Fatigue Flexural Properties of Glass Fiber Reinforced Plastic Composites Subjected to Low Cyclic Impact


Abstract—Fiber-reinforced polymeric composites find widespread applications involving high and low engineering concepts. This is due to their unique properties of light weight, stiffness and high strength weight ratio. During processing and servicing, the composite materials exhibit defects such as matrix crazing, fiber breakage, fiber pull-out, delamination, and debonding. These are associated with multimechanisms. Surface and internal damages that are not visible can reduce the residual stiffness and strength of the composite laminates. Fatigue damage accumulates in composites with cyclic loading and catastrophic failure occurs when the damage exceeds a critical level. Damage mechanisms and damage accumulation in composites under cyclic loading has been the subject of many recent investigations. The basic problem in the development of a damage accumulation model is that of the definition of damage. Owing to the high complexity of mechanisms, micro damage is not directly measurable as strain and deformations. This paper deals the flexural properties of bidirectional polymeric composite through low cyclic impact test.

Keywords—GFRP composites, flexural strength, fatigue, low cyclic impact.

I. INTRODUCTION

LOW-velocity impact-induced damage in Ti/GFRP laminates as titanium-based Fibre-Metal Laminates (FMLs) was investigated to reveal the extent of internal damage in the in-plane direction and to evaluate the effects of titanium face sheets on impact damage in the GFRP core. It was found that interlaminar delamination in the GFRP layer expands widely due to crack initiation in the titanium layer on non-impacted side. However, matrix cracks and residual out-of-plane deformation are suppressed by energy absorption achieved by the bottom titanium layer. Furthermore, impact responses and damages obtained by finite element analysis with detailed modelling agree well with the experimental results. Thus, a study confirmed that the impact behaviour of the Ti/GFRP laminates is dominated by a fracture in the titanium layer on non-impacted side that fails in tension and that this layer plays a major role in preventing impact damages in the GFRP core [1].

Tae Jin Kang and Cheol Kim explained that there have been a number of reports in the field of impact behavior of composite materials, especially on the problem of the performance reduction of composite structures induced by impact. Laminated composite structures, which offer an attractive potential for reducing the weight of high-performance aerospace structures, have inferior through-thickness properties, such as interlaminar shear strength, since the laminated structures have no reinforcements in the thickness direction. There has been a considerable amount of work on these problems by many researchers, mostly with carbon fiber.

Composites, which are susceptible to low energy impact damage. This localized damage is potentially a source of mechanical weakness, particularly under compression loading. Most of the preceding studies had been devoted to analyzing the impact properties and post-impact compression behavior of carbon-fiber-reinforced composites with a view of improving their impact-tolerance properties. The delaminated areas in the woven laminates were much larger than those in the multiaxial warp-knit composites, while the delamination energy absorption was slightly higher since the impact fracture toughness of the woven laminate was much smaller than those of the multiaxial warp-knit composite [2]. The performance of a fibre-reinforced composite is determined by its fiber orientation. Unidirectional fibers provide maximum strength and modulus when the load is applied in the fibre orientation [3]. Performance of an engineering product largely depends on its design, manufacturing quality and service response.

Apart from strength requirements of composite, specifically high-energy dissipation/unit mass is also possible with composite materials by initiating and maintaining proper failure mechanisms during the crack event. Metals absorb energy through plastic deformation, whereas glass fiber reinforced composites absorb energy through failure mechanisms involving delamination, interply cracking, and fiber fracture, energy absorbency of a structure is directly dependent on the failure mode that occurs, and the failure mode is a function of the loading history and environment [4]. The impact damage profile was strongly related to the degree of anisotropy in their tensile properties. For weft knitted fabric
composites with a high degree of anisotropy like rib fabric composites, impact damage was confined to one region that is perpendicular to the weakest direction of the tensile properties, namely the course direction. For weft knitted fabric composites with a low degree of anisotropy like Milano fabric composites, the impact damage was more distributed in all directions. The impact damage was assessed by using ultrasonic C-scan and X-ray tomography. The tomography technique was used to reveal three dimensional images of the impacted knitted fabric composites. Compared to other textile fabric composites such as woven fabric composites, knitted fabric composites absorb more impact energy than woven fabric composites. However, the residual tensile properties of knitted fabric composites, which are simulated by doing open hole structure tests, are higher than the tensile properties of woven fabric composites with holes [5].

