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INVESTIGATION OF THE COMPOSITE BEAM BEHAVIOR SUBJECTED TO IMPACT FATIGUE LOADING

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Abstract:

The objective of this research is to investigate the effect of repeated low velocity impacts experimentally on composite materials which two types of laminated composite beam are used (2D and 3D woven fabric/lamination (80:20) resin) under repeated impact tests. The tests were performed and exposed to repeat low velocity impacts (1.4 m/s) for all tests by using an impact fatigue apparatus which is designed and manufactured. The effect of repeated impacts is studied on peak load, number of laminate, drop masses with respect to number of cycles under gravity fall. A comparison is made between 2D & 3D samples for all layers of composite materials. Results show that the mechanical properties of all specimens decrease with increase in number of impacts per unit time, experimental results also shows that the 3D samples have more resistance to impact damage than 2D samples so that samples of 3D five layers are stronger and they have longer lifetime fatigue from 2D six layers samples. The comparison between 2D-6 layers and 3D-5 layers appeared that 3D-5 layers is more efficient and more resistance to impact where the increasing in lifetime percentage at energy 12.63J, 7.13J, 4.69J and 3.36J were 100%, 64%, 42% and 37%. The stiffness of 2D & 3D laminate composite beam are reduced by 30% when the samples are failure.

Keywords: *2D & 3D laminate composite beam, Impact Fatigue, Experimental analysis*

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دراسة سلوك عتبة من مادة مركبة تتعرض الى صدمات متكررة

الخلاصة:
الهدف من هذا البحث هو لدراسة تأثير الصدمات المتكررة عمليا بسرعة واطئة على مواد مركبة لعتبة مادة مركبة حيث تم استخدام نوعين من نماذج العينات (حصيرة الياف من نوع 2D و 3D مدعم برزن من نوع (80:20) lamination) تحت تأثير اختبارات صدمات متكررة. الاختبارات نفذت تحت تأثير صدمات متكررة بسرعة واطئة (١,٤ م/ثا) لجميع الاختبارات باستخدام جهاز ضربات متكررة حيث تم تصميم وتصنيع الجهاز محليا. تم دراسة تأثير هذه الضربات على اقصى حمل، عدد الطبقات، والكتل الضاربة نسبة الى عدد الضربات تحت تأثير السقوط الحر بالجاذبية الارضية. النتائج اظهرت ان الخواص الميكانيكية تنخفض مع زيادة عدد الضربات لجميع العينات المستخدمة. النتائج العملية اظهرت ايضا بأن العينات من نوع 3D لديها القابلية الاكبر على تحمل الصدمات من العينات ذات نوع 2D حيث ان العينات من نوع 3D ذات الخمس طبقات تكون اكثر قوة وتمتلك عمر اطول لتحمل الضربات من العينات من نوع 2D ذات الست طبقات حيث بلغت نسبة الزيادة في العمر الافتراضي عند الطاقات ١٢,٦٣، ٧,١٣، ٤,٦٩ و ٣,٣٦ جول بمقدار ١٠٠%، ٦٤%، ٤٢% و ٣٧% على التوالي.عند فشل العينات تنخفض الصلابة للعينات المستخدمة بحوالي ٣٠% من قيمتها الاصلية.

١. Introduction

Fatigue is the weakening of the material that occurs when the material is exposed to cyclic loading, and leads to cracks and damages in the material after a number of loadings. Composite materials are designed to be insensitive to fatigue, but they still suffer from fatigue loads. One reason among others is because the failure of composites is sudden and without prior notice, it is therefore important to understand and to predict the fatigue life of composites [1]. In service many elements or structures are subjected to repeated impacts, this phenomenon known as Impact Fatigue (IF). The repeated impacts could appear due to the service loads, like in the case of gear teeth, hydraulic hammer, roller chain, or are produced as additional impacts for wagon axles or assemblies mounted by clamping [2]. The sports goods in particular, like tennis rackets, golf heads, boat hulls where the sustenance of repeated impacts during handling and use has drawn the attention of the designers. These structures often encounter fluctuating loads, causing degradation of the materials under fatigue [3]. The dynamic behavior of composite laminates under impact fatigue load is very complex because there are many concurrent damage mechanisms, fiber breakage, delaminations, matrix cracking, debonding (fiber/matrix separation)[4]. High-performance fiber-reinforced polymer composites (FRPs) are now well established in many applications such as military aircraft, high-speed marine vessels and sports equipment. The original reason for using these materials was the high-specific strength and stiffness [5].

Rita Roy et al [3] examined two types of unidirectional carbon fiber, one of high strength (DHMS) and another of medium strength (VLMS) reinforced vinylester resin composites. They observed that both the composite samples are followed by a progressive endurance by decreasing applied impact energy below the threshold fracture energy. Tamer Sınmazc et al [6] studied impact fatigue properties of unidirectional carbon fiber-reinforced polyetherimide (PEI) composites by subjecting standard Izod impact samples to low velocity impact loading. They observed that the decrease in impact energy resulted in an increase in the number of impacts of failure. Ian A.Ashcroft et al [5] studied two cases of impact types on carbon fiber reinforced polymers (CFRPs) samples. One representing a high-performance applications standard fatigue loading and the other is a repetitive low-energy impacts, or impact fatigue. They noticed that there is a significant variation in the failure modes of the samples and that the crack propagation rate is highly dependent on the fracture mode. K. Azouaoui et al [4] examined how multiplication of low-velocity impacts on glass/epoxy cross ply laminates affects damage progression. Bernard Schrauwen [7] described the results of falling weight impact tests on glass-fiber-reinforced laminates. The impact behavior of cross-ply laminates based on a brittle unsaturated polyester resin and a more ductile vinyl ester resin system with two types of glass reinforcement, woven- and multiaxial non-crimp fabric. Rita Roy et al [8] studied the impact fatigue for 63.5% glass fiber reinforced vinylester resin notched composites. The accumulation of residual stresses in each impact causing delamination and debonding initially followed by fiber damage have been attributed to the cause of the impact fatigue failures. K. Azouaoui et al [9] compared between two composite (Glass/Epoxy Woven fabrics (GEW) and Glass/Epoxy Cross-Ply laminates (GECP)) subjected to impact fatigue loading to determine the effect of impact energy and number of impacts on stiffness and damage parameter evolutions. S. Kono et al [10] designed and manufactured a machine to perform high-cycle impact fatigue tests in order to examine the impact fatigue durability of CFRP. G. Belingardi et al [11] determined the residual flexural properties of laminates subject to single and repeated impacts. Also the correlation between residual properties and the Damage Index is discussed. G R Rajkumar et al [12] investigated response of repeated low velocity impact tests on glass fiber/ epoxy-Al metal laminates (GEAML) and carbon fiber/ epoxy-Al metal laminates (CEAML) using drop-weight tester. They concluded that: - GEAML offer a better energy absorption than CEAML due to carbon based FML allows the propagation of cracks within the structure. A. Can ALTUNLU et al [13] presented an investigation on the impact fatigue characteristics of valve leaves that are prevalently used in hermetic reciprocating compressors especially for the household type refrigerators. M. Yarmohammad Tooski et al [14] performed repeated low velocity impact tests using a drop impact tower. The effect of impact location distance on plate response, damage parameters and absorbed energy were studied. The damage evolution was evaluated using visual inspection, ultrasonic C-scan, SEM and mechanical sectioning techniques. Ernesto Guades et al [15] investigate the behavior of fiber reinforced polymer (FRP) composite tubes under axial impact. The effects of damage parameters such as the mass of the impactor, incident energy and number of impacts on their behavior of (FRP) were studied. The presence of third directional fibers in 3D textile performs (orthogonally woven, multi-axial warp knitted, multi-layered woven-interlocked and stitched) not only hinders crack propagation but also increases the impact resistance and damage tolerance of the composites reinforced with them. Delamination prone ply interphases can also be eliminated in multi-directional weaving such as multi- axial warp knit performs and 3D orthogonal weaves. Many related research studies have shown that the composites reinforced by 3D woven and multi-axial warp knits outperform 2D woven laminates under impact not only by sustaining substantially less shear damage but also by exhibiting better resistance to failure [16].

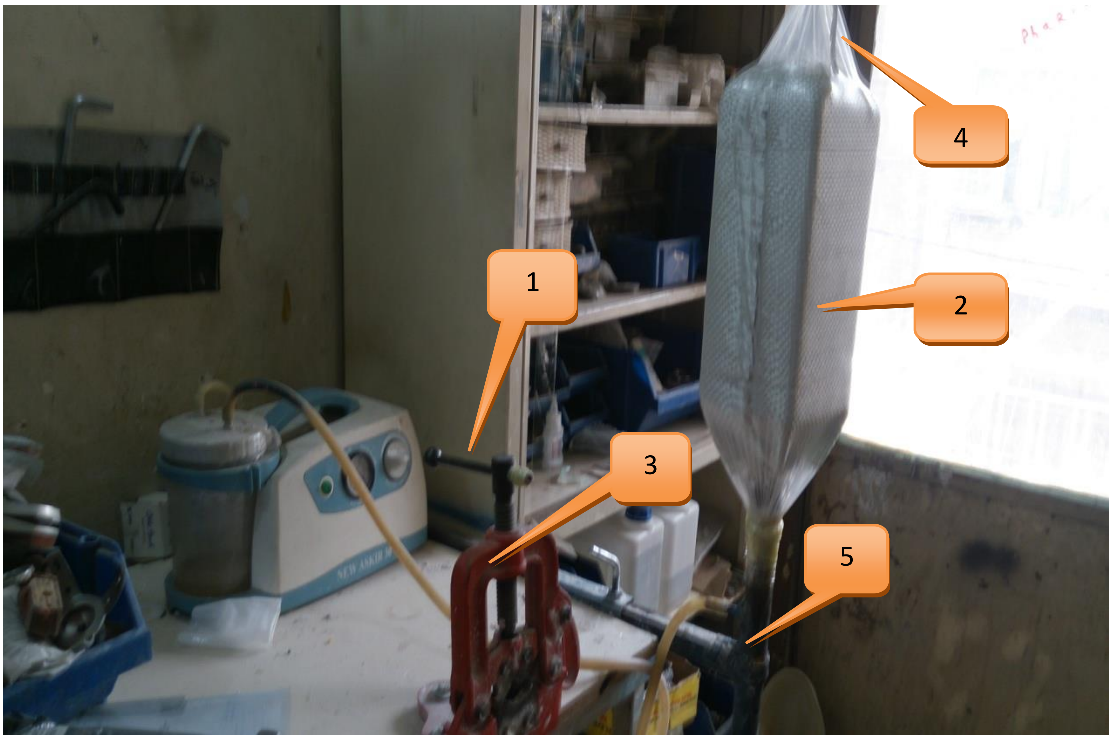
From the reviewed literatures, the impact fatigue (IF) tests can be classified in two groups, the first is the stationary system of IF tests when the impact amplitude is keep constant (Machines with falling hammer) and non-stationary system of IF when impact amplitude vary or when the drops are interfering a cyclic load (Machines with rotating disk). Therefore, it will be designed a new device differs from both types, and combines both mechanisms (falling hammer and rotating disk) in one mechanism.

