Penerbit
Akademia Baru

Journal of Advanced Review on Scientific Research
ISSN (online): 2289-7887 | Vol. 16, No.1. Pages 1-11, 2015

Review on the Dynamic Impact Characteristics of Fiber Metal Laminates

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Abstract - *This paper reviewed on the emergence and development of fiber metal laminates. The effect of material properties of the constituents of fiber metal laminates was thoroughly summarized. Then, the mechanical responses of fiber metal laminates were reviewed. Finally the methods used by various literatures are summarized.*

Keywords: Fiber metal laminates, dynamics impact, hybrid composites

1.0 INTRODUCTION

In the recent decades, fiber metal laminates (FMLs) have one of the major interesting research subjects due to increasing requirement for superior lightweight, durable and damage tolerant materials by particularly aircraft and aerospace industries. The substantial development of FMLs started at Fokker/TU Delft in the Netherlands, during the late 1970s. Typically, it has been suggested that thin sheets of metal alloy are laminated with alternating composite layers to form an FML hybrid composite. There is a consensus among social scientists that fiber metal laminates integrates the optimal fatigue and fracture properties of fiber reinforced composite and superior durability characteristics of metal while at the same time eliminates their individual drawbacks. FMLs also comprise of high strength properties, fatigue resistance, impact and corrosion resistance compared to monolithic aluminum or fiber reinforced composite [1-4].

There are many advantages of using FMLs instead of using only the constituent materials. In 1979, Schijve et al. [5] demonstrated that the use of laminated thin layers of material rather than one thick monolithic layer can minimize the fatigue crack growth rates. Adhesive layers act as crack dividers, redistribute and reduce stress in an event of crack in any of the layers. The above finding is consistent with the study by Vlot [6]. Vlot identifies complimentary residual stress system between aluminum alloy layers and composite lamina through fiber bridging of fatigue cracks; imparting superior fatigue resistance. From the past research on fiber reinforced polymer composites, specific strength, stiffness, fatigue and corrosion resistance are the advantages of FRP [7]. However, in the 2000s, Mitrevski et al. pointed that barely visible internal damage that might occur on composites due to localized low velocity impacts can reduce residual strength up until 60% thus are distinguished as very dangerous [8]. The research study by Sayer et al. and Karakuzu et al. also found delamination, matrix cracking, transverse cracks and fiber fracture internally due to barely visible impact damage [9, 10]. The incorporation of aluminum alloy sheets in FML alleviates this problem by offering impact damage visibility due to its plastic deformation [3, 11, 12].

While the structural materials of commercial aviation transport comprises of 80% aluminum material causes considerable financial problems, use of polymer in FMLs significantly reduces weight compared to current metallic structures. Furthermore, fatigue and impact resistance of FMLs reduces cost on repair and maintenance costs of aircraft [1].

Previous reports indicate potential use of FMLs as fire retardants and thermal resistants [1, 13]. Corrosion resistance of FML is excellent because the high corrosion resistance of polymer based fiber laminates layers and moisture barriers between various Al layers, [1, 3, 11]. However, to the best of knowledge, there is no comprehensive review on the dynamic impact characteristics of fiber metal laminates. Moreover, there is even lesser paper comparing the methods of analyzing fiber metal laminates very deeply.

2.0 DEVELOPMENT OF FIBER METAL LAMINATES

The first type of FML created was ARALL (Aramid Reinforced Aluminum Laminates) in 1980s and was selected to design lower wing panel for Fokker-27 and C-17 cargo doors [1, 11, 12]. However, Asundi and Choi [1] concluded that ARALL have low interface strength between fibers and adhesive causing poor peel strength and interlaminar shear properties.

Delft University then developed GLARE with alternating aluminum sheets and glass fiber reinforced layers [6, 11, 12]. Outstanding mechanical properties and damage tolerance capabilities of GLARE resulted in it being implemented in Airbus A380, Boeing 777 impact resistant bulk cargo floor and fuselage of A340 [3, 11, 12]. In contrast of Aramid fibers, the adhesion between glass fibers and adhesive is much superior [1]. Furthermore, impact loading on various FMLs done by Vlot [11] shows higher energy is required to create first crack for GLARE compared to aramid and carbon fiber FMLs.

Carbon Reinforced Aluminum Laminates, or CARAL is another variant of FML to explore improvements and other possible applications. Unfortunately, there have been several studies in the literature reporting exceedingly limited deformation attributable to high stiffness and brittleness of the carbon fibers [14-16]. Asundi and Choi [1] added that CARAL has fatigue problems during flight simulation fatigue tests at elevated stress levels.

3.0 MATERIAL PROPERTY EFFECT ON FIBER METAL LAMINATES

The performance of fiber metal laminates can be attributed to many factors: material properties, fabrication process, geometrical factors, type of mechanical loading and environmental effects [17, 18]. Hence, the ideal FML is difficult to achieve due to mutual dependency between the various factors [19]. Material parameters of FMLs constitute the type of metal, composite, fiber, matrix, lay-up, metal volume fraction and fiber volume fraction.

In 2014, Chai and Manikandan [19] reported that the aluminum layers in FML plays a vital role of giving higher strain and gradual extension before fracture, residual strength and excellent blunt notch strength. The comparison of metal constituents Al 7475-T6 and Al 2024-T3 on the drop weight impact of FMLs was carried out by Liu and Liaw [20]. FML with Al 7075-T6 show small permanent deflection, lower delamination and brittleness due to high stiffness and strength. From the load-displacement plot, the energy until failure of Al 7075-T6 is 1/3 lower than Al 2024-T3, resulting in poorer impact energy absorption. Deformation of ductile Al 2024-T3 shown more plastic deformation of larger area while the Al 7475-T6 shown relatively local plastic fracture deformation. In addition, according to Abdullah and Cantwell [21], 2024-T3 aluminum is once again proven ideal for FML for its superior impact resistance compared to 2024-O aluminum alloy. On the other hand, Cortes and Cantwell [22] explored on the possibility of magnesium alloy in FMLs for its low density, higher strength to weight ratio and lower cost compared to aluminum alloys. From their research, it is suggested that by allocating the optimum volume fraction, Mg based FML can be as strong as aluminum. However, it was later shown by Alderliesten et al. and Sadighi et al. [23, 24] that FMLs with AZ31 B-H24 magnesium alloy instead of 2024-T3 aluminum do not enhance the impact resistance of FMLs. In 2002 Burianek and Spearing [25] investigated using Titanium in FML. The results indicate Ti alloy FMLs as poor impact energy absorbers because of low ductility and poor fatigue performance.

The three main types of composites used in FMLs were aforementioned in Section 1 in ARALL (aramid fiber composite), GLARE (glass fiber composite) and CARAL (carbon fiber composite). From above, it has been known that glass fibers are superior especially for uses in impact mitigation and this is consistent with report by Chai and Manikandan [19] stating that it is due rate sensitivity of both aluminum and glass fiber reinforced composite. Another type of FML composed of polypropylene composites was investigated by [21, 26]. It was demonstrated that polypropylene laminates are good for localized impact loading mitigation but have difficulty of adhering with composite and aluminum. This results in substantial delamination and debonding.

Fibers of composites of FMLs can come in various types and orientations such as unidirectional (UD), woven or chopped strand mat. Vlot and Gunnink [12] highlights the impact performance of unidirectional glass fibers higher than woven glass fibers. The finding is consistent with Izod impact tests 10 years later by Badawy [27] on UD laminated composites. These results were contradicted by the experiments of Ibekwe [28] who considered drop weight impact test on panels. This shows that the performance of different types and orientations of fibers depends greatly on the loading direction applied. A study of fiber types on FMLs by Zhu and Chai [29] demonstrates FML with UD fibers can sustain higher load with larger plastic zone than woven with more localized deformation. It is reported that increased impact resistance is caused by higher failure strength and stiffness of UD fibers. Comparatively, there is no research done on chopped strand matt configuration perhaps due to its relatively poorer properties. A novel type of 3D glass fabric with bi-directionally woven fabrics in vertical braided pillars was studied by Asaee et al. [7]. The results show improved impact absorption but lower impact energy resistance.