Cyclic loading behavior of composites differs considerably from that of metals in that they exhibit several modes of failure. One major difference between the behavior of composites and metals in cyclic loading is the change in stiffness [6]. This phenomenon has been observed in fatigue testing of glass, graphite, and boron fiber reinforced epoxy, glass fiber reinforced polyester and boron fiber reinforced aluminum. Exposure to low frequency and high amplitude fatigue load has resulted in a marginal rise in flexural strength and modulus, depending upon the frequency and magnitude of loading [7].

Impact loading is especially important for composite materials, because of the relatively brittle nature of the materials that makes composite materials sensitive to damage. Model components are likely to sustain impacts during their service. It is vital that the reduction in performance caused by a normal impact is not so large, as to make the component unsafe. Fiber reinforced polymeric composites, especially CFRP, are very susceptible to accidental impact damage and to reduction in compressive strength under hot-wet condition [8].

The mechanical performance of the composites which are reinforced with glass knitted fabrics composed of tuck stitches have been investigated for tensile, compression, impact and compression-after-impact (CAI) and the results of the composites reinforced with full cardigan derivative knitted fabrics and 1 X1 rib knitted fabrics of glass fibers have been compared. As for a composite material, performance depends not only on the strength of the constituent materials but also on the internal structural geometry of the constituents, it is interesting to study the effects of the tuck stitch which is one of three different types of loops that can be used to build the knitted fabrics and has a different geometry than the other loop types [9]. The low velocity impact behaviour of laminated carbon fibre/epoxy plates with and without compressive preloading was investigated and the results showed that an increased deflection for the preloaded composite plates, which lead to a higher extent of material damage compared to the unloaded plates with delaminations as one important energy absorption mechanism. Therefore, the total absorbed energy was higher for the preloaded plates. The intralaminar and interlaminar damage was higher for the NCF material compared to the prepreg material resulting from lower stiffness and strength properties. Delaminations occurred only between the few quadraxial package interfaces, while they may occur between any ply in the prepreg material [10].

Impact damage in composites comprises fiber failure, matrix cracking, fiber/matrix debonding and delamination. Delamination is due to the bending stiffness mismatch and transverse shear. The largest delamination will be present between the laminae with the largest difference in ply orientation [11]. Matrix cracking is mainly due to shear. The combinations of damage types affect the tensile as well as the compressive strength of the composite. This damage may further grow under cyclic loading; hence, it may be necessary to specify permissible tolerance of damage in composite. The salient features in force-time history curves can be related to fracture processes occurring in the laminates, and that the established relationships between impact force and incident kinetic energy (IKE) can be used to identify damage initiation without examining impacted specimens, which is later confirmed by the damage force maps. The constructed damage force and energy maps have shown not only damage initiation in an unstable fashion but also increase of damage size withIKE and force until reaching their load-bearing capabilities. Residual compressive strengths are reduced very rapidly with the increase of impact damage due to extensive delamination [12].

Further it is necessary to identify the defects influenced by machining and to assess the influence of such defects on the strength properties of machined component. Present work deals that the effect of low cyclic impact fatigue on flexural strength of bidirectional composites.

II. EXPERIMENTAL DETAILS

Bidirectional glass fabric reinforced plastic composite of 4 mm thickness was used for conducting the studies. The reinforcing material used was bi-directional glass fabric. The matrix used was epoxy resin LY-556 and the hardener HT 917. Due to low cure shrinkage, GFRP laminates are stable and free from internal stress. The laminates were made by hand lay-up method. The laminate was cured by atmospheric room temperature for about 24 hours. Care was taken to ensure complete wetting of the fibres and removal of entrapped air and excess resin. The nominal fibre volume fraction was 0.4. The details are given in Table 1.

