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Effect of Ply Thickness on Damage Mechanisms of Composite Laminates under Repeated Loading

Barely visible impact damage (BVID) occurs in composite laminates subjected to low-velocity impact. They can then exhibit significant effect on mechanical performance of laminates. Previously, it is shown, analytically and experimentally, that BVID occurs at a critical energy level and below this energy level there is no induced damage. However, repeated impact may cause BVID even below the critical energy level. This paper is a novel investigation that deals with the cyclic behaviour of quasi-isotropic glass/epoxy laminated composites under indentation, which is a quasi-static version of low-velocity impact. In particular, this study aims to investigate the ply thickness effect on matrix crack-induced delamination damage in the case of laminated composites under cyclic quasi static indentation loadings. The effect of different parameters, such as load level and ply thickness, on the damage evolution were here investigated. Tests were performed according to the ASTM 7136 standard. Since the glass layer was translucent, it was also possible to visually inspect the matrix delamination during the tests. The laminates were subjected to load levels lower than the critical load level, while there was no evidence of damages when samples were indented just once. However, by increasing the number of cycles, matrix crack-induced delamination appeared in the samples. In brief, it was observed that the ply thickness and energy level have significant effects on the intensity of the induced damage.

Keywords: *Glass/epoxy, laminates, low-velocity impacts, cyclic indentation, damage, delamination, critical energy level.*

1. INTRODUCTION

Due to the excellent properties of composites, such as light-weight, high-strength and corrosion resistance [1], the use of these materials has increased drastically in a large assortment of multi-faced applications and market products [2], involving different industrial sectors and market segments such as aerospace and aircrafts [3, 4], automotive and motorbikes [5, 6] or their parts [7], sport equipment, architecture and interiors, energy and wind-farms, oil and gas, sailing and boat building [8, 9] or many others (Figure 1).

Composites, if wisely used [10], place the designer in a position to best exploit the peculiar characteristics of them [11, 12], such as the marked anisotropy in mechanical properties. It is not always possible to replace a more traditional material (such as steel or aluminum) with a composite material, but in case it is possible, the benefits in terms of products and processes can be incredibly significant.

Quite recently an increasing trend in the massive use of composites, especially carbon fibre reinforced polymers (CFRP), has been highlighted in the aerospace and aviation industries to enable the construction of very light and efficient aircrafts.

Figure 1. Examples of the variety of applications of composite materials including aerospace, architecture, automotive, energy, marine, pipe & tank.

Despite the increasing usage of composite materials, poor impact and out of plane behaviour of these materials represent a challenging and yet unsolved obstacle, which limit the wider application of composite structures. Impact induced damage, and the problems associated with that, are the limiting design criteria for composite material in aeronautical structures [14, 15].

At the same time, impact induced damage in a laminated composite can be visible or non-visible [16,

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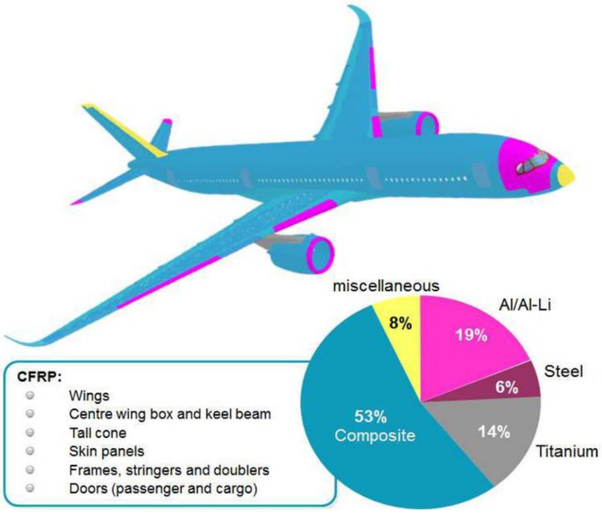
17]. High velocity and high energy impacts result in visible damage; while low velocity and low energy impacts cause invisible damage, improving the overall risk related to the use of composite parts.



The adoption of CFRP, higher than 50%, results in the reduction of fuel consumption in modern aircrafts, like, for example, in the case of *Airbus A350* and *Boeing* 787 *Dreamliner* (Figure 2) [13].

Figure 2. Materials used Airbus A350 XWB [13]

Under low velocity impact loading conditions, the contact time is relatively long, which results in kinetic energy to be accommodated away from the contact point. However, high velocity impact loading generates concentrated type of response, leading to the dissipation of energy over a relatively small area [18].

For example, in an aircraft, accidents i.e. bird strike events and tool drop during manufacturing and maintenance can cause low-velocity impact (LVI) [19]. This accidental damage is usually categorised by the naked eye detectability (as illustrated in Figure 3) and compared to barely visible impact damage (BVID). BVID is a crucial concept concerning aircraft structures damage tolerance [20, 21]. It is evident how those aspects are relevant for safety and maintenance plans.

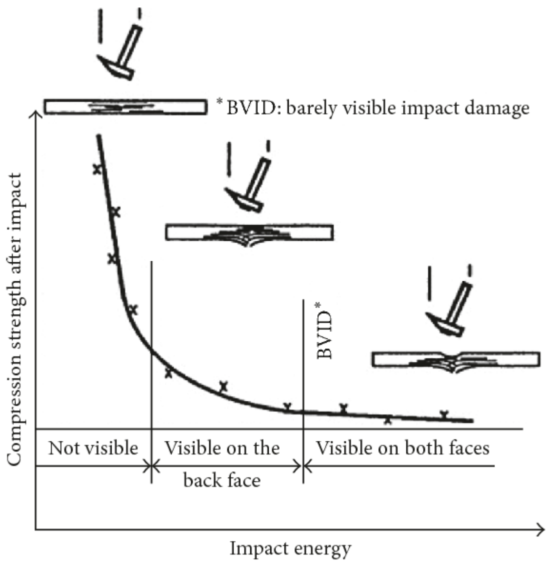


Figure 3. Effect of BVID on compression after impact strength [19].

LVI induced damage, in fact, might be left undetected and can cause severe reduction in the laminate strength and stiffness [22-24]. Figure 3 also shows the effect of this damage on compression after impact strength.

The need for impact resistant composites has pushed researchers to focus on the way for reducing impact induced damage and improving impact performance by different methods such as fibers properties [25, 26], matrix toughening [27, 28], laminate stitching [29], optimization of stacking sequence and braided fabric [30, 31], edge cap reinforcement [32], and interleaving the ply interfaces with ductile materials such as micro and nanoparticles – and films [33-38].

Different parameters such as laminate's in-plane dimensions, thickness, lay-up configuration, fibre direction and material properties were reported to be important factors in low-velocity impact behaviour and the evolution of impact induced damage [39-42]. By several authors, it was also reported that quasi-static indentation (QSI) and LVI tests induce similar damage mechanisms [43]. Consequently, QSI is often used as a replacement for the LVI to allow better evaluation of damage (as in [44]) also permitting to simplify experimental testing.

Fatigue of LVI is another challenging issue that has been investigated by some authors to evaluate the effect of this loading on the damage tolerance of composites [45]. It was reported that there exists a threshold critical energy above which the delamination damage occurs in laminated composite under just one impact.

When a laminated composite structure is under LVI cyclic loading, these transverse matrix cracks can join up and cause matrix crack-induced delamination damage (see Figure 4), even at energy levels much lower than the threshold critical energy that causes the barely visible delamination damage [46, 47].

Under the threshold critical energy, the number of fatigue cycles those can induce a critical damage level was used as a damage tolerance index for laminated composites [45].

Structural components made of composites are often subjected to cyclic indentation/impact and understanding their long-term behaviour is important as this could help to better design, and to predict their lifetime and schedule future maintenance. This damage mainly occurs at low stress levels during the lifetime of composite structures due to cyclic impact and indentation loadings [48].

