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A Review of Impact Drop Testing of Composite Laminate Plates

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***Abstract*—Today, composite materials are widely used in many industrial applications due to their advanced properties such as a higher strength-to-weight ratio. However, low-velocity impact failure in composites poses maintenance issues since it may result in unseen damage. This work provides a detailed overview of impact drop testing of composite laminate plates. The principal objective of this work is to comprehend the impact damage behaviour and failure mechanism in composite laminates. The paper also provides examining new techniques for making composite laminates and how these techniques might affect the impact performance of composite materials.**

Keywords—composite materials, fiber reinforced plastics, materials testing, material properties

I. INTRODUCTION

Composite materials are created by mixing two or more fundamental materials. They are typically constructed of several layers of polymer matrix reinforced by fibres of great strength. While the polymer matrix transmits stresses between the fibres and serves as an adhesive to hold them together, the fibres' main job is to convey load in the direction of the fibres. Frequently, composites take the form of laminates, which are constructed from bonded layers of various fibre alignments. The stiffness of a composite laminate depends on the direction of the fibres in relation to the direction of the applied load, thus the physical characteristics of composites are typically anisotropic in nature. Due to their distinctive qualities and ability to be customised to fulfil specific needs, composites are widely employed in a variety of applications, including aircraft, cars, and sports equipment [1].

The composite structure's susceptibility to low-velocity impact is a significant issue regarding its structural integrity. Such collisions could cause a variety of damage mechanisms, which could considerably decrease the strength and integrity of composite structures. The interlayer gap between the fibres and the matrix and the brittleness of the polymer matrix could cause the impact damage to spread through the entire construction. The intensity of the various damage modes is affected by several factors, including the impactor's mass and velocity as well as the composite structure's material orientation. There have been reports of several impact damage patterns in composite laminates, including an elliptical form for a spherical impactor and a roughly rhombic or triangular form for a diamond-shaped impactor. Visible damage can be easily found, and repairs can be made right away to preserve the structural integrity. The issue with low-velocity impact damage is that it frequently can not be seen during routine visual assessment. The expansion of hidden, undiagnosed flaws brought on by fatigue and low-velocity impact is a serious concern. Failure to identify any internal deterioration initially could cause the composite structure to collapse catastrophically [1]-[3].

The failure in composites under low-velocity impact is a complicated issue. Mixed damage modes and various failure scenarios are possible. Examples of diverse failure modes include matrix cracking, fibre breakage, fibre debonding and delamination. The process of damage origination and propagation in composites has been the subject of numerous investigations. Due to the significant stress concentration, it has been determined that the matrix cracks immediately beneath the damaged area are the first to initiate. Once started, cracks typically spread among fibres, particularly along the fibre-matrix contact. Cracks often run the whole thickness of a ply and are perpendicular to the direction of a load. In a cross-ply plate, cracks can extend the whole thickness of one ply but cannot extend into the neighbouring ply because its fibres are aligned in a different direction; as a result, the cracks end at the joint between the two plies. The resultant high inter-laminar strains, however, create ideal circumstances for delamination to begin at the ply contact. Fatigue causes more delamination to initiate and spread. Another sort of damage is also seen as more delamination's start to appear. A composite is effectively reduced to singular plies to support the load applied when cracks or delamination's hinder load distribution between plies. The failure of the weakest ply will cause the fibres to fail as well; the fibres may begin to debond, and fractures will become visible [1]-[3]. Fig. 1 illustrates a side view of an impacted laminate showing extensive delamination without visible surface damage. A scheme of barely visible impact damage (BVID) in composite structures is shown in Fig. 2.

The paper provides an overview of impact drop testing of composite laminate materials. The overview extends the understanding of the failure mechanism of impact damage behaviour in composite laminates. It also analyses new methods of creating composite laminates and how these methods might affect the impact performance of composites.