Due to little researches on 3D woven fabric with impact fatigue loading, so it will be tested 3D woven fabric samples and compared with 2D samples.

2. Experimental works

2.1. Material and samples

Two groups of materials were tested, included 2D and 3D woven fiber composite. The material used is a lamination (80:20) Polymethyl methacrylate resin reinforced by E-glass woven mates at density 2500 Kg/m^3 fibers. The vacuum molding process is used which is shown in the figure (1) with these parts:-



1 –vacuum device 2- textured mold with a conical cup on the upper side of mold to feed the resin 3-thick hose used to discharge air out of the mold 4-A two PVA bags which are placed (clothed) on the mold and woven 5- Holder to fixed the mold which is contained a hole in order to pull the air from inside the mold

Figure (1) The molding process

To manufacture the 3D woven fabric, a stitching process as shown in figure (2) is used. The stitching process consists of inserting a needle carrying the stitch fiber through a stack of fabric layers to form a 3D structure.

Figure (2) Stitching process

Specimens are cut to 16cm length and 4cm width with a different thickness according to No. of layers. Five sets of samples were produced (2D woven (2-4-6) layers and 3D woven (4-5) layers) as shown in figure (3). The mechanical properties of composite materials were measured using a tensile test according to ASTM-D 3039 measured in Tinius Olsen (H100KU), having Young's modulus of 13.7 GPa and 11.96, tensile strength of 322.8 MPa 266 Mpa for 2D and 3D respectively. The volume fraction of the samples is equal 40%.

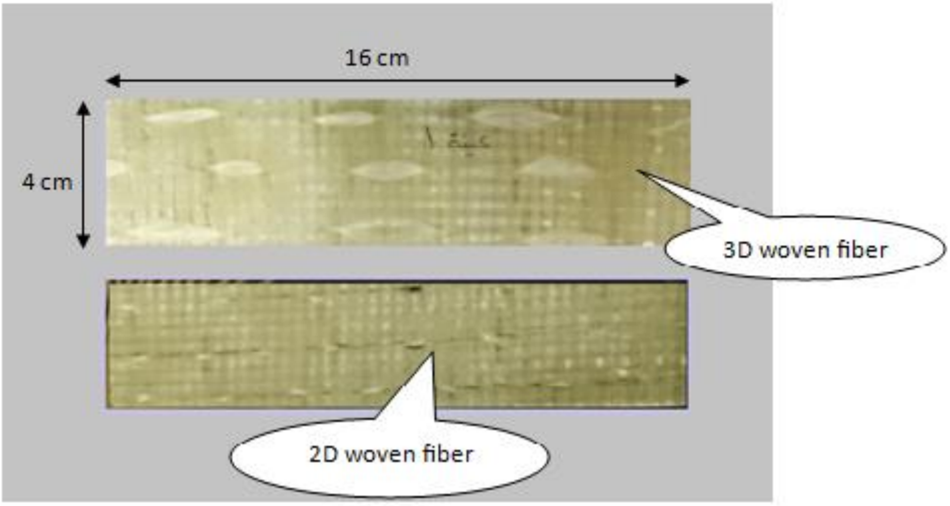
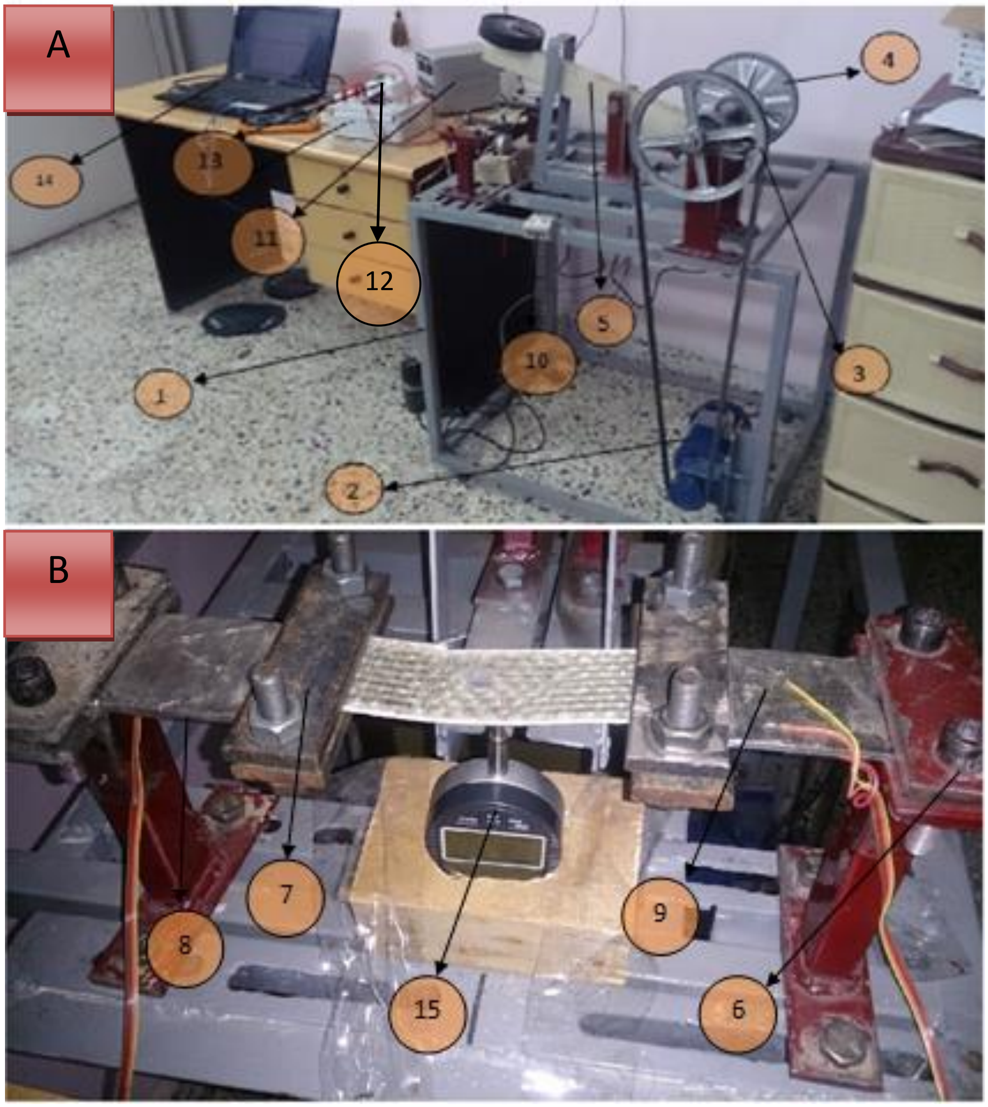


Figure (3) The final shape of sample

2.2. Impact fatigue test

The impact fatigue apparatus is designed to perform repeated impact test. It consists of two basic components. The first mechanical components which are responsible for creating impact fatigue loads. The second part is to measure the impact load and also to measure the numbers of the cycles testing.

The testing rig is shown in fig (4).



1-Base 2-motor 3-Transformations system 4-Slotted disk 5-Arm 6- Fixtures 7-clamp_ 8- strain gauged plate 9-strain gauge 10-counter of cycles 11-power supply 12. Amplifier and filter 13- Digital oscilloscope 14- Computer

Figure (4) a) The complete test apparatus

b) Laminate composite beam under testing

2.3. Test Procedure

To perform an impact fatigue test, the following procedures were followed:-

1- The specimen is fixed by clamps
2- Turn on the power supply voltage.
3- Turn on the switch of amplifier circuit.
4- Connect the oscilloscope with a computer.

5- Fix the dual gauge on the bottom of the specimen to measure the instantaneous static deflection.
6- The test was started with high energy (critical energy) that makes the sample fails with one blow and then reducing the impact mass blocks and calculates the number of impact needed for failure of the specimen. Taking into account access to the same degree of failure at each test in order to compare the different cases.
7- After several drops, the motor is stopped to save data (load and No. of impacts) and measure the changing in static deflection by applying this formula to evaluate the static stiffness:-

$$S = \frac{p}{\delta} \text{ (N/m)}$$

Where:-

P: - is weight (N)

δ: - static deflection (m)

8- After saving the impact wave of testing in the computer, the maximum amplitude voltage was calculated and multiplied by the value of force calibration. This value represents the peak force of the drop. The peak force values were taken for many blows in order to draw relationships between peak force histories and the number of impacts.

3. RESULTS AND DISCUSSION

The experimental results discuss the change of peak force with number of impacts and also involve the effects of drop mass, number of layers versus the number of impacts to failure developed by impacting composite samples.

A comparison is made between the 2D woven and 3D woven fabric samples and the energy required to fail samples from one below is presented.

Through experimentation, it was observed that the maximum force suffers from multiple changes (especially when the impact energy is less than 50% of the critical energy failure) until reaching to the failure, as shown in following figure(5).