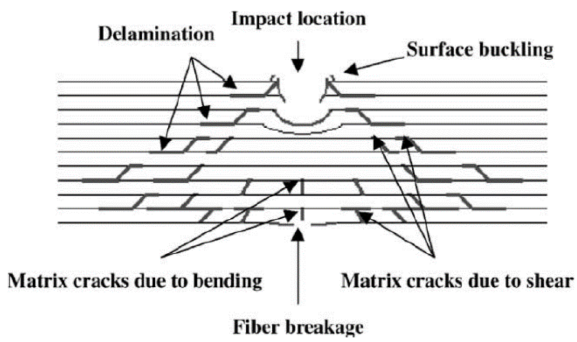


Figure 4. Schematic representation of LVI induced damage for a composite laminate [50].

Matrix crack-induced delamination damage can significantly reduce the residual strength as the accumulated damage size can be even higher than the damage size induced due to a high impact energy level [48, 49]. So, it is imperative to characterize and detect this damage extent under repeated LVI and QSI loadings.

In line with the aforementioned topics, the aim of this work is to investigate the effect of ply thickness on matrix crack-induced delamination damage in laminated composites under cyclic quasi-static indentation loadings. Specifically, the analysis deals with glass/ epoxy laminates under indentation, as a quasi-static version of low-velocity impact. Laminates were subjected to load levels lower than the critical load level while matrix delamination was inspected during the tests. By increasing the number of cycles, matrix crack-induced delamination appeared in the samples. The produced knowledge can help us in improving the impact performance and assure a safe and reliable operation.

2. EXPERIMENTAL PROCEDURES

2.1 Materials

Uni Directional (UD) Hexcel S-glass/8552 epoxy prepreg was used to manufacture the laminates. Those prepregs are specially formulated resin matrix systems that are reinforced with man-made fibres such as carbon, glass and aramid. Table 1 summaries the prepreg properties used.

The stacking sequence (SS) of the laminates is quasi-isotropic (QI) i.e. $[45_m/0_m/90_m/-45_m]_{ns}$ where m and n denote the varying values depending upon the type of layup used.

Table 2 summarises the values of m and n used in ply-blocked and sub-laminate lay-ups, where total number of 32 layers are used. The recommended dimensions of the sample are kept as 150 mm long and 100 mm wide in accordance with ASTM [51]. Figure 5 shows schematic of the geometry and angle of each ply in the investigated layups.

Table 1. Properties of the prepreg used.

Material	S-glass/8552 epoxy
E_{11} (GPa)	47.7
E_{22} (GPa)	12.3
G_{12} (GPa)	4.83
G_{IIC} (N/mm)	1.00
Poisson's ratio (υ_{12})	s0.28
Cured ply thickness (mm)	0.155
Areal weight (g/m^2)	190
Strain to failure (%)	3.87
Resin type	8552
Manufacturer	Hexcel

Table 2. Investigated layups.

Lay-up name	m	n	Thickness (mm)	
			Plate	Ply
Ply-blocked	2	2	4.96	0.310
Sub-laminate	1	4	4.96	0.155

Figure 6 shows the different stages of the manufacturing process aiming to produce laminates and samples: hand lay-up phase; applying vacuum; autoclave curing; cutting the cured plates.

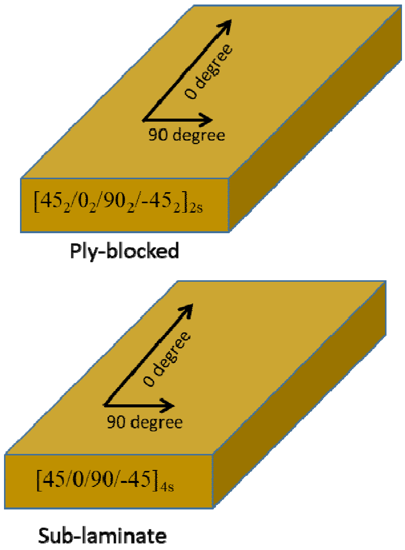


Figure 5. Schematic of the geometry and angle of each ply in the investigated layups.

2.2 Specimen manufacturing

The prepregs were laid up in the desired sequence. Particular attention was paid to the vacuum application phase which had the dual function of an initial consolidation of layers, but also (and above all) favouring the escape of molecules of air, trapped between the layers.

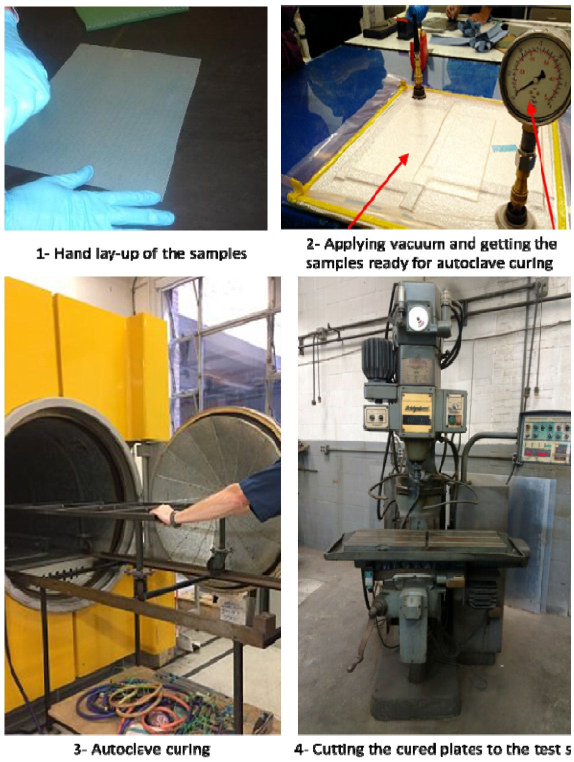


Figure 6. The experimental test set-up for the QSI tests.

The tool plates were then placed in autoclave for the thermal treatment. The recommended curing cycle was followed 8552 epoxy resin. Initially the laminate was cured at 110°C for 60 minutes. After that it followed for 120 minutes at 180°C under 0.69 MPa constant pressure.

After curing, tile cutter was utilised to cut the laminates into desired shapes and dimensions, in accordance with test standards and procedures.

For indentation testing, rectangular fixtures were used. The window of the fixture was 125 mm long while the width of it was 75 mm. This setup closely followed the ASTM D7136/D7136M [51] is the recommended test method for such type of set ups and was closely followed in this study. 3 samples from each configuration were tested to check the repeatability of the data.

2.3 Test procedure

All the quasi-static (QI) indentation tests reported in this manuscript were performed on Instron 8872 servo-hydraulic testing machine as shown in Figure 7. The machine has a universal hydraulic computer-controlled system. 25 kN load cell and a hardened steel indenter of 16 mm diameter was used for the testing of the samples.

Testing was conducted under displacement control and displacement control rate was kept at 1 mm/min. This loading rate remained same for loading and unloading phases, with immediate reloading. The displacement control was kept same for all the tests reported in this manuscript.

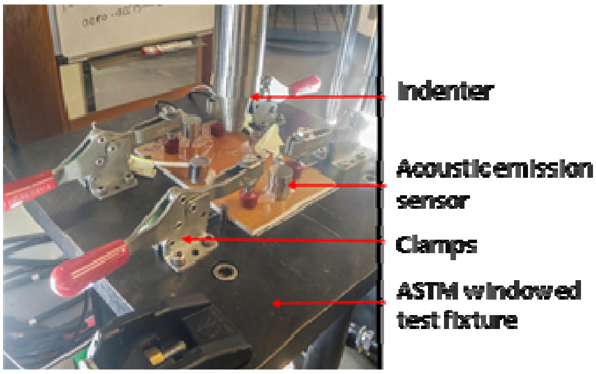


Figure 7. The experimental test set-up for the QSI tests.

3. RESULTS AND DISCUSSION

3.1 Quasi-static tensile test results:

A representative load-displacement plot for the overall behaviour of the S-glass/epoxy samples is shown in Figure 8. The samples were kept loaded until complete fibre failure occurred at their back face due to tension. The associated three region of degradation mechanism due to propagation and evolution can be summarised as following:

Region 1: Linear behaviour in the beginning of the loading phase is categorised under this region. The region has an elastic response and no underlying delamination damage in the laminate was noted in this region.

Region 2: In this region, the initiation and propagation phases are related. This results in losing local rigidity. This is very apparent by change in the load/displacement slope. This change in slope noted to be independent of the laminate thickness. The number and size of delamination enhanced due to the high load in this region.

Region 3: In this final region, fibre failure at the back face of the sample under tension occurred and hence the drop.

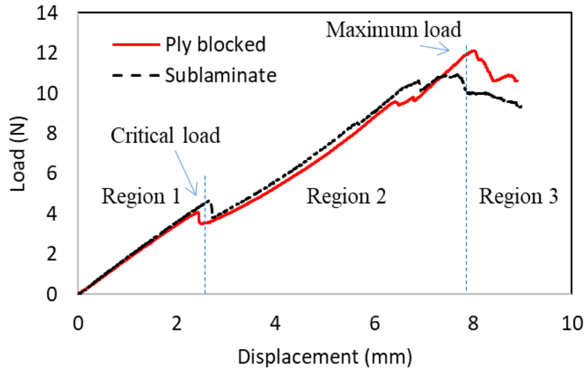


Figure 8. Typical load-displacement responses for the S-glass/8552 epoxy samples under quasi-static indentation.

3.2 Quasi-static cyclic indentation test results:

It is shown in Figure 8 that Barely Visible Impact Damage (BVID) occurs at a critical load level and below this load level there is no induced damage. However, repeated indentations may cause BVID even below the critical load level. To investigate this, as shown in Figure 9, various percentages of the critical load level were applied on the laminates to initiate delamination. Load levels for cyclic indentations were well below the critical load, at a load level of 80% and 90% of the critical load.

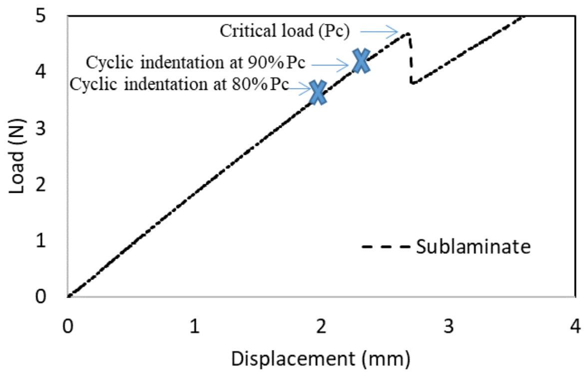


Figure 9. Typical load-displacement response for the sub-laminate S-glass/8552 epoxy sample under quasi-static indentation, and the cyclic indentation scenarios.

Since the glass layer was translucent, it was possible to visually see the matrix crack-induced delamination during the tests. Figure 10 shows the appearance of the samples after being under cyclic indentation for 300 cycles. The un-damaged areas appear brown, and the locally matrix-cracked and delaminated areas are visible as bright. The central area of the plate is under the indenter and appears to be brown due to the compressive load that hinders the damage appearance.

From Figure 10, the sub-laminate laminate has less visible damage and the damage size for the 80% and 90% cyclic indentations is very similar. However, the ply-blocked laminate has higher indentation induced damage, and there is a higher damage area for the 90% cyclic indentation than the 80%. The difference between the sub-laminate and ply-blocked laminates is due to the change in their ply thickness, where the ply thickness for the ply-blocked laminate is two times higher than the sub-laminate sample. As a result, due to the low energy release rate, thinner ply in the sub-laminate sample had no microcracks and/or delamination.

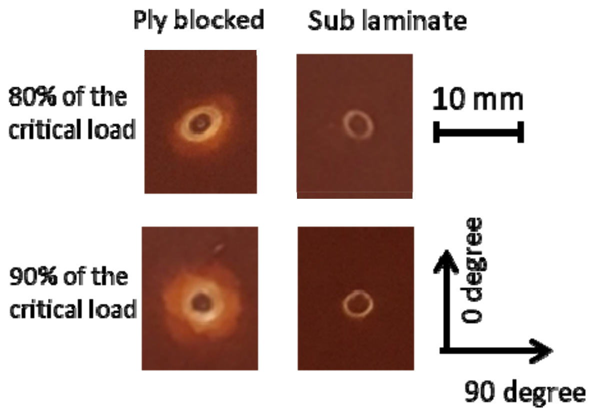


Figure 10. Appearance of the S-glass/8552 epoxy samples after 300 cyclic indentations.