II. OVERVIEW OF RELATED STUDIES

Throughout their lifespan, composites may be subject to impacts. For instance, during maintenance, a tool could accidentally strike a composite, or a flying fragment could hit the composite's structure, such as a rock strike a mountain bike frame. The damage that results from such hits typically takes the form of delamination. Other types of damage such as fibre breakage and matrix failure may also

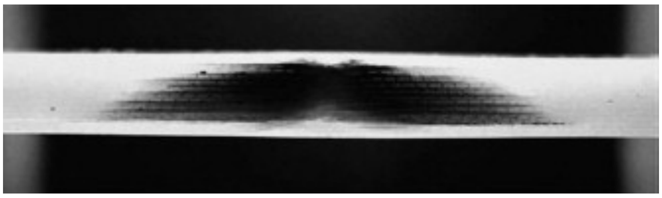

Fig. 1. Side view of an impacted laminate showing extensive delamination without visible surface damage [15].

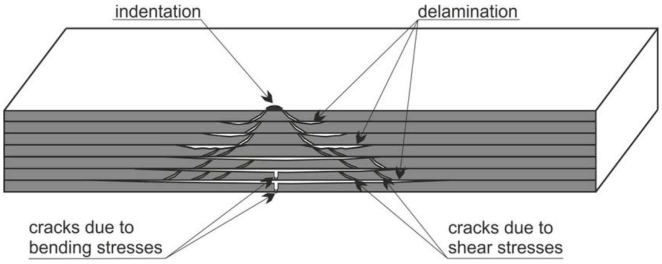

Fig. 2. Scheme of barely visible impact damage (BVID) in composite structures [4].

be seen at high impact energies. Most research on low-velocity impacts have used hemispherical impactors [5]. However, an object which has a low-velocity impact with a composite structure can take many shapes. It is therefore crucial to understand how impactor form affects composites' reactivity to low-velocity impacts.

The influence of impactor shape on thin woven carbon/epoxy composites' drop-weight impact performance was studied by Mitrevski et al. [6] and Mitrevsli et al. [7]. They came to the conclusion that a conical impactor caused the specimen to absorb more energy. The peak contact force and shortest contact interval were achieved when impacting the specimen using hemispherical impactors. In a different work, Mitrevski et al. [8] examined how the impactor form responded to preloaded carbon/epoxy laminates. This work shows that the impactor form has an unimportant influence when preloaded conditions are in place. Zhou [9] investigated the laminates of woven glass-reinforced cloth under a low-velocity impact using a flat-ended impactor. The paper claims that geometry has an impact on the structural characteristics of these impact damage processes.

Numerous applications that are subject to impacts have utilised hybrid composites. When two or more fibres are combined into one composite, the benefits of each fibre system are maximised. Most often, one of the fibres will be a low modulus and low-cost fibre, for example, Kevlar, and the other fibre will be a high modulus and high-cost fibre, for example, carbon. Low modulus fibre lowers the cost while increasing the composite's resistance to damage and providing rigidity and load bearing capacity. Benefits of this approach include a balance between stiffness and strength, decreased cost and/or weight, increased impact resistance, and fracture toughness.

The "hybrid effect," which is also known as the synergy effect, is one of the appealing aspects of the hybridisation technique. The "positive hybrid effect" occurs when obtained composite material properties are greater than the value expected through the rule of mixture. Various researchers discovered that the strain at failure and tensile modulus of carbon/aramid fibre hybrids had positive hybrid effects [10]-[12]. The study by Hosur et al. [13] used a hemispherical impactor to execute low-velocity impact testing on thin hybrid composites. They came to the conclusion that hybrid composites outperformed carbon/epoxy laminates in relation to load carrying capability while just slightly reducing stiffness.

Without spending the money and time necessary for real testing, finite element analysis (FEA) has been used to analyse composites. FEA models can produce incredibly useful results for a variety of instances after being validated using experimental data [14]-[17]. A computational model for composite laminate plates was created by Zhang et al. [18] to forecast the onset and progression of matrix cracking and delamination damage in low-velocity impact testing.

Zhang et al. [19] investigated modifying epoxies with carbon nanotubes (CNT) to improve the mechanical and electrical characteristics of carbon fibre composites. Mass fractions of CNTs were dissolved and comprehensively mixed beneath ultrasound. It was discovered that a modified epoxy having 0.2wt% of CNT content has the optimum bending, compressive, tensile strengths, and bending modulus. Although a modified epoxy having a CNT content of 0.3wt% or higher performs much better than a standard carbon fibre reinforced composite, it would have agglomerated CNTs in the composure matrix leading to degradation of the epoxy matrix properties. Various other studies have also shown a marked improvement in the mechanical characteristics of carbon fibre composites after the introduction of CNTs to the epoxy matrix as discussed in [20]-[23].

Many research publications discussed and analysed the fast and energy-efficient microwave curing procedures for composite materials. Xu et al. [24] observed a 39% reduction in cure time as well as a 22% increase of the compressive strength of a composite manufactured using a vacuum bagging assisted by microwave curing process in comparison to a conventionally produced vacuum bagged laminate. Nightingale and Day [25] concluded that "microwave curing could produce composites with comparable mechanical properties to autoclave cured composites but in a much shorter time." However, it was also noted that higher pressure during the microwave curing is crucial for producing composites that are void free.

III. Discussion

A. Summary of Impact Test Results

Table I demonstrates the summary of results obtained from the published works on impact drop testing. In the first work listed in Table I, Bibi and Rahman [1], it is noticed that more impact damage is initiated following to the increase in the impact energy. Compared to other specimens that produce surface impact damage that is almost visually undetectable at these impact energies, the damage of the 8-ply specimen was more extensive. On the 8-ply specimen, the impactor's penetration at 10J is readily visible. Using a scanning electron microscopy (SEM) machine, matrix cracks, fibre breakage, and delamination were observed in all 8-ply composite specimens, while the severity of each defect was lower with lower impact energies, their existence in the 1J specimen is proof of BVID as the damage to the surface is virtually invisible. This is the type of damage that needs to be identified at an early stage, as failure to do so can result in the damage propagating and leading to a catastrophic failure of the entire structure.

B. Hybrid Composites

Table II shows the summary of work on hybrid composites. According to several researchers, carbon/aramid fibre hybrids demonstrated beneficial hybrid effects

TABLE I. SUMMARY REPORT OF IMPACT DROP TEST WORK

Authors	Composition of Material	Fibre Lay-up (°)	Impactor Shape	Dimensions/Layers	Ref.
Bibi and Rahman	Carbon fibre/Epoxy	0/90	Hemispherical 11.7mm diameter	50×50mm; 8-ply 2.4mm thickness; 16-ply 4.8mm; 24-ply 7.2mm.	[1]
Wronkowicz-Katunin et al.	Carbon fibre/Epoxy	0/0	Hemispherical 10mm diameter	100×100×2.5mm	[4]
Deng et al.	Graphite/Epoxy	0/+45/−45	Hemispherical 12.5mm diameter	65×87.5×3.2mm	[5]
Mitrevski et al.	Carbon fibre/Epoxy	45/0/45/0	Hemispherical (H), conical (C), ogival (O), all 12mm diameter	215×215×1.9mm	[6]
Mitrevski et al.	Carbon fibre/Epoxy	45/0/45/0	Hemispherical (H), conical (C), ogival (O), all 12mm diameter	215×215×1.9mm	[7]
Mitrevski et al.	E-Glass fibre/ Polyester resin	0/90/45/0/90	Hemispherical (H), conical (C), ogival (O), Flat (F), all 12mm diameter	215×215×1.97mm	[8]
Zhou	E-Glass fibre/Polyester resin; S-Glass fibre/ phenolic resin	0/90	Flat-ended 25mm diameter	100mm and 500mm area circular plates; E-glass 10 and 25mm thickness; S-glass 14 and 19mm thickness.	[9]

on their tensile modulus and strain at failure [10]-[12]. Low-velocity impact testing on hybrid composites were implemented during study by Hosur et al. [13] using a hemispherical impactor. They found that while stiffness was marginally reduced, hybrid composites beat carbon/epoxy laminates in terms of load carrying capacity. Rajasekar et al. [12] reported that the combined carbon/aramid fibre properties retain the best properties from each of the carbon or aramid fibres. This is an example of the "positive hybrid effect."

C. Finite Element Analysis (FEA)

A summary report of the collected FEA work is featured in Table III. Maio et al. [15] present a continuum damage mechanics (CDM)-based method for evaluating the whole spectrum of in-plane deterioration of composite materials. Material degradation model is applied to analyse the delay in ply uploading after the start of the damage process, by offering a precise framework for predicting composites' quasi-brittle failure process. The CDM symbolises a material's gradual loss of its elastic properties. In the research of Bouvet et al. [16], a 25J impact test yielded displacement and force-time curves for experimental and FEA data. This study shows how a simulation model is created to mimic the forms of damage that occur: cracking of the matrix, fibre failure, and delamination. Interface components are also used to simulate intra-laminar damage or matrix cracks, based on a failure criterion. Both sets of data show a good correlation between the experimental data and FEA predicted data indicating that the methods used to create the FEA models are relatively accurate.

However, the FEA model of Bouvet et al. [16] seems to have a closer resemblance to the experimental results, with the model seeming to be better at predicting the anomalies of the experimental test. The FEA model by Maio et al. [15] seems to follow a more linear path, indicating that the model is less accurate. The maximum force predicted by both models would seem to confirm this, as the model by Maio et al. [15] is almost 100N less than the experimental results, while the model by Bouvet et al. [16] is almost identical to the experimental even whilst being a much larger force. If the models for both tests were changed, it is

TABLE II. SUMMARY REPORT OF HYBRID COMPOSITE WORK

Authors	Composition of Material	Fibre Lay-up (°)	Testing	Dimensions/ Layers	Ref.
Sevkat et al.	Glass fibre-Graphite fibre/ Epoxy	45/−45	Charpy-straight line; 25.4mm spherical; 12.7mm spherical; 10mm flat-ended cylindrical.	101.6×101.6mm GL/GR/GL 18 layers glass fibre, 16 layers graphite fibre, 34-ply; GR/GL/GR 16 layers graphite fibre, 16 layers glass fibre, 32-ply; 6.35mm thickness for both.	[2]
Hu et al.	Carbon/Epoxy (CE); Carbon -Aramid/Epoxy (CA)	$[45/0/-45/90]^4$; $[-45/0/45/90]^2$ $[0/45]^4[0/-45]^4[-45/0/45/90]^2$; $[0/90]^8$	Hemispherical 16mm diameter impact test	500×500×4mm	[10]
Wu et al.	Carbon/Epoxy (CaCb); Carbon-Aramid/Epoxy (CaKb); Aramid-Carbon/ Epoxy (KaCb)	3D5d braided composite	Hemispherical 12.7mm diameter impact test	135×25×4mm	[11]
Rajasekar et al.	Carbon/Epoxy (CE); Aramid/Epoxy (AE); Carbon-Aramid/Epoxy (CAE).	Interlaced prepreg 0/0°	Tensile and flexural tests	300×300×2mm	[12]
Hosur et al.	S2-glass fibre/Epoxy, Carbon fibre/Epoxy, Hybrid S2-glass-carbon fibre/Epoxy.	GE = 5 layers of glass (G^5); CE = 5 layers of carbon (C^5); HB1 = $G^1C^3G^1C^3G^1$; HB2 = $C^2G^1C^2G^1C^2G^1$; HB3 = $G^1C^2G^1C^2G^1C^2$; HB4 = $C^3G^3C^3$; 0/0°.	Crosshead impact test	100×100×3mm	[13]

