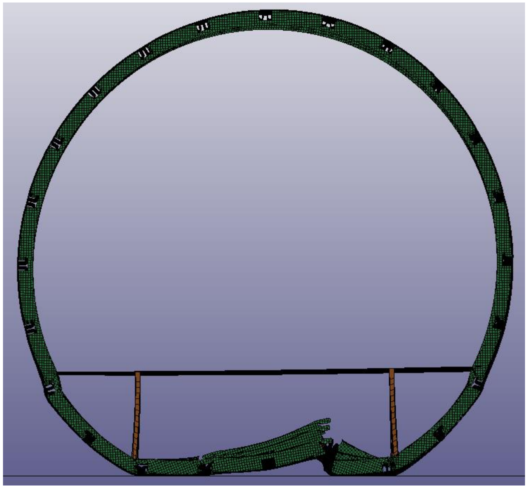

Figure 7: Glass/Epoxy skin fuselage

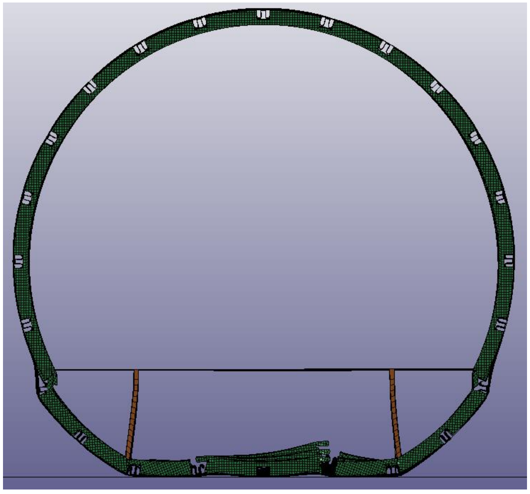

Figure 8: Graphite/Epoxy skin fuselage

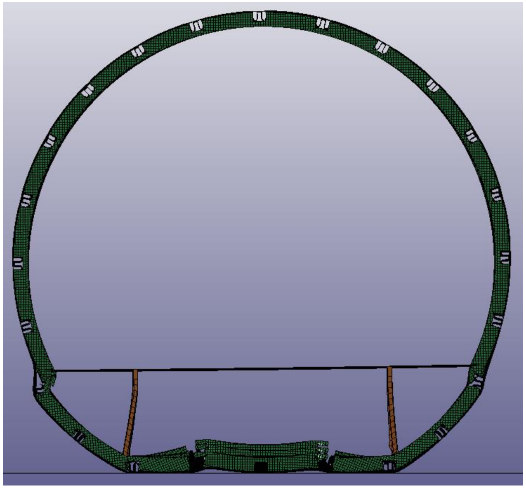

Figure 9: Kevlar/Epoxy skin fuselage

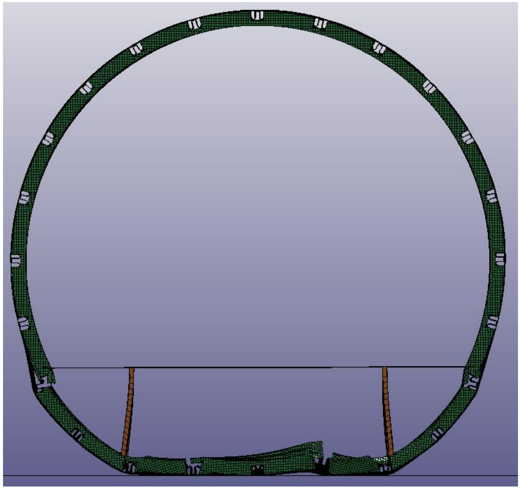

Figure 10: Boron/Epoxy skin fuselage

Figure 11 shows the internal energy of different fuselage components made of aluminium at an impact velocity of 7 m/s. The trend of the graphs is the same as shown in Figure 3.

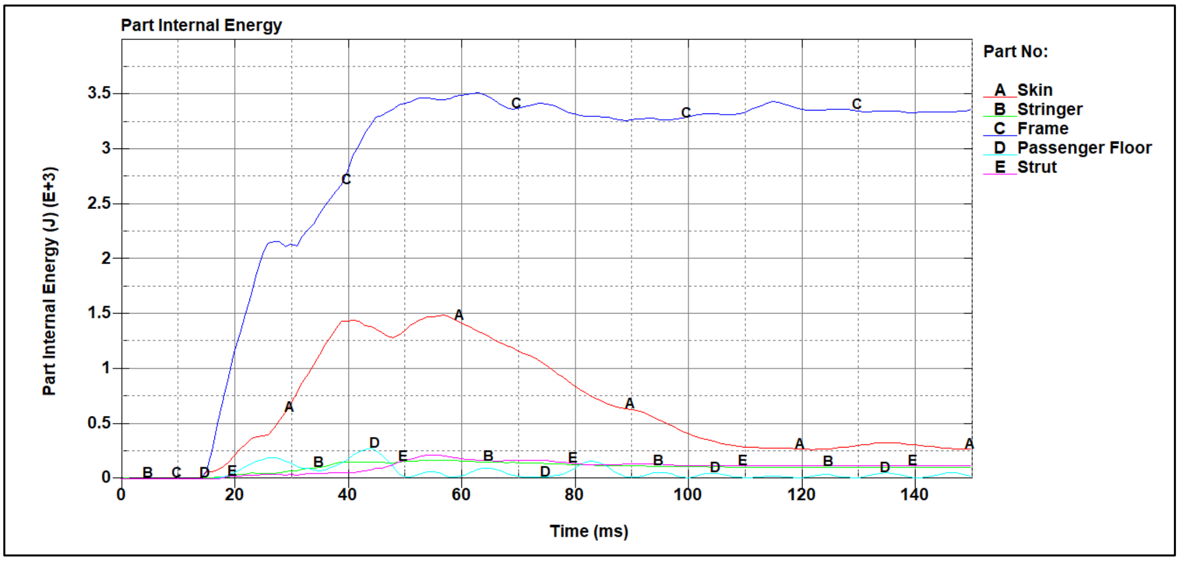

Figure 11: Internal energy plot for Aluminium fuselage at 7 m/s

Figure 12 shows the comparison of energy absorption of the skin using different materials. At 150 ms, the energy absorbed by graphite/epoxy is 1.35 kJ, glass/epoxy (1.77 kJ), Kevlar/epoxy (1.25 kJ) boron/epoxy (1.19 kJ), and aluminium (0.27 kJ). Glass/epoxy absorbed higher energy compared to other materials while aluminium absorbed the least. Figure 13 shows the overall internal energy absorbed by the whole structure and it can be seen that glass/epoxy absorbs higher amount of total energy followed by boron/epoxy, graphite/epoxy, Kevlar/epoxy and lastly, aluminium.

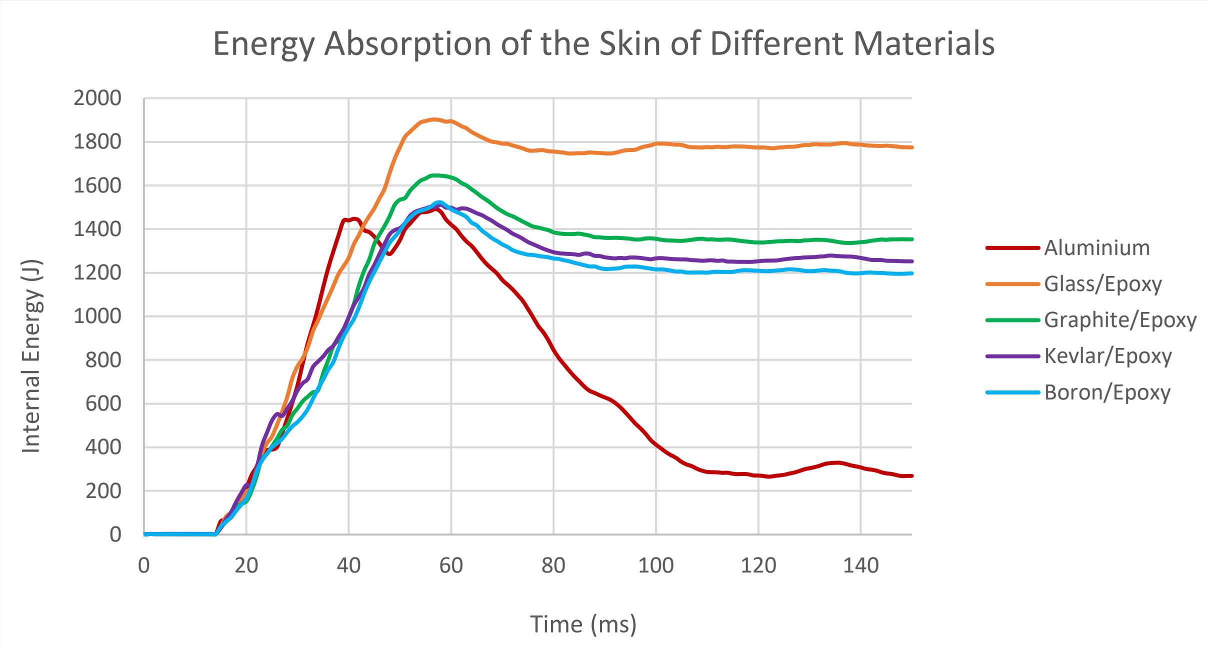

Figure 12: Energy absorption of the skin of different materials

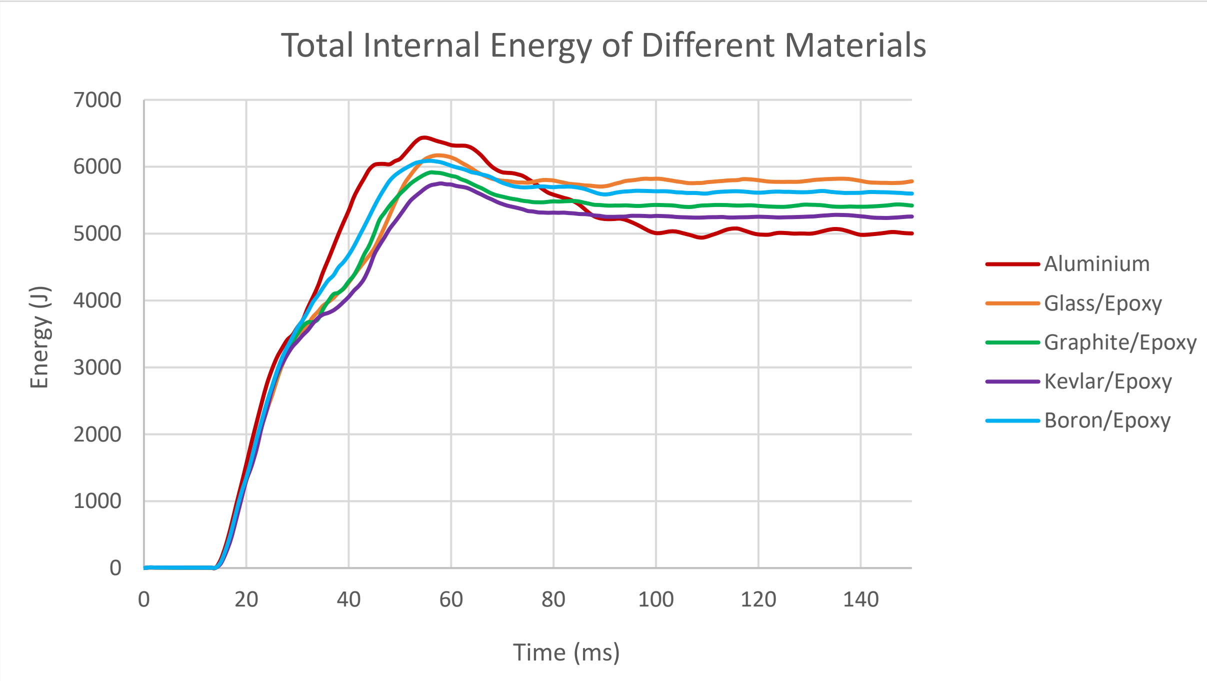

Figure 13: Total internal energy of fuselage made of different composite materials with unidirectional laminate

3.3 Energy Absorption of quasi-isotropic laminate

For quasi-isotropic laminate, a layup of $[90_5/45_5/0_5/-45_5]_s$ was used. Comparing Figure 13 and Figure 14, when the skin is made with quasi-isotropic laminate, the energy absorbed reduced as compared to unidirectional laminate. This is because with quasi-isotropic laminate skin, the fuselage becomes stiffer as quasi-isotropic is known to have a laminate with 0°, ±45° and 90°. Thus, it absorbed less energy and have lesser damage. However, in this case glass/epoxy absorbed the highest energy followed by boron/epoxy, Kevlar/epoxy and lastly, graphite/epoxy.

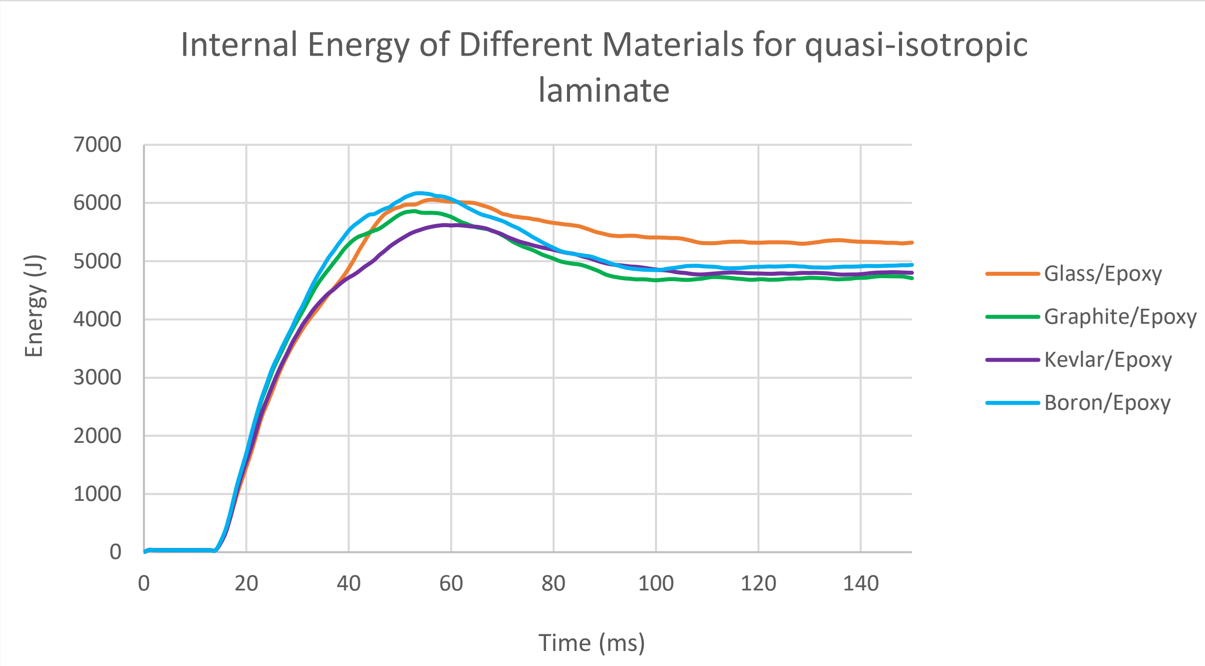

Figure 14: Total internal energy of fuselage made of different composite materials with quasi-isotropic laminate

Table 3: Specific energy for different materials

Materials	Mass of the structure (kg)	Specific energy (J/kg) (Unidirectional)	Specific energy (J/kg) (Quasi-isotropic)
Aluminium	282.791	17.692	17.692
Glass/Epoxy	257.679	22.704	20.891
Graphite/Epoxy	245.182	22.130	19.202
Kevlar/Epoxy	238.363	22.046	20.143
Boron/Epoxy	257.816	21.716	19.149

As the advantage of composites is on weight savings, it is important to compare the specific energy absorption. The mass of the structure can be computed directly from LS-Dyna and it is included in the Table 3 above for comparison. It can be noted from Table 3 that fuselage made of unidirectional glass-epoxy laminate proved to be the best in absorbing energy with the least mass. Similarly, fuselage made of Kevlar/epoxy with least mass, has higher specific energy as compared to boron/epoxy. The specific energy absorbed by aluminium fuselage is also included here for comparison. Fuselage made completely of Aluminium has the lowest specific energy as compared to any other composite laminates.

4 CONCLUSIONS

This study simulates fuselage crash tests on rigid ground using LS-Dyna. The aluminium fuselage skin was replaced with different materials to study the effect of different materials on energy absorption characteristics of a fuselage. It was noticed that the lower part of fuselage deformed the most due to the impact and the results showed that frames and skin contribute the most in energy absorption while passenger floor and strut contribute the least, regardless of any material. As for the effect of different materials on energy absorbing capability, it is found that glass/epoxy absorbs more energy than any other composite materials as well as aluminium. Finally, it was found that fuselage made of glass-epoxy laminate with highest specific energy proved to be the best laminate in absorbing energy with the least mass.

REFERENCES

1. Adams, A., & Lankarani, H. M. (2003). A modern aerospace modeling approach for evaluation of aircraft fuselage crashworthiness. International Journal of Crashworthiness, 8(4), 401–413. https://doi.org/10.1533/ijcr.2003.0234
2. Adrian P. Mouritz (2012). Materials and material requirements for aerospace structures and engines. (2012). Introduction to Aerospace Materials, 39–56. https://doi.org/10.1533/9780857095152.39
3. Smith, F. (2013). The use of composites in aerospace: past, present, and future challenges. Avalon Consultancy Services LTD, 1–40. https://avaloncsl.files.wordpress.com/2013/01/avalon-the-use-of-composites-in-aerospace-s.pdf
4. Carruthers, J. J., Kettle, A. P., & Robinson, A. M. (1998). *Energy absorption capability and crashworthiness of composite material structures: A review*. http://appliedmechanicsreviews.asmedigitalcollection.asme.org/
5. Ramakrishna, S., & Hamada, H. (1998). Energy absorption characteristics of crash worthy structural composite materials. *Key Engineering Materials*, *143 PART II*, 585–620. https://doi.org/10.4028/www.scientific.net/kem.141-143.585
6. Noh, N. N., Samsudin, A. H., & Mahmud, J. (2017). Failure analysis of Glass/Epoxy and Graphite/Epoxy laminates due to the effect of variation in lamination scheme and angle of fibre orientation. *Materials Science Forum*, *889 MSF*, 36–44. https://doi.org/10.4028/www.scientific.net/MSF.889.36
7. Kim, J. H., Mates, S. P., Heckert, N. A., Woodcock, J. W., & Holmes, G. A. (2019). *Effect of strain rate on glass fiber failure process in a glass fiberepoxy model composite*. https://doi.org/10.6028/NIST.TN.2057
8. Abdewi, E. F., Sulaiman, S., Hamouda, A. M. S., & Mahdi, E. (2008). Quasi-static axial and lateral crushing of radial corrugated composite tubes. *Thin-Walled Structures*, *46*(3), 320–332. https://doi.org/10.1016/j.tws.2007.07.018
9. Xue, P., Ding, M. L., Qiao, C. F., & Yu, T. X. (2014). Crashworthiness study of a civil aircraft fuselage section. *Latin American Journal of Solids and Structures*, *11*(9), 1615–1627. https://doi.org/10.1590/S1679-78252014000900007
10. Mou, H., Zou, T., Feng, Z., & Ren, J. (2014). Crashworthiness simulation research of fuselage section with composite skin. Procedia Engineering, 80, 59–65. https://doi.org/10.1016/j.proeng.2014.09.060
11. Yidris, N., Zahari, R., Majid, D. L., Mustapha, F., Sultan, M. T. H., & Rafie, A. S. M. (2010). Crush simulation of woven c-glass/epoxy unmanned ariel vehicle fuselage section Flapping Wing Micro-Air-Vehicle. In *International Journal of Mechanical and Materials Engineering (IJMME)* (Vol. 5, Issue 2). https://www.researchgate.net/publication/266597778
12. Yu, Z. L., & Xue, P. (2017). Crashworthiness study of composite fuselage section. *Key Engineering Materials*, *725 KEM*, 94–98. https://doi.org/10.4028/www.scientific.net/KEM.725.94
13. Ali, J. S. M., & Hasfareeza, M. Y. (2017). Crash Analysis of an Aircraft Fuselage under Belly Landing. International Journal of Recent Research Aspects ISSN: 2349-7688, 4(4), 75–78.
14. Riccio, A., Saputo, S., Sellitto, A., & Di Caprio, F. (2020). A numerical assessment on the influences of material toughness on the crashworthiness of a composite fuselage barrel. Applied Sciences (Switzerland), 10(6). https://doi.org/10.3390/app10062019
15. Sun, G., Guo, X., Li, S., Ruan, D., & Li, Q. (2020). Comparative study on aluminum/GFRP/CFRP tubes for oblique lateral crushing. *Thin-Walled Structures*, *152*. https://doi.org/10.1016/j.tws.2019.106420
16. Liu, X., Guo, J., Bai, C., Sun, X., & Mou, R. (2015). Drop test and crash simulation of a civil airplane fuselage section. In *Chinese Journal of Aeronautics* (Vol. 28, Issue 2, pp. 447–456). Chinese Journal of Aeronautics. https://doi.org/10.1016/j.cja.2015.01.007
17. Autar K. Kaw. (2006). *Mechanics of composite materials*. Taylor & Francis.
18. Wang, J., Olortegui-Yume, J., & Müller, N. (2010). Stress And Vibraiton Analysis For Woven Composite Axial Impeller. http://www.asme.org/about-asme/terms-of-use