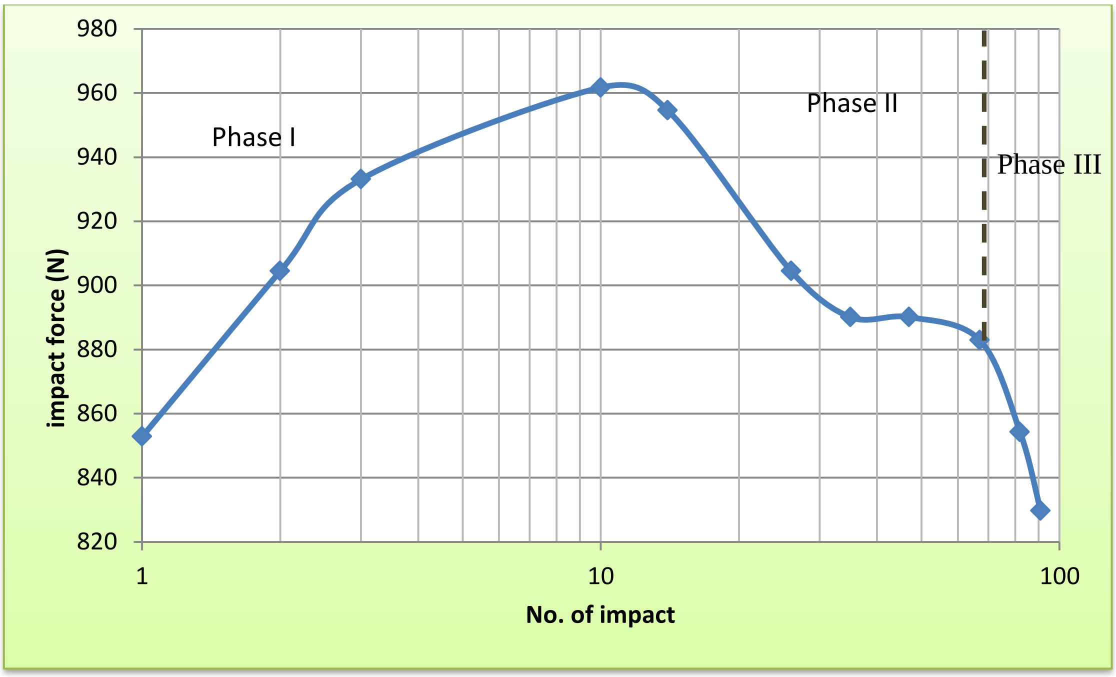


Figure (5) Phases of the failure

Where the shown curve, it can be divided into three sections which representing the stages of failure in the composite material samples.

Phase I: - An increase in the peak force in sample occurs in this stage. As it well known, through the first strike, most of the applied load is borne by the matrix. The matrix is more ductile than the fiber, so it absorbs a larger amount of energy than the fiber. So the maximum load increase when the matrix begins to fracture and the fibers begin to bore the load.

Phase II: - The peak load starts decreasing gradually after breaking the matrix and the damage starts in the fibers, which represent the delamination in laminates. This phase takes the largest number of strikes compared to other stages.

Phase III: - In this phase, the peak load continues to decrease by larger values due to the fiber breaking and collapse. A large decrease in static stiffness occurs.

Figure (6) shows the behavior of load history in 2D samples having 6 layers at different values of energies

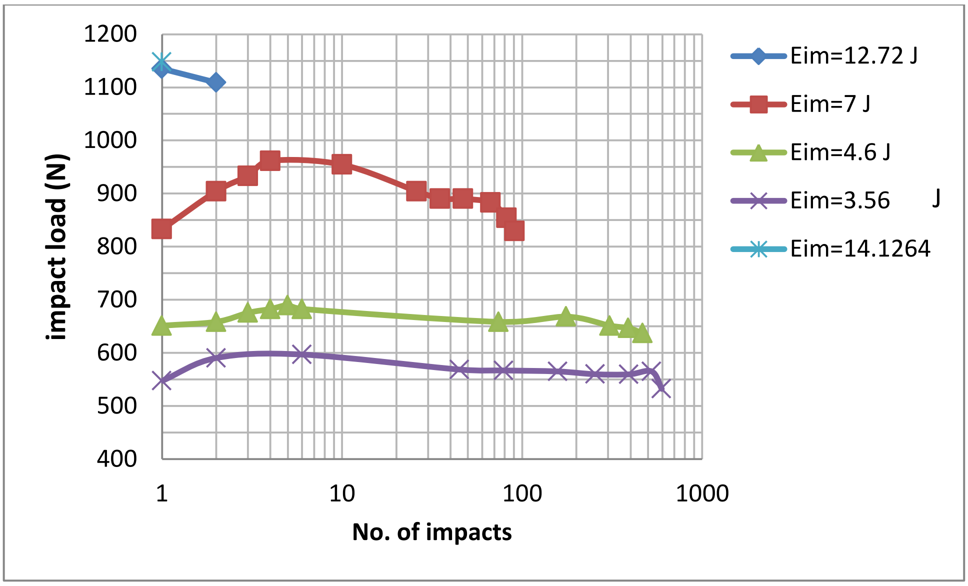


Figure (6) The load history in tests

It can be noted that in the case of high energies, it is difficult to distinguish stages of failure. This is because the number of strikes to reach failure is few. In other words, the failure stages overlap and occur together at the same time. It is interesting to know that the ratio of the peak forces at different impact energy is close to the square root of the impact energy only in the cases of low energies (Less than 50% of the failure energy).