TABLE III. SUMMARY REPORT OF FEA WORK

Authors	Composition of Material	Fibre Lay-up (°)	Impactor shape	Dimensions/Layers	Ref.
Feng and Aymerich	HS300/ET223 Graphite/Epoxy	0/+45/−45	Hemispherical 12.5mm diameter	65×87.5×3.2mm	[14]
Maio et al.	Carbon/Epoxy	0/45/90/−45	Hemispherical 12.7mm diameter	125×75×1mm	[15]
Bouvet et al.	T700/M21 Carbon/Epoxy	0/45/90/−45	Hemispherical 16mm diameter	100×150×1.5mm 8-ply	[16]
Caputo et al.	Carbon/Epoxy	45/−45/0/90	Hemispherical 19mm diameter	100×150×4.4mm 24-ply	[17]
Zhang et al.	Carbon/Epoxy	0/90	Hemispherical 25mm diameter	60×60×1.4mm 8-ply	[18]

TABLE IV. SUMMARY REPORT OF CARBON NANOTUBE WORK

Authors, Year	Composition of Material	Fibre Lay-up (°)	Testing	Dimensions/Layers	Ref.
Zhang et al., 2022	T700 Carbon fibre/Carbon nanotube reinforced epoxy, 0.1, .0.2, 0.3, and 0.5% nanotube contents	Tow spread	Transverse fibre bundle testing (TFBT) and Interlaminar shear strength (ILSS) testing	Tow spread 24mm width	[19]
Abidin et al., 2019	Carbon fibre/CNT reinforced epoxy homogeneously distributed CNTs (HM); Carbon fibre/CNT reinforced epoxy heterogeneously distributed CNTs (HET). CNT content of 2.5%, 5%, 10%, 25%.	0/0	Interlaminar shear strength (ILSS)	15×25×3mm	[20]
Xiao et al., 2018	T300 Carbon fibre/ Multi-walled CNT Reinforced E44 epoxy	0/0	Tensile strength, Tensile modulus, Flexural strength, Flexural modulus.	230×25×2mm tensile; 110×10×4mm flexural.	[21]
Zhang et al., 2019	JH-T800 Carbon fibre/CNT reinforced epoxy		Bending strength, Bending modulus, interlaminar shear strength (ILSS)	Manually wound around a unidirectional mould.	[22]
Sarasini et al., 2020	Carbon/Epoxy; Carbon/MWCNT reinforced epoxy.	0/90	Impact drop, Hemispherical 12.7mm diameter impactor	100×150×2mm	[23]

likely the maximum force results for Bouvet et al. [16] would be almost 1KN lower than the experimental results, suggesting that the model used by Bouvet et al. [16] is more accurate and should be considered for use in any future work.

D. Carbon Nanotubes (CNT)

Table IV features the collected work on CNT. It should be noted that only one of the papers features an impact drop test. A search of the Scopus database [28] revealed that there is a good amount of research available in the field of CNT, but a lack of impact testing research. The research included here shows testing for interlaminar shear strength (ILSS), transverse fibre bundle testing (TFBT), tensile strength, flexural strength, bending strength and their modulus. If, as shown in the research, these properties of carbon fibre can be enhanced by introducing carbon nanotubes to the epoxy, then it is reasonable to assume that the impact resistance of the material can also be improved. Sarasini et al. [23] conducted impact testing to reveal a rather inconclusive result on this front, at 5J the MWCNT-reinforced carbon performed marginally worse than standard carbon/epoxy, with 4.13KN compared to 4.14KN, respectively. At 7.5J however, the MWCNT-reinforced carbon produced an impact force of 4.93KN compared to the standard carbon/epoxy which produced 4.81KN. These results can be also seen in Fig. 3. These interesting results and the lack of research in the area of impact testing of CNT -reinforced carbon fibre leads to the conclusion that this is an area in need of further impact drop testing research.

E. Microwave Curing

Microwave processing is regarded as the economically viable and promising approach for composites cost reduction. Due to the unique heating mechanism, microwave curing has a number of exceptional benefits over traditional thermal curing, including reduced processing times, faster throughput, cheaper operating costs, and more efficient heating. A microwave curing process designed by Li et al. [27] shows that the cyclic heating and cooling process is required during microwave curing because of inability of the microwave to operate at a steady heat like a conventional oven. It is also noticeable that the current microwave curing process is over two hours faster than

TABLE V. SUMMARY REPORT OF MICROWAVE CURING WORK

Authors, Year	Composition of Material	Fibre Lay-up (°)	Testing	Dimensions/Layers	Ref.
Xu et al., 2016	T800 Carbon fibre/Epoxy Microwave cured	0/0	Compressive strength and modulus.	175×90×4mm 14-ply	[24]
Nightingale and Day, 2002	Carbon fibre/Epoxy Autoclave; Carbon fibre/Epoxy Microwave cured.	0/90	Flexural strength, modulus, and Interlaminar shear strength (ILSS)	130×100×4mm 16-ply Autoclave; 80×80×4mm 16-ply Microwave;	[25]
Xu et al., 2016	T700 Carbon fibre/Bismaleimide (CB) Microwave, oven, and Autoclave cured	0/0	Flexural strength, Interlaminar shear strength (ILSS)	120×13×2.8mm Flexural; 20×6×2.8mm ILSS.	[26]
Li et al., 2017	T700 Carbon fibre/Bismaleimide (CB) Microwave cured.	$0^2/-45/0/45/0/90/0^4/90/0/45/0/-45/0^2$	Tensile strength, Tensile modulus, Flexural strength.	200×200×2.3mm 18-ply	[27]

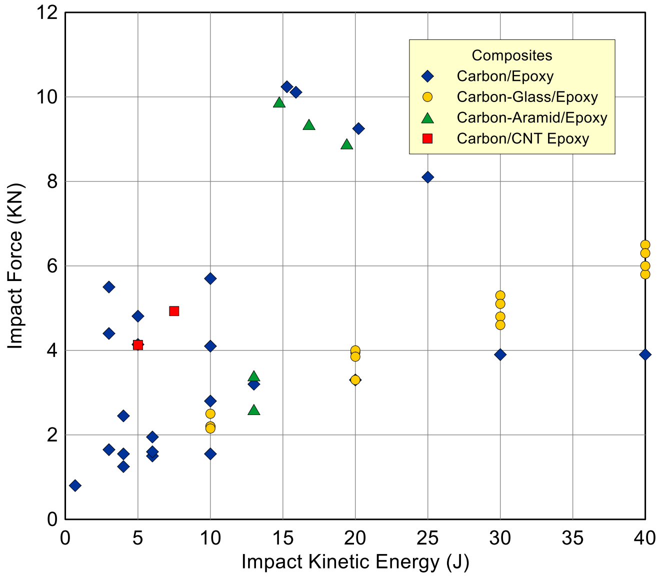

Fig. 3. Comparison of impact tests for Carbon fibre/Epoxy, Carbon-Glass fibre/Epoxy, Carbon-Aramid fibre/Epoxy, and Carbon fibre/CNT-reinforced epoxy.

autoclave curing. This would be considered a very good improvement if microwave curing can produce a comparable composite to the autoclave process.

However, the new microwave process is over 50% faster than the autoclave. The benefits of reducing the production time by over 50% would be enormous, however, the microwave curing could produce more voids within the composite compared to the autoclave process. This leads to weaker components as the voids act as crack initiation points within the composite. This can be reduced by adding pressure during the curing, vacuum bagging is most commonly used for this purpose, however, the void content of microwave cured composites is still generally larger than what is found in autoclave cured composites. Table V shows the summary of the microwave curing work reviewed in this work. Similar to the CNT section, there is plenty of work on interlaminar shear stress (ILSS), compressive, tensile, flexural strength, and modulus, except here there is no impact testing work. A search of the Scopus database [28] revealed a complete absence of impact testing carried out on microwave cured composites, which would make this a very good area for future impact drop test work.