As highlighted by Chai and Manikandan [19], impact characteristics such as maximum impact force, delamination area and damage width are dependent on layer stacking sequence of the laminates. Recent research by Seyed Yaghoubi and Liaw [30, 31] on the lay-up orientation by cross-plying 0 and 90 degrees of UD specimen and quasi-isotropic laminates offered great contact resistance force compared to UD specimens. The cross-ply lay-up is a favored configuration by other researchers [32-34] for its ideal impact resistance.

Metal Volume Fraction is the ratio of the sum of metal layers to total FML thickness [29] and is used to predict tensile strength and shear yield strength and depict mechanical and material properties of FMLs [12]. In 1993, Vlot [6] used MVF to establish material property of GLARE using the equation: $FML\ property = MVF \times Metal\ property + (1 - MVF) \times Fiber\ property$. The optimized thickness of aluminum sheets in FMLs were 0.3-0.4mm while optimum thickness of composite layer is not fixed [12]. Recent studies have confirmed that increasing the number of composite layers increases maximum impact force and minimizes damage of FMLs [7, 35, 36].

Fiber content in composite also plays an important role in impact resistance as increase of fiber percentage enhances the impact resistance [37]. Effect of fiber volume fraction on Izod impact strength of UD GFRP was attempted by Badawy [27] and it was shown that significance of fiber content depends on the direction and orientation of load controlling failure mode. This is evident on 0° UD, fibers actively restrict crack propagation while 45° and 90° UD the crack propagates through the matrix without fiber bridging effect.

4.0 MECHANICAL RESPONSE OF FML

For many engineering applications, impact data are required to design for adequate energy absorption or against failure under use or abuse conditions [38]. The knowledge of dynamic response of structure and its damage resistance is much needed to optimize the structure requiring high safety like aircraft structural applications [19]. Normal impact is the worst case scenario compared to oblique impacts, multiple impacts and tumbling impacts, [39].

Quasi-static compression punch test used to obtain primary estimation of required energy for penetrating FML specimens, [40]. Low Velocity Impact is generally <11 m/s, eg: service trucks, cargo containers, dropped tools during maintenance operations, [11, 12]. 13 per cent repairs of primary structure in Boeing 747 aircraft caused by impact dmg, [3]. FML hybrid laminates are characterized by a complex failure mechanism caused by impact, [2] Complete understanding of relationships between damage and impact responses, identification of dmg types and the understanding of damage propagation mechanisms is an essential issue for the hybrid laminates resistance to impact, [2]. Impact on FML is characterized as Barely Visible Damage when it is impacted at very low impact energy. Impact on different locations have little effect on impact response of FML, [35]. Effect of impact energy division over repeated low-velocity impact on FML was done by comparing between single impact and double impacts with same sum of amount of energy. Specimen responds stiffer in second impact, due to elastic-plastic behavior of aluminum sheets causing strain hardening and impact energy division and sequence are so influential that failure modes and impact parameters of each arrangement are considerably different, [40]. At 2014, Haghi Kashani et al. [40] reported that when specimen subjected to single impact with total amount of E, the specimen's behavior is local, but when subjected to several impacts with less amount of energy, specimen behaves globally, increasing amount of strain E and total EA. Low velocity impact event can be treated as a quasi-static deformation process if strain-rate do not exceed 10 m s^{-1}, [2, 41]. There is a consensus among researchers that low velocity impact responses of FML are the essentially identical to those of quasi-static response given that the velocity of impact is very small or the impact mass is much larger than the mass of FMLs [11, 29, 42].

High Velocity Impact are generally >11m/s up to 100m/s and are realistic for runway debris, ice from propeller, bird strike and hail strikes on aircraft structure, [11, 12]. A gas gun consisted of a pressure vessel was used for high velocity impact tests [6, 11, 14, 43]. After burning through a membrane of the gas gun, the expanding gas or air accelerates a projectile or a steel ball bearing to the velocities ranging between 25 and 100m/s. Velocity of impactor prior to impact can be measured as it exited the barrel by interruption of two laser beams a known distance apart by using light emitting diode photovoltaic cell pairs [44].

Fatigue Crack Propagation loading is critical in FMLs. FML have high fatigue resistance, achieved by intact bridging fibers in wake of crack which restrain crack opening [11]. Fatigue crack propagation of FMLs mainly involves crack growth of the aluminum and the delamination of metal to prepeg surfaces, as mentioned by [45]. Crack growing rate of FML is low and tends to steady state after 10% of the fatigue life and catastrophic fracture is less probable, [46, 47]

Delamination or interfacial fracture is also a prominent failure mode in FMLs. Mechanical properties of composite materials are governed by the adhesion between fiber and matrix. Same properties of FMLs are governed by the interface bond between composite ply and metal ply. Determination of adhesion: interlaminar shear and interfacial fracture tests [44]. There are 3 kinds of test methods according to the interlaminar shear loading types: I. Compression loading, II. Three and five-point bending and III. Short beam shear loading, according to [44]. In interfacial fracture tests, degree of adhesion between the composite and metal plies was investigated using the single cantilever beam (SCB) geometry. This geometry yields mixed-mode I/II loading (tension/shear) conditions at the crack tip in the sample. [22, 26, 48]. Interfacial toughness is associated with the formation of fiber bridging during crack propagation. Rising R-curve in Interfacial fracture energy vs Crack length graph was generally associated with the development of extensive fiber bridging and the presence of significant plastic deformation in the PP interlayer in the wake of crack, [49]. Mode II interlaminar fracture is a key parameter controlling impact behavior at low energies. [50]

As mentioned before, FMLs especially GLARE has very high strain rate dependency. Some composite materials have shown rate-sensitive behavior, e.g. an increase of strength or Young’s modulus when subjected to high-rate loading, [51]. Very strain rate dependent of fiber glass. Strength and absorbed energy of GLARE laminates measured by tensile tests was shown to increase at higher rates of loading, [11]. A strain rate of 100s^{-1} increases the tensile strength of unidirectional glass/epoxy by 10% when compared to quasi-static conditions, [43]. Reported extensive dynamic experiments for GRP using a servo-hydraulic testing apparatus shows that the modulus of GRP increases trivially in the range of $0.00 \leq \dot{\varepsilon} \leq 5.33s^{-1}$ and, that the strength and strain to failure did not change significantly when the strain rate is less than $10s^{-1}$, [52]. Metal ductility decreases when strain rate or thickness increases, [43]. It is well known that the resistance to plastic deformation, strain to failure and fracture toughness of polymer matrices is strongly dependent on strain rate as a consequence of their viscoelastic natures. [53]. Maximum impact force of FML increase with increasing dynamic impact energy, [36].

5.0 METHODS TO ANALYZE FMLS

5.1 Analytical Method

A number of analytical methods have been developed by previous researchers, [46, 54]. The solution will vary based on the nature (elastic, plastic, anisotropy, low-velocity, high-velocity, blast impact) and condition of problem (infinite, finite, thin, thick plate), the level of non-linearity, size of the equations and availability of input data [19]. The Classical Laminate Theory integrated into an energy-balance model appears to be a promising technique due to its generic nature, [39]. Available solution modes are classified into four categories: spring-mass models, energy balance models, complete models based on Classical Plate theory, Mindlin's First order Shear Deformation Theory and some novelty methods [55]. Recently, it is summarized that the analytical model to study low-velocity impact response related to FML is still in at its infant stage. All the presented models have their own limitations. Apart from the work of Moriniere [56], none of the other analytical models accounts the damage phenomenon [19].

5.2 Experimental Method

Experimental methods are used by many researchers in conjunction with analytical or numerical methods for validation purposes. Height of impactor before the drop is a first estimate for the impact energy to be applied, then velocity is acquired by measuring velocity right before impact, [24, 50]. Experimental impact characterization of hybrid materials is very time consuming, [39]. After testing, the specimens could be sectioned, polished and then viewed under an optical microscope in order to elucidate the failure mechanisms during impact [44]. Experimental impact results of [4] were used to validate the simulation predictions in [57]. Simple Mechanistic Model was established by using empirical relationships for the maximum contact force and the perforation energy were developed using the experimental data, force-displacement curve is a second-degree polynomial fitting the test curve of the load path, [58]. Quantitative analysis was reported using localized blast loading behavior evaluated using linear trend lines related to the plate thickness in a straightforward way, [59, 60]. Delamination between glass-ply or disbanding between the aluminum layer and glass-ply could not be determined using C-scan, since delamination type discontinuities are very good ultrasound reflectors, [34].

5.3 Numerical Method

LS-DYNA or ABAQUS commercial finite element software is very popularly used by researchers on FMLs. Numerical models using FE analysis are relatively quick and inexpensive to develop, [39]. Numerical analysis tools can be used to reduce the number of tests required, decreasing development costs and lead-time. Experimental testing is, however, essential for the basic material characterization, validation of numerical models and final certification of aircraft components, [61]. In addition to specific material properties, only a reasonable number of structural tests are required for validation purposes, [39]. For numerical models to make valid contributions to the aircraft design process they must be shown to correctly represent material and structural behavior right through the loading process, [61]. Numerically simulating the dynamic, non-linear and transient behavior of composite laminates under impact load is very complex because of highly localized contact load and concomitant damage phenomena like fiber breakage, delamination, matrix cracking, and plastic deformations with large deformation in the impacted structure [19]. By refining mesh size, smoother results were obtained, [30]. Quarter symmetric model used to further decrease computational time due to the double symmetry, [30]. Explicit FE code is preferred over implicit versions because full 3D FE models can be implemented to simulate the 3D deformation process involving large transverse compression and strain-rate sensitivity in FMLs, [62]. 3D Fiber Glass response hard to model and predict by numerical, [7]. Numerical and experimental investigation of metal type and thickness effects on the impact resistance of FML was carried out by Sadighi [24]. Song et al. investigated carbon reinforced aluminum laminates (CARALL) under low velocity impact using ABAQUS using shell with Hashin's failure criterion for composite and 8-node solid element without failure criterion for aluminum alloy, [33]. Another paper studied on simulating GLARE panels with diverse impact damages with 2 and 3-D failure criteria in

ABAQUS code to model stiffness degradation in the panels. Energy to create barely visible impact damage (BVID) and energy to create clear visible impact damage (CVID) by both 2 and 3-D failure modes showed good agreement with experimental results, [57].

6.0 CONCLUSION

This paper presented an inclusive review on the impact characterization of fiber metal laminates. A vast number of available references showed that FMLs have great potential. It is found in many cases that FMLs is superior compared to conventional aluminum alloy or fiber reinforced polymer composites. Currently a lot of research is needed to improve the methodology used to study the material and further expand the possibilities of applications. There is still many underlying uncertainties regarding the structural and material mechanics within the FMLs.

REFERENCES

[1] A. Asundi, A.Y.N. Choi, Fiber metal laminates: An advanced material for future aircraft. Journal of Materials Processing Technology 63 (1997) 384-394.

[2] M. Sadighi, R.C. Alderliesten, R. Benedictus, Impact resistance of fiber-metal laminates: A review. International Journal of Impact Engineering 49 (2012) 77-90.

[3] L.B. Vogelesang, A. Vlot, Development of fibre metal laminates for advanced aerospace structures. Journal of Materials Processing Technology 103 (2000) 1-5.

[4] G. Wu, J.-M. Yang, H.T. Hahn, The impact properties and damage tolerance and of bi-directionally reinforced fiber metal laminates. Journal of Materials Science 42 (2007) 948-957.

[5] J. Schijve, H.T.M. Van Lipzig, G.F.J.A. Van Gestel, A.H.W. Hoeymakers, Fatigue properties of adhesive-bonded laminated sheet material of aluminum alloys. Engineering Fracture Mechanics 12 (1979) 561-579.

[6] A. Vlot, Impact properties of fibre metal laminates. Composites Engineering 3 (1993) 911-927.

[7] Z. Asaee, S. Shadlou, F. Taheri, Low-velocity impact response of fiberglass/magnesium fmls with a new 3d fiberglass fabric. Composite Structures 122 (2015) 155-165.

[8] T. Mitrevski, I.H. Marshall, R. Thomson, The influence of impactor shape on the damage to composite laminates. Composite Structures 76 (2006) 116-122.

[9] R. Karakuzu, E. Erbil, M. Aktas, Impact characterization of glass/epoxy composite plates: An experimental and numerical study. Composites Part B: Engineering 41 (2010) 388-395.

[10] M. Sayer, N.B. Bektaş, O. Sayman, An experimental investigation on the impact behavior of hybrid composite plates. Composite Structures 92 (2010) 1256-1262.

[11] A. Vlot, Impact loading on fibre metal laminates. International Journal of Impact Engineering 18 (1996) 291-307.

[12] A. Vlot, J.W. Gunnink, SpringerLink (Online service), Fibre metal laminates an introduction. 2001, Springer Netherlands,: Dordrecht. p. 1 online resource..

[13] G.H.J.J. Roebroeks, Fibre-metal laminates: Recent developments and applications. International Journal of Fatigue 16 (1994) 33-42.

[14] G.D. Lawcock, L. Ye, Y.W. Mai, C.T. Sun, Effects of fibre/matrix adhesion on carbon-fibre-reinforced metal laminates—ii. Impact behaviour. Composites Science and Technology 57 (1998) 1621-1628.

[15] C.F. Li, N. Hu, Y.J. Yin, H. Sekine, H. Fukunaga, Low-velocity impact-induced damage of continuous fiber-reinforced composite laminates. Part i. An fem numerical model. Composites Part A: Applied Science and Manufacturing 33 (2002) 1055-1062.

[16] H. Nakatani, T. Kosaka, K. Osaka, Y. Sawada, Damage characterization of titanium/gfrp hybrid laminates subjected to low-velocity impact. Composites Part A: Applied Science and Manufacturing 42 (2011) 772-781.

[17] H. Daiyan, E. Andreassen, F. Grytten, O.V. Lyngstad, T. Luksepp, H. Osnes, Low-velocity impact response of injection-moulded polypropylene plates – part 1: Effects of plate thickness, impact velocity and temperature. Polymer Testing 29 (2010) 648-657.

[18] H. Daiyan, E. Andreassen, F. Grytten, O.V. Lyngstad, T. Luksepp, H. Osnes, Low-velocity impact response of injection-moulded polypropylene plates – part 2: Effects of moulding conditions, striker geometry, clamping, surface texture, weld line and paint. Polymer Testing 29 (2010) 894-901.

[19] G.B. Chai, P. Manikandan, Low velocity impact response of fibre-metal laminates – a review. Composite Structures 107 (2014) 363-381.

[20] Y. Liu, B. Liaw, Effects of constituents and lay-up configuration on drop-weight tests of fiber-metal laminates. Applied Composite Materials 17 (2010) 43-62.

[21] M.R. Abdullah, W.J. Cantwell, The impact resistance of polypropylene-based fibre–metal laminates. Composites Science and Technology 66 (2006) 1682-1693.

[22] P. Cortés, W.J. Cantwell, The fracture properties of a fibre–metal laminate based on magnesium alloy. Composites Part B: Engineering 37 (2005) 163-170.

[23] R. Alderliesten, C. Rans, R. Benedictus, The applicability of magnesium based fibre metal laminates in aerospace structures. Composites Science and Technology 68 (2008) 2983-2993.

[24] M. Sadighi, T. Pärnänen, R.C. Alderliesten, M. Sayeaftabi, R. Benedictus, Experimental and numerical investigation of metal type and thickness effects on the impact resistance of fiber metal laminates. Applied Composite Materials 19 (2012) 545-559.

[25] D.A. Burianek, S.M. Spearing, Fatigue damage in titanium-graphite hybrid laminates. Composites Science and Technology 62 (2002) 607-617.

[26] G. Reyes V, W.J. Cantwell, The mechanical properties of fibre-metal laminates based on glass fibre reinforced polypropylene. Composites Science and Technology 60 (2000) 1085-1094.

[27] A.A.M. Badawy, Impact behavior of glass fibers reinforced composite laminates at different temperatures. Ain Shams Engineering Journal 3 (2012) 105-111.

[28] S.I. Ibekwe, P.F. Mensah, G. Li, S.-S. Pang, M.A. Stubblefield, Impact and post impact response of laminated beams at low temperatures. Composite Structures 79 (2007) 12-17.

[29] S. Zhu, G.B. Chai, Low-velocity impact response of fibre–metal laminates – experimental and finite element analysis. Composites Science and Technology 72 (2012) 1793-1802.

[30] A. Seyed Yaghoubi, B. Liaw, Thickness influence on ballistic impact behaviors of glare 5 fiber-metal laminated beams: Experimental and numerical studies. Composite Structures 94 (2012) 2585-2598.

[31] A. Seyed Yaghoubi, B. Liaw, Effect of lay-up orientation on ballistic impact behaviors of glare 5 fml beams. International Journal of Impact Engineering 54 (2013) 138-148.

[32] M. Haghi Kashani, M. Sadighi, M. Mohammadkhah, H. Shahsavari Alavijeh, Investigation of scaling effects on fiber metal laminates under tensile and flexural loading. Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials Design and Applications (2013).

[33] S.H. Song, Y.S. Byun, T.W. Ku, W.J. Song, J. Kim, B.S. Kang, Experimental and numerical investigation on impact performance of carbon reinforced aluminum laminates. Journal of Materials Science & Technology 26 (2010) 327-332.

[34] N. Tsartsaris, M. Meo, F. Dolce, U. Polimeno, M. Guida, F. Marulo, Low-velocity impact behavior of fiber metal laminates. Journal of Composite Materials (2011).

[35] J. Fan, Z.W. Guan, W.J. Cantwell, Numerical modelling of perforation failure in fibre metal laminates subjected to low velocity impact loading. Composite Structures 93 (2011) 2430-2436.

[36] J. Patryk, B. Jaroslaw, M. Krzysztof, O. Monika, S. Barbara, The impact behavior of aluminum hybrid laminatesnull. Aircraft Engineering and Aerospace Technology 86 (2014) 287-294.

[37] J.L. Thomason, The influence of fibre length, diameter and concentration on the impact performance of long glass-fibre reinforced polyamide 6,6. Composites Part A: Applied Science and Manufacturing 40 (2009) 114-124.

[38] A.A. Khalid, The effect of testing temperature and volume fraction on impact energy of composites. Materials & Design 27 (2006) 499-506.

[39] F.D. Morinière, R.C. Alderliesten, R. Benedictus, Modelling of impact damage and dynamics in fibre-metal laminates – a review. International Journal of Impact Engineering 67 (2014) 27-38.

[40] M. Haghi Kashani, M. Sadighi, A. Lalehpour, R. Alderliesten, The effect of impact energy division over repeated low-velocity impact on fiber metal laminates. Journal of Composite Materials (2014).

[41] M.O.W. Richardson, M.J. Wisheart, Review of low-velocity impact properties of composite materials. Composites Part A: Applied Science and Manufacturing 27 (1996) 1123-1131.

[42] G.J. Tsamasphyros, G.S. Bikakis, Analytical modeling to predict the low velocity impact response of circular glare fiber–metal laminates. Aerospace Science and Technology 29 (2013) 28-36.

[43] M.S. Hoo Fatt, C. Lin, D.M. Revilock Jr, D.A. Hopkins, Ballistic impact of glare™ fiber–metal laminates. Composite Structures 61 (2003) 73-88.

[44] T. Sinmazçelik, E. Avcu, M.Ö. Bora, O. Çoban, A review: Fibre metal laminates, background, bonding types and applied test methods. Materials & Design 32 (2011) 3671-3685.

[45] R.C. Alderliesten, On the available relevant approaches for fatigue crack propagation prediction in glare. International Journal of Fatigue 29 (2007) 289-304.

[46] R.C. Alderliesten, Analytical prediction model for fatigue crack propagation and delamination growth in glare. International Journal of Fatigue 29 (2007) 628-646.

[47] Y.-J. Guo, X.-R. Wu, A phenomenological model for predicting crack growth in fiber-reinforced metal laminates under constant-amplitude loading. Composites Science and Technology 59 (1999) 1825-1831.

[48] J.G. Carrillo, W.J. Cantwell, Mechanical properties of a novel fiber–metal laminate based on a polypropylene composite. Mechanics of Materials 41 (2009) 828-838.

[49] M.R. Abdullah, Y. Prawoto, W.J. Cantwell, Interfacial fracture of the fibre-metal laminates based on fibre reinforced thermoplastics. Materials & Design 66, Part B (2015) 446-452.

[50] G. Bibo, D. Leicy, P.J. Hogg, M. Kemp, High-temperature damage tolerance of carbon fibre-reinforced plastics. Composites 25 (1994) 414-424.

[51] I.M. Daniel, B.T. Werner, J.S. Fenner, Strain-rate-dependent failure criteria for composites. Composites Science and Technology 71 (2011) 357-364.

[52] M.M. Shokrieh, M.J. Omidi, Investigating the transverse behavior of glass–epoxy composites under intermediate strain rates. Composite Structures 93 (2011) 690-696.

[53] Y. Hirai, H. Hamada, J.-K. Kim, Impact response of woven glass-fabric composites—ii. Effect of temperature. Composites Science and Technology 58 (1998) 119-128.

[54] G.H. Payeganeh, F. Ashenai Ghasemi, K. Malekzadeh, Dynamic response of fiber–metal laminates (fmls) subjected to low-velocity impact. Thin-Walled Structures 48 (2010) 62-70.

[55] S. Abrate, Modeling of impacts on composite structures. Composite Structures 51 (2001) 129-138.

[56] F.D. Morinière, R.C. Alderliesten, M. Sadighi, R. Benedictus, An integrated study on the low-velocity impact response of the glare fibre-metal laminate. Composite Structures 100 (2013) 89-103.

[57] H. Seo, J. Hundley, H.T. Hahn, J.-M. Yang, Numerical simulation of glass-fiber-reinforced aluminum laminates with diverse impact damage. AIAA Journal 48 (2010) 676-687.

[58] G. Caprino, G. Spataro, S. Del Luongo, Low-velocity impact behaviour of fibreglass–aluminium laminates. Composites Part A: Applied Science and Manufacturing 35 (2004) 605-616.

[59] G.S. Langdon, S.L. Lemanski, G.N. Nurick, M.C. Simmons, W.J. Cantwell, G.K. Schleyer, Behaviour of fibre–metal laminates subjected to localised blast loading: Part i—experimental observations. International Journal of Impact Engineering 34 (2007) 1202-1222.

[60] S.L. Lemanski, G.N. Nurick, G.S. Langdon, M.C. Simmons, W.J. Cantwell, G.K. Schleyer, Behaviour of fibre metal laminates subjected to localised blast loading—part ii: Quantitative analysis. International Journal of Impact Engineering 34 (2007) 1223-1245.

[61] R.M. Frizzell, C.T. McCarthy, M.A. McCarthy, Simulating damage and delamination in fibre metal laminate joints using a three-dimensional damage model with cohesive elements and damage regularisation. Composites Science and Technology 71 (2011) 1225-1235.

[62] D. Karagiozova, G.S. Langdon, G.N. Nurick, S. Chung Kim Yuen, Simulation of the response of fibre–metal laminates to localised blast loading. International Journal of Impact Engineering 37 (2010) 766-782.