Table 2. Investigated layups.

Experiment	Damage aread (mm2)	STDV (%)
Ply-blocked-80%	10.5	12
Sub-laminate-80%	33.3	6
Ply-blocked-90%	10.2	7.5
Sub-laminate-90%	70.0	3

The induced damage areas are measured and plotted in Figure 11 and listed in table 3, for the comparison purpose, where it is clearly showing the significant difference in the damage size for different layups and load levels.

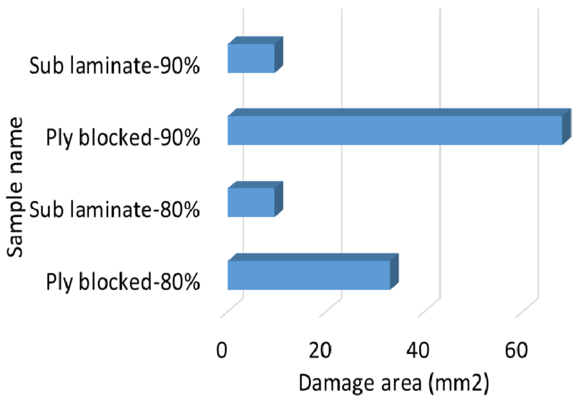


Figure 11: Measured damage area for the investigated samples.

4. CONCLUSION

In this manuscript, load level effect and ply thickness on the matrix crack-induced delamination damage is investigated for glass/epoxy laminates under cyclic quasi-static indentation loadings. The laminates were subjected to load levels lower than the critical load level, the load that causes delamination, and there was no damage for the indented sample when indented just once. However, by increasing the number of cycles, matrix crack-induced delamination appeared in the samples. It was observed that the ply thickness and load level have significant effects on the intensity of the induced damage, where decreasing the ply thickness and load level resulted in a lower matrix crack-induced delamination area. The study suggests that ply thickness is an important parameter and should be considered when designing a laminate with high-performance in cyclic indentation and impact.

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УТИЦАЈ ДЕБЉИНЕ СЛОЈА НА МЕХАНИЗМЕ ОШТЕЋЕЊА КОМПОЗИТНИХ ЛАМИНАТА ПОД ПОНАВЉАНИМ ОПТЕРЕЋЕЊЕМ

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Једва видљива оштећења приликом удара (БВИД) настају у композитним ламинатима који су изложени ударима при малим брзинама и могу показати значајан утицај на механичке перформансе ламината. Претходно је аналитички и експериментално показано да се БВИД дешава на критичном енергетском нивоу и испод овог нивоа енергије нема индукованих оштећења. Међутим, поновљени удар може изазвати БВИД чак и испод критичне бразине енергије. Овај рад је ново истраживање које се бави цикличним понашањем квази-изотропних стакло / епоксидних композита ламинираних под удубљењем, што је квази-статичка верзија удара мале брзине. Посебан циљ овог рада је да се истражи утицај дебљине слоја ламинарних композита на оштећења деламирања изазваног пуцањем на матрици под цикличним квази статичким оптерећењима. Овде је истражен утицај различитих параметара, као што су ниво оптерећења и дебљина слоја, на развој оштећења. Тестови су изведени према АСТМ 7136 стандарду. Пошто је стаклени слој био провидан, такође је било могуће визуелно прегледати одлагање матрице током тестова. Ламинати су подвргнути нивоу оптерећења нижем од критичног нивоа оптерећења док није било доказа о оштећењу када су узорци урезани само једном. Међутим, повећањем броја циклуса, у узорцима се појавила деформација изазвана пуцањем пукотина. Укратко, примећено је да дебљина слоја и ниво енергије имају значајан утицај на интензитет индукованог оштећења.