F. Collected Impact Test Results

The collected impact drop test results from the papers reviewed in this work are visualised in Fig. 3 and Fig. 4. The results have been collated via material in order to best compare the results for each material. Fig. 3 shows a graph comparing the data for carbon fibre/epoxy, carbon-glass fibre/epoxy, carbon-aramid fibre/epoxy, and carbon fibre/CNT-reinforced epoxy. The graph is quite congested and a little difficult to read even though there are only around half of the total results available shown. It is therefore suggested that the data should be used by selecting specific data which is relevant to any proposed impact test. Fig. 4 is an example of this, here only the results for carbon fibre/epoxy up to an impact kinetic energy of 14J is shown, which makes the graph much easier to read. It is clear that there are three results at 3J, 4J, and 6J, as well as four results at 10J. If an impact drop test of carbon fibre/epoxy is intended to take place, matching up with these impact kinetic energies and test parameters will give multiple results which can be compared to.

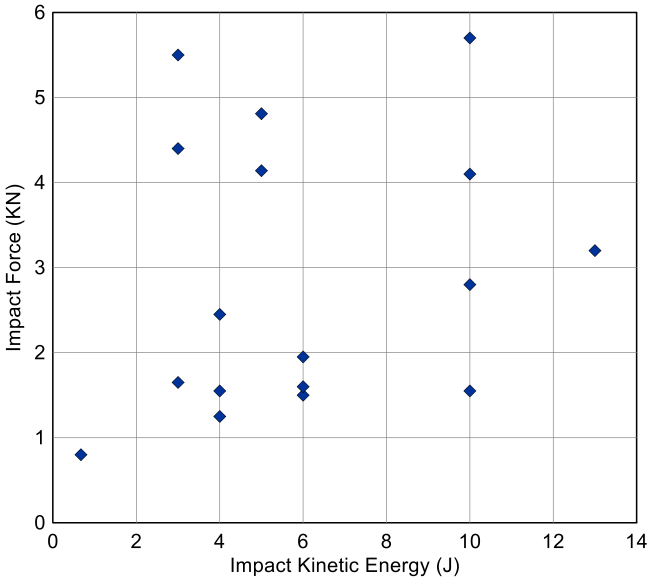

Fig. 4. A detailed showcasing the impact test results for Carbon fibre/Epoxy up to 14J of impact kinetic energy.

V. CONCLUSION

From the work produced here, it is hopeful that the collection of a large amount of data from various impact drop tests can benefit any future impact drop testing. This work can be a basis from which a lot of different types of impact drop tests can draw due to the various types of materials used in the test results shown in Fig. 3 and Fig. 4. It is clear from the research that the areas of CNT-reinforced carbon fibres and microwave curing are prime for more research and should therefore be keen areas of interest for future impact drop testing.

While the research has shown that CNT-reinforced carbon fibres can outperform standard carbon fibres in impact drop resistance [23], the benefits of microwave curing should make this area more appealing. If microwave curing could produce composites having properties identical to composites manufactured using autoclave curing, then all manufacturers would switch to microwave curing instantly to benefit from the faster processing times. More research is required to refine this process and create higher quality components before this can happen, however, the current processes available should also be investigated further.

Impact testing microwave cured composites could help identify the strongest components available from these processes. Comparing the impact test results from microwave cured composites would help identify where these composites could be used best. While autoclave cured composites would most likely be more suited for areas where impacts are a concern, microwave cured composites could be introduced to less impact prone areas and could possibly reduce production time in those areas by over 50%.

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