Also, as the number of layers increases the total number of impacts by samples for the same volume fraction and under same impact energy is increase. As shown in figure (7).

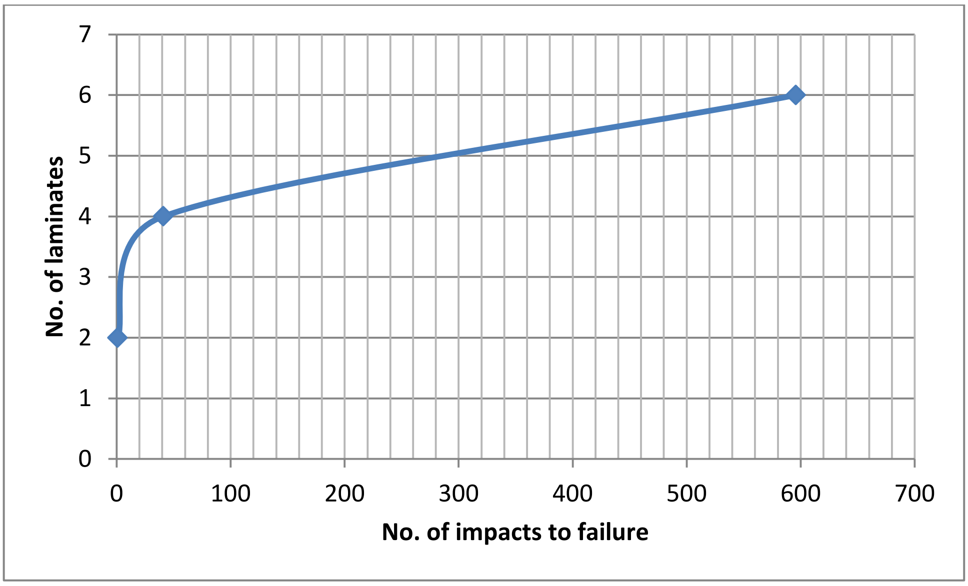


Figure (7) effect of no. of layers on no. of impacts to failure

Fig (7) shows that an exponential increase in the number of drops to failure corresponds to an increasing number of layers.

When the applied impact energy is decrease the life of the number of impacts to failure are increase. The relation between them is a power relationship (In other words, the relationship can be represented by power equation which usually described as (E-N) curves) as shown in figure (8)

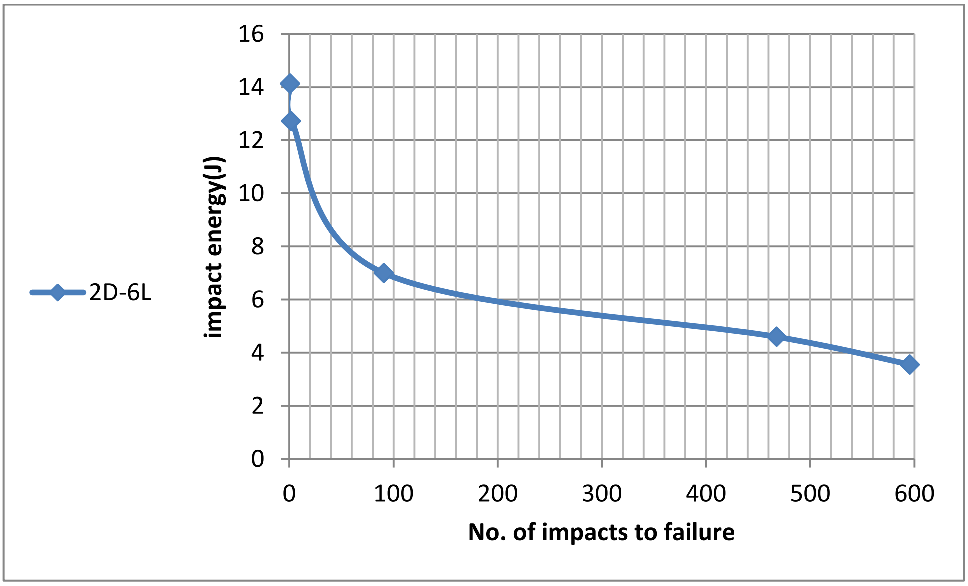


Figure (8) effect of impact energy on no. of impacts to failure

Figure (9) represented the comparison between 2D and 3D woven fabric. It was indicated that when the layers were stitched by z-direction fiber which is the same materials of woven, it was improved the damage resistance.

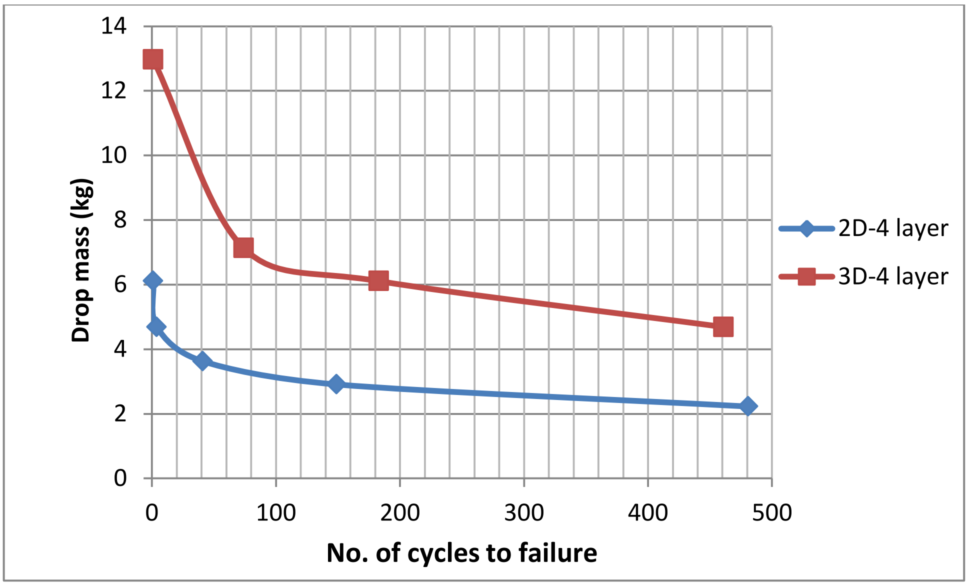


Figure (9) comparison between 2D-4L and 3D-4L

Through the above figure it was shows that the energy required to fail the 3D samples is so higher and the number of drops to failure increase.

In order to be the comparison is more useful we will carry out a comparison between five layer of 3D woven fabric and six layer of 2D woven, and the figure (10) had shown this comparison.

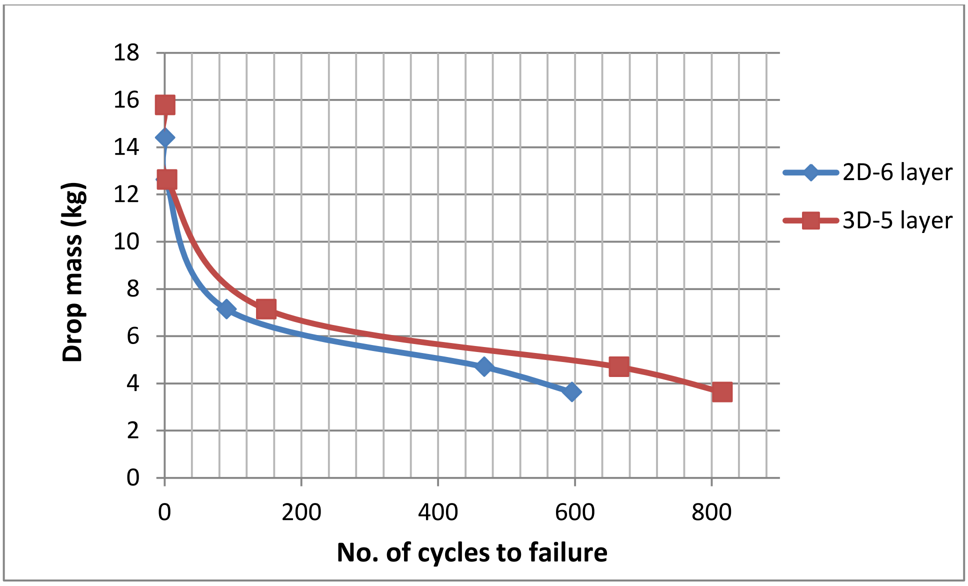


Figure (10) comparison between 2D-6L and 3D-5L

Although the 2D samples is more stiffness and thickness than 3D samples, but the results showed that the 3D samples are more resistance to impact damage and was needed more drops to failure than 2D samples.

It can be noted from this figure that the increasing in lifetime percentage is high in a high energy level, where at energy 12.63J, the lifetime percentage increased by 100%, while at energy 7.13J, 4.69J and 3.63J the lifetime percentage increased by about 64%, 42% and 37% respectively. The difference in drops is increased whenever the impact energy decreased.

An overview of the maximum impact energy of all laminate configurations is shown in Figure 11. Energies varied between 6-15 J for laminates
The lowest impact performance was reported for the 2D-4-layers configurations based on woven fiber. The 3D woven fiber reinforcements showed an increase in critical energy, which can be due to the higher strength and damage resistance of the 3D woven fiber

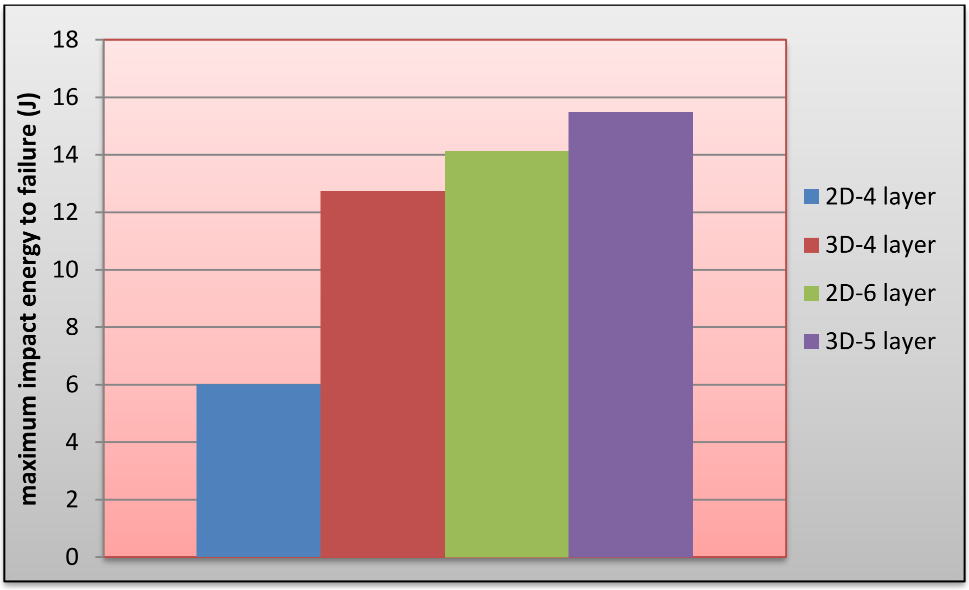


Figure (11) Comparison between failure energies for the layers

Logically with the continuation of the strikes on the sample, the stiffness will taken to decrease gradually, but rate of decreasing varies depending on phases of failure described previously as shown in the figure (12)

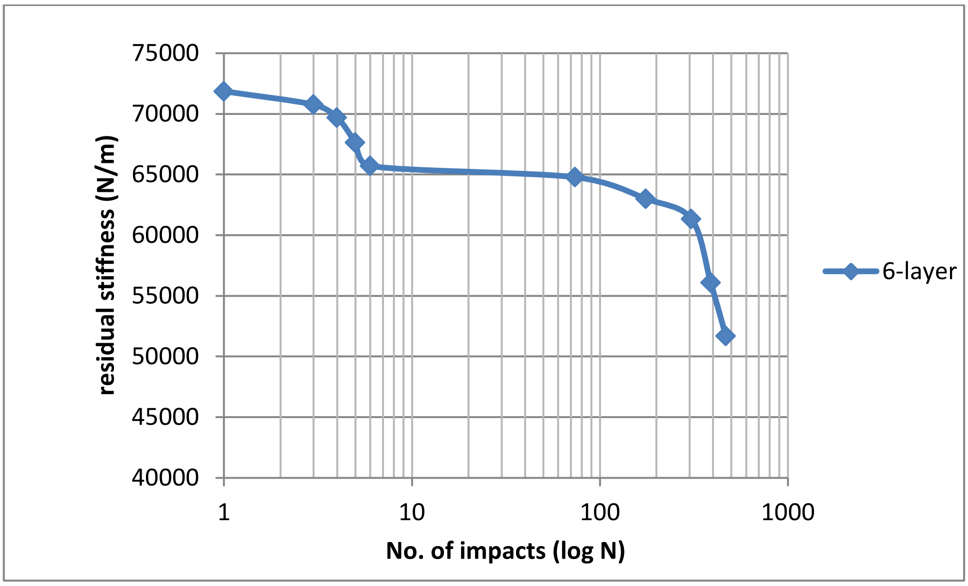


Figure (12) Residual stiffness under effect of drops

The curve of stiffness evolution with impact number of 2-woven-6-layer at impact energy of 4.6 Joules detects three clear phases: initiation delaminations and cracking of matrix (phase I), delamination of layers (phase II) and ply cracking with fiber breaking (phase III). In the first part of the curves (Fig. 5), the sample stiffness decrease moderately indicating cracks in matrix (phase I) and the second part of curve where the stiffness suffer a low decreasing and propagation of delamination at various interfaces were occur. The third part presents an obvious decrease of the stiffness values until final failure

4. Conclusions

- The maximum force increased in the first drops, after that it began to decrease to reach at failure, the maximum force in the test occurred at the end of stage1, while the minimum force occured at the end of the test.
- The composite materials experienced three stages before reaching failure, each stage takes about 9%, 74%, 17% respectively of the total lifefraction (β).
- Whenever, the number of layers increased, the number of impacts to failure exponentially increased, at the same impact energy.
- The increase in the number of layers leads to an increase in the stiffness, hence the maximum force increase, while the absorbed energy decrease.

- The comparison between 2D-6 layers and 3D-5 layers showed that 3D-5 layers are more efficient and more resistant to impact. The increase in lifetime percentage at energy of 12.63J, 7.13J, 4.69J and 3.36J were 100%, 64%, 42% and 37% respectively. Consequently, this improves the ability of impact resistance using less material to manufacture samples, In other words, the cost required to manufacture samples is decreased.

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