<table>
<thead>
<tr>
<th>Work material</th>
<th>Bidirectional glass fibre/epoxy resin</th>
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<tbody>
<tr>
<td>Fiber volume fraction</td>
<td>0.4</td>
</tr>
<tr>
<td>Method of Manufacture</td>
<td>Hand lay up</td>
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The laminates were properly cut for the dimensional requirement as per the ASTM standard 80mm x 10mm for flexural test. The work piece was subjected to low frequency high amplitude cyclic impact loads prior to the flexural tests. The load hold i.e., number of cycles was increased by increasing the exposure time such as 10 min, 20 min, 30 min.
etc. Most of the design applications for wind tunnel models involve cantilever beam type loading; hence initial trials on polymeric composite have been undertaken to evaluate its response to flexural bending. Polymeric composite specimen was held as a cantilever beam in a laboratory designed set up and subjected to flexural bending. The specimens were loaded and unloaded repeatedly for several times, to determine the response of the polymeric composite in terms of, the permanent set of the deflection if any and the amount of energy absorbed during plastic deformation. The frequency of loading was fixed as minimum as possible i.e., 100 cycles/min. The maximum deflection of the specimen during loading was fixed as 7 mm. The experimental set-up for straining the workpiece is shown in Fig. 1.

Fig.1 Low cyclic impact fatigue load test rig

Fibres being the principal load-bearing element of the composite structure contribute significantly for its strength and stiffness. The elastic modulus of the high performance fibres used in the composite is much higher than that of the matrix, hence under low velocity impact situations, fibres exhibit rigidity and initial damage is more matrix and interphase dominated. Fibre’s ability to store energy elastically is the fundamental parameter influencing the low velocity impact response of the composite. Glass fibres, although have lower strength and stiffness, show better impact resistance than carbon fibres in the composites due to higher strain to failure.

The behavior of textile structures subjected to low velocity impact, but the research focus should progress towards development of newer reinforcements and performance for composites with desired impact damage tolerance through perform engineering. The other issue that needs to be explored is the method of designing composites with impact damage tolerance. This becomes critical when the composite is used for aerospace/transport applications, in which the structure has to undergo impact damage during emergency and needs to provide safety without catastrophe. As of now, impact design data for composites is obscure which is further complicated by large variations available and other issues. One possible solution would be that, for routinely used constructions, simulative studies should be carried out along with the design data based on past experience. However, except in select situations, when it comes to designing composites with impact damage tolerance, a case to case basis approach seems practical with experiments carried out in laboratory [13].

III. RESULTS AND DISCUSSION

A. Response of polymeric composite to low cyclic impact loading

Unlike metallic materials, with flexural bending (within limits) the stiffness of polymeric composite increases with applied load. Marginal reduction in bending property was observed with increase in cycles of impact load. Possibility of defect annihilation can be reason for the observed marginal changes. This calls for careful handling of the polymeric composite for model application. The observed change in the structural response (stiffness) around the critical duration of time was associated with a visible change in the hysteresis area, indicating thereby the onset of fatigue degradation [14].

Fractographic analysis revealed fracture by primary debonding, with fibre breakage and pull-out in the tensile zone, but a shear fracture of fibre bundles in the compressive zone of the specimen. Residual strength measured after impact fatigued showed retention of the property at high impact energy levels, up to about $10^2$ impact cycles, thereafter a gradual drop to about $10^3$ impact cycles followed by a rapid drop. The residual modulus and toughness showed a gradual drop with the increasing number of impacts endured. It is suggested that a few large cracks and an increased volume of microcracks in the matrix, with damaged fibres at high and low impact endurances, respectively, account for the failures of the composites under impact fatigue [15].

Flexural strength is one of the basic requirements for high performance structures, such as aircraft frames. