Studies on factors influencing Low Velocity Impact of Composite Materials – A Review

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Abstract. Composite Materials has been the de-facto material of choice in the aerospace and automotive industry mainly due to its high strength to weight ratio. Composite materials fabricated by different methods have been used in the above fields, some have found to be resistant to failure while some have failed to live-up to the expected results. Therefore, it is evident that, although composite materials provide excellent directional properties, failure in composite materials is a key area that many researchers have been studying for many decades and may still continue with development of newer materials. One such failure that can occur in composite materials is due to impact loading and the focus of this paper is to review the factors associated with Low Velocity Impact. In general, damage in composite material is a serious issue and factors that contribute needs to be studied in depth, since this may lead to catastrophic failure and some failures that is generated, may not be visible to the naked eye. Failure arising from LVI is not limited to fibre matrix cracking, de-bonding, delamination, fibre pull out and possible ways to overcome these effects may be of significant importance particularly in the aerospace industry and possible ways to improve them is discussed in this paper.

Keywords: Low Velocity Impact, Damage Mechanism, Impactor, Stacking Sequence

1. Introduction
Composite Materials are more promising materials in the aerospace, automotive, consumer, wind power applications. One of the renowned benefits of composite materials is high strength to weight ratio and far superior mechanical characteristics as compared to metallic materials. Another promising features of composite materials is the net zero cost in the area of maintenance due to the fact that it has excellent corrosion resistance [1] enabling engineers to use such a material as an alternative to steel structures. Even though composites are extensively used in the above areas of application, it is essential to understand that composite materials are susceptible to damage and may lead to plastic deformation resulting in matrix cracking, delamination, fibre pull out. The damage mechanism may be caused due to impact and the type of impact can be categorised into three types (i) Low Velocity (ii) Intermediate / High Velocity (iii) Hyper Velocity Impact [2]. In one case study with reference to Boeing 747, it was found from a sample of 71 aircraft with over 600+ repair parameters, with a little over 13% of the repairs was found to be with reference Low Velocity Impact from foreign body impact (damage) [3]. Possible causes of Low Velocity Impact (LVI) may be from tool drop, maintenance and potential bird strike. Table 1 shows the classification of types of impact velocities.
Table 1. Impact Velocity Parameter

| Velocity Type          | Velocity (ms\(^{-1}\)) |
|------------------------|-------------------------|
| Low Velocity           | 0-6 m/s                 |
| Intermediate / High    | > 6 m/s                 |
| Ballistic Velocity     | > 500 m/s               |
| Hyper Velocity         | > 1700 m/s              |

Figure 1. Damage due to LVI and its internal structure. [4]

As indicated above, a LVI can result in several types of damages and lead to catastrophic failure. With such a failure, the damage mechanism may not be visible at the surface and may result in exponential degradation of the composite panel and in turn reduce the overall performance of the composite panels [5]. In any impact process a list of prospective damage mechanism can be recorded and some of them are listed in Table 2.

Table 2. Prospective Damage Types due to Low Velocity Impact [6-7]

| Sl. No. | Types of Damage                                |
|---------|-----------------------------------------------|
| 01      | Delamination                                   |
| 02      | Fibre Pull Out                                 |
| 03      | Matrix Cracking                                |
| 04      | Damage / Dent at the location of Impact        |
| 05      | Surface Buckling                               |
| 06      | Fibre Matrix Cracking                          |
| 07      | Inter-laminar Damage                           |
| 08      | Surface Buckling                               |

When it comes to space scenario, low velocity impact is of significant importance, since there are several satellites that are orbiting around the earth and a chance of impact is very much possible, this is also not limited to re-entry scenario, this was the case when the space shuttle Columbia during its re-entry an impact with the foam on the wing lead to failure of the space shuttle [8]. For more than three decades the fabrication industry related to composites have been using thermosetting resin system. This however has some issues related to irrevocable exothermic reaction during the curing process [9]. It is worth noting that there are new systems such as thermoplastic resins that can improve
the overall performance of composite materials in areas such as processing, recyclability etc. Refer to the Table 3 for comparison between TS (Thermosetting) and TP (Thermoplastic) resin

Table 3. TS and TP resin system [10]

| Parameter          | TS          | TP          |
|--------------------|-------------|-------------|
| Toughness          | Average     | Excellent   |
| Fabrication Temp   | Poor        | Excellent   |
| Recycle Status     | Average     | Good        |
| Service Temp       | Excellent   | Average     |

Researchers have done extensive work related to comparison between QSI and LVI related damage in PMC, it is found that composite laminates damage initiation due to the above two cases has led to similar results [11-14]. There are several factors that influence the impact properties of composite laminates which is shown in Figure 2.

Figure 2. Factors Influencing Impact Response [15]

It is evident that above factors are not a dataset that influence the impact response of the composite laminates, there are several other factors which influence the impact damage performance of a composite materials. To review this, LVI process is always followed by CAI (Compression after Impact) test, which is essential since CAI assess the overall performance of the composite materials as this helps researchers in finding the residual strength left in the composite material after impact. It is always advised to carry out CBI (Compression before Impact) to enable researchers know the strength of the composite laminates before impact there by assessing its residual strength of the panel of interest. Further, impact response of the composite panels is also affected by chemical and mechanical
characteristics which can lead to composite damage and resulting in different failure modes. Failure may also result due to laminate stacking sequence such as inter / intra ply.

Based on the several factors, this review paper will facilitate the user to understand the factors that can probably influence the impact damage of composite laminates due to Low Velocity Impact with varying parameters.

2. Parameters Affecting LVI Process

2.1. Process Parameter
In any low velocity impact test there are several process involved before the test can be performed. Process parameter usually involves fabrication related information, such as, type of resin involved as indicated in table 3, type of fabrication involved namely – Vacuum Bagging Process, VARTM – Vacuum Assisted Resin Transfer Molding, Compression Molding etc. The extent of damage is significantly noticed.

2.2. Material Parameter
The material parameter plays a significant role in determining the LVI process, parameters such as material fiber orientation - unidirectional, bi-directional. Material type - Glass, Carbon, Kevlar or Natural fibers. Stacking sequence – [0/90], [0/45/90/45/0] etc. and Inter / Intra Layered stacking sequence can significantly influence the impact properties of composite laminates.

2.3. Test Parameter
The test parameters associated with LVI process includes height of fall, types of impactors, mass of impactor. These parameters can significantly affect the LVI process based on the geometry of the composite laminate such as flat or curved, thickness of the panel and orientation of the fiber.

2.4. Standard Plot related to LVI
Any composite material when subjected to Low Velocity Impact undergoes various types of deformation and it experiences damage at different stages such as Contact, Impact, Deformation, Rebound, Perforation and finally Penetration. A typical LVI plot is shown in Figure 3, which illustrates the parameters as listed above.

![Figure 3. Typical LVI – Force vs Deflection Graph [15]](image-url)
3. Basic Parameters Affecting LVI Process

During the service life of the composite material, it can be subjected to several internal or external damages. Some of them may not be limited to matrix cracking, fibre – matrix de-bonding, fibre breakage etc. Therefore, it is necessary to improve the overall resistance to damage of the composite material, in order to improve the LVI properties. There were several methods proposed to improve the properties related to composite materials such as matrix toughening, thickening of laminate, enhancing the woven fabric architecture via hybrid fibres using different material and via different stacking sequence as reported by Kim [16].

3.1. Fibre Orientation on LVI process

As illustrated earlier, fiber orientation plays a significant role in enhancing the LVI properties. Composites provide better properties across in-plane as compared to transverse directional properties and in turn undergo damage or deformation [17]. The delamination in a composite laminate is a serious scenario and needs better methods to overcome this issue and in turn enhance the residual strength of the composite laminate [18]. To address this issue, usage of UD, Woven composite laminates are on the rise and in turn better composite panels can be prepared to over the issues due to fiber fracture, fiber pull out and fiber matrix cracking when subjected to LVI process. Possible ways to overcome the effect of fiber failure could be to increase the fiber size of the cloth under consideration there by overcoming the potential effects of fiber failure due to localized and general damage of the composite panels. Another possible way to reduce the failure is to adopt z direction stitching of composites along with woven cloth there by enabling the overall impact damage resistance. All these is possible when a user can adopt 3D fabric along with warp and weft, transverse directional properties can be enhanced by adopting z directional reinforcements. It can be found that these reinforcements can enhance the structural integrity and delamination resistance along with greater energy absorption. Many researchers have found that 3D based composites have enhanced the overall performance of the composites as compared to 3D composites [19]. By switching over from 2D to 3D composite panels, the overall performance of composite laminates due to LVI has significantly increased [20]. Further research work carried out with reference to 2D and 3D composites showed a 50% less damage area, better structural performance and better impact properties [21] refer to the figure 4 below for better weaving process to enhance the damage resistance due to fiber architecture. In a nutshell the 3D composites provide better solution for all issues related to LVI.

![Figure 4](image-url)

**Figure 4.** a) Orthogonal b) Interlock c) layered Interlock d) Modified Layered Interlock [22]
3.2. Resin and its role in LVI process

The resin is another important entity of the composite materials and also plays a significant role in LVI process. Resin related properties as listed in Table 3 gives a clear understanding that TP type resins will provide better and superior impact damage resistance and is highly recommended for composite fabrication process. The one main advantage of TP type resins is that it ensures the fiber pattern (orientation) in place and enables reduced fiber damage properties [23]. Another reason in adopting TP type resins in aerospace application is that it has superior damage resistance and exhibits toughness about ten times as compared to TS resin. Further the fatigue properties are also superior as compared to TS resin. But only one area where creep is considered the TS fares well [24]. It further noted that in terms of specific energy absorption properties of TS and TP, TP favors better roughly around 57.3% better than TS resins of the same configuration of composite panels when they were investigated in-situ using a digital microscopy and later analyzed via SEM [25]. Many researchers have concluded that TP will have better properties as compared to TS resin [26-28].

4. Other Parameters Affecting LVI Process

4.1 Fracture and its role in LVI process

As indicated earlier, TP resins enables better performance characteristics of LVI process, therefore toughness properties enhance [25]. With reference to temperature, the values increase as reported by Kim and Ye [29]. Further it can be noted that parameters such as fiber orientation and resin toughness can enhance the overall toughness of the composite materials. In addition to these factors, other factors that can potentially affect the fracture toughness are temperature, moisture, humidity.

4.2 Thickness and its role in LVI process

It is well understood that thickness plays a significant role in determining the effect of LVI process. It further understood that any thickness beyond 8 mm cannot be used as laminate structure and rather focus on sandwich panel type is preferred. But appropriately selecting the orientation of plies and selecting a suitable thickness enhances the overall performance due to LVI. But gradually increasing the thickness of composite laminates increases the failure threshold of the composites. When comparing with thin laminates thick ones favored better impact resistance. In a certain type of composites, the Hertzian value increased with increase in thickness [30].

4.3 Impactor and its role in LVI process

Impactors play a significant role in performing LVI studies. Several researchers have carried out studies on different impactors and the most commonly used impactor is hemispherical type and also it has a higher factor of influence on the level of damage. It is also clear that the tests performed on a controlled environment is different from a real time scenario, where the type of impact and the nature of impact can vary. To be more precise the impactor of size 12.7 mm of hemispherical type is the most general configuration used in the impact studies as this provides a greater damage and higher penetration through the specimen. Further the damage tolerance increases with increased diameter. Impactors such as flat is also preferred by researchers as this provides a study related to surface damage mechanics and the effect of LVI process. Impactors such as truncated, spherical, ogival are also used for studying the impact damage assessment of composite structures, these are used based on the type of application. It is evident that higher impact results in deeper understanding of the energy absorption process [31-35].

4.4 Stacking Sequence and its role in LVI process

Stacking sequence plays a significant role. Composite materials offer unique advantage when they are tailored to meet specific design requirements by means of stacking process. In case of stacking of composite panels, adopting glass fiber cloth on top of the stacking enables better impact resistance as compared to any other fabric. By focusing on a changing stacking sequence delamination and deformation can be significantly reduced. In stacking sequence lay-up process has a dominant role as
it alters the LVI process. Temperature and Stacking sequence does not have any role in enhancing the overall of impact resistance. Stacking process can be adopted to increase the stiffness of the composite panel, however, the damage due to impact may not have a significant role. By altering the ply orientation marginal increase in impact damage can be increased. By increasing the number of interface, damage tolerance can be marginally increased [36]. Adopting optimized stacking sequence for TS and TP layers and in turn inserting alternate TP layers among the TS and TP resulted in increased failure resistance by 15 times [37].

4.5 Temperature and its role in LVI process
The effect of impact properties and damage mechanics is greatly affected by temperature variation, humidity and hygro-thermal variations. TP and TS systems play a vital role in damage mechanism, TP composites at low temperature provides better performance of composites since they offer increased matrix ductility. Hygro-thermal ageing is another parameter that affects the LVI properties, at higher temperature and the residual strength reduced by 60-70%. Many researchers have carried out temperature related works on the Low Velocity Impact and the range of temperature were found to be between -80°C to +180°C and majority of the researchers have been concluded

- Reduction in Residual Strength
- Decrease in Energy Absorption
- At low Temperature Reduced Delamination
- Increase in BVID (Barely Visible Impact Damage)

5. Conclusion
There are several parameters that affect the performance of composite structures and LVI process is one such component that drastically reduces the service life of composites. In order to overcome these pitfalls, parameters that govern the LVI is essential to understand and adopt suitable methods to overcome them. Although in some cases, there are solutions that can improve, while in others an ideal parameter is yet in the developmental stage. Among all the listed parameters mentioned above, some of the key takeaway are listed below.

In case of process parameter related to preparation of composite panel, it is essential to prepare a laminate under controlled environment and in turn curing them using an autoclave in order to develop a high performance composite material. There by enhancing the performance of the composite material. Also by adopting a suitable fabrication process such as VARTM (Vacuum Assisted Resin Transfer Moulding), VB (Vacuum Bagging) process based on the type of application of composite, the overall shelf life of the panels can be enhanced.

The performance can be enhanced in case of composite laminates by choosing an appropriate material for a particular application. In case of general purpose applications, glass fibre could be adopted and in areas which require higher toughness, combination of Glass and Kevlar could be adopted or even combination of Glass Carbon and Kevlar could be used. Material selection could also be via a hybrid stacking sequence and also via 2D and 3D hybrid composites. This can enhance the service life of the composites and in turn increase the damage tolerance of composites.

All the factors that affect the damage tolerance, can be suitably addressed by selecting appropriate parameters that is relevant to the type of application. By choosing ideal resin such as TP over TS the overall performance increases including fracture toughness, by adopting a suitable stacking sequence the performance of composite panels can increase. Further by adopting a suitable lay-up with optimum thickness, the strength to weight ratio can be maintained. In case of impact region, by adopting inserts concepts, the extent of damage at the susceptible region can be reduced and in turn enhance the service life. In areas related to temperature, by focusing on temperature resistant material, the damage extent can be reduced due to LVI process. In areas related to residual strength, the extent of damage on the specimen may vary compared to the extent of damage on the structure and limited knowledge is available, this in turn needs better studies related to LVI process of structures and panels.
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References
[1] K B Katnam, L F M Da Silva and T M Young 2013 Bonded repair of composite aircraft structures: a review of scientific challenges and opportunities, Progressive Aerospace Sci. 61 26–42. DOI: https://doi.org/10.1016/j.paerosci.2013.03.003
[2] S. Abrate 1998 Impact on Composite Structures (United Kingdom: Cambridge University Press, Cambridge) DOI: https://doi.org/10.1017/CBO9780511574504
[3] Vogelesang L B and Vlot 2000 A Development of fiber metal laminates for advanced aerospace structures. J. Mater. Process Technol. 103 1–5. DOI: https://doi.org/10.1016/S0924-0136(00)00411-8
[4] J. Jefferson Andrew, Sivakumar M Srinivasan, A Arockiarajan and Hom Nath Dhakal 2019 Parameters influencing the impact response of fiber-reinforced polymer matrix composite materials: A critical review Composite Structures 224 111007. DOI: https://doi.org/10.1016/j.compstruct.2019.111007
[5] Richardson M and Wisheart M 1996 Review of low-velocity impact properties of composite materials Compos. A. Appl. Sci. Manuf. 27 1123–31. DOI: https://doi.org/10.1016/1359-835X(96)00074-7
[6] Greenhalgh E and Hiley M 2003 The assessment of novel materials and processes for the impact tolerant design of stiffened composite aerospace structures. Composites Part A 34(2) 151–61. DOI: https://doi.org/10.1016/S1359-835X(02)00188-4
[7] Andrew J Jefferson, Srinivasan Sivakumar M and Arockiarajan A 2018 Influence of patch lay-up configuration and hybridization on low velocity impact and post-impact tensile response of repaired glass fiber reinforced plastic composites J. Compos. Mater. 53(1) 3-17. DOI: https://doi.org/10.1177/0021998318799430
[8] López-Puente J, Varas D, Loya J A and Zaera R 2009 Analytical modeling of high velocity impacts of cylindrical projectiles on carbon/epoxy laminates Composites Part A;40(8):1223–30. DOI: https://doi.org/10.1016/j.compositesa.2009.05.008
[9] Liu X, Yu W and Pan N 2011 Evaluation of high performance fabric under light irradiation J. Appl. Polym. Sci. 120 552–6. DOI: https://doi.org/10.1002/app.33200
[10] Vishwas Mahesh, Sharnappa Joladarashi and Satyabodh M Kulkarni 2021 A comprehensive review on material selection for polymer matrix composites subjected to impact load Defence Technology 17(1) 257-77. DOI: https://doi.org/10.1007/j.dt.2020.04.002
[11] Aoki Y, Suemasu H and Ishikawa T 2007 Damage propagation in CFRP laminates subjected to low velocity impact and static indentation Adv. Compos. Mater. Off. J. Japan. Soc. Compos. Mater. 16 45–61. DOI: https://doi.org/10.1163/156855107779755318
[12] Lee SM and Zahuta P 1991 Instrumented Impact and Static Indentation of Composites J. Compos. Mater. 25 204–22. DOI: https://doi.org/10.1177/002199839102500205
[13] Azwan S M S, Yazid Y M, Amran A and Abdi B 2014 Quasi-Static Indentation Behaviour of Glass Fibre Reinforced Polymer Adv. Mater. Res. 970 317–9. DOI: https://doi.org/10.4028/www.scientific.net/AMR.970.317
[14] Kaczmarek H and Maison S 1994 Comparative ultrasonic analysis of damage in CFRP under static indentation and low-velocity impact Compos. Sci. Technol. 51 11–26. DOI: https://doi.org/10.1016/0266-3538(94)90152-X
[15] S Z H Shah, S Karuppanan, P S M Megat-Yusoff and Z Sajid 2019 Impact resistance and damage tolerance of fiber reinforced composites: A review Comp. Structures 217 100–21. DOI: https://doi.org/10.1016/j.compstruct.2019.03.021
[16] Kim, Jang Kyo. "Methods for improving impact damage resistance of CFRPs." In Key Engineering Materials, vol. 141, pp. 149-168. Trans Tech Publications Ltd, 1998.
[17] Cantwell W and Morton J 1991 The impact resistance of composite materials-a review Compos.
Wisnom M R 2012 The role of delamination in failure of fibre-reinforced composites Phil. Trans. R. Soc. A 370 1850–70. DOI: https://doi.org/10.1098/rsta.2011.0441

[19] Alam, Md Ashraful, and Khalid Al Riyami. "Shear strengthening of reinforced concrete beam using natural fibre reinforced polymer laminates." Construction and Building Materials 162 (2018): 683-696.

[20] Bandaru A K, Sachan Y, Ahmad S, Alagirusamy R and Bhatnagar N 2017 On the mechanical response of 2D plain woven and 3D angle-interlock fabrics Compos. B. Eng. 118 135–48. DOI: 10.1016/j.compositesb.2017.03.011

[21] Shah, S. Z. H., P. S. M. Megat-Yusoff, S. Karuppanan, R. S. Choudhry, F. Ahmad, Z. Sajid, P. Gerard, and K. Sharp. "Performance comparison of resin-infused thermoplastic and thermoset 3D fabric composites under impact loading." International Journal of Mechanical Sciences 189 (2021): 105984. DOI: 10.1016/j.ijmecsci.2020.105984

[22] P. Potluri, P Hogg, M. Arshad, Jetavat and P Jamshidi 2012 Influence of Fibre Architecture on Impact Damage Tolerance in 3D Woven Composites Appl. Compos. Mater. 19 799–812. (https://link.springer.com/article/10.1007/s10443-012-9256-9)

[23] Bhatnagar A 2016 Lightweight ballistic composites: military and law-enforcement applications. (Woodhead Publishing)

[24] Sylvie Beland 1990 High performance thermoplastic resins and their composites (United States: Imprint: William Andrew).

[25] Tan W and Falzon B G 2016 Modelling the crush behaviour of thermoplastic composites. Compos. Sci. Technol. 134 57–71. DOI: https://doi.org/10.1016/j.compscitech.2016.07.015

[26] Hart K R, Chia P X L, Sheridan L E, Wetzel E D, Sottos N R and White S R 2017 Comparison of compression-after-impact and flexure-after-impact protocols for 2D and 3D woven fiber-reinforced composites Compos. A Appl. Sci. Manuf. 101 471–9. DOI: https://doi.org/10.1016/j.compositesa.2017.07.005

[27] Umer, R., H. Alhussein, J. Zhou, and W. J. Cantwell. "The mechanical properties of 3D woven composites." Journal of Composite Materials 51, no. 12 (2017): 1703-1716.

[28] Wang M, Cao M, Wang H, Siddique A, Gu B and Sun B 2017 Drop-weight impact behaviors of 3-D angle interlock woven composites after thermal oxidative aging Compos. Struct. 166 239–55. DOI: https://doi.org/10.1016/j.compositesa.2017.01.046

[29] Kim K-Y and Ye L 2004 Interlaminar fracture toughness of CF/PEI composites at elevated temperatures: roles of matrix toughness and fibre/matrix adhesion. Compos. A Appl. Sci. Manuf. 35 477–87. DOI: https://doi.org/10.1016/j.compositesa.2003.10.005

[30] Wang Wenjie, Chouw Nawawi and Jayaraman Krishnan 2016 Effect of thickness on the impact resistance of flax fibre-reinforced polymer J. of Reinfl. Plastic Composites 35(17) 1277–89. DOI: https://doi.org/10.1177/0731684416648780

[31] Nassir Nassier A, Guan Z W, Birch R S and Cantwell W J 2018 Damage initiation in composite materials under off-centre impact loading Polym. Test. 69 456–461. DOI: 10.1016/j.polymertesting.2018.06.006

[32] Özen M 2017 Influence of stacking sequence on the impact and postimpact bending behavior of hybrid sandwich composites Mech. Compos. Mater. 52(6) 759–66. DOI: 10.1007/s11029-017-9626-3

[33] Atas C and Sayman O 2008 An overall view on impact response of woven fabric composite plates Compos. Struct. 82(3) 336–45. DOI: https://doi.org/10.1016/j.compositesstruct.2007.01.014

[34] Patel Shivdayal and Guedes Soares C 2018 Reliability assessment of glass epoxy composite plates due to low velocity impact. Compos. Struct. 200 659–68. DOI: 10.1016/j.compositesstruct.2018.05.131

[35] Sutherland L S 2018 A review of impact testing on marine composite materials: Part III – Damage tolerance and durability Compos. Struct. 188 512–18. DOI: https://doi.org/10.1016/j.compositesstruct.2018.01.042

[36] Reis L and De Freitas M 1997 Damage growth analysis of low velocity impacted composite panels Compos. Struct. 38 509–15. DOI: https://doi.org/10.1016/S0263-8223(97)00086-X
[37] Sonnenfeld C, Mendil-Jakani H, Agogué R, Nunez P and Beauchêne P 2017 Thermoplastic/thermoset multilayer composites: a way to improve the impact damage tolerance of thermosetting resin matrix composites Compos. Struct. 171 298–305. DOI: https://doi.org/10.1016/j.compstruct.2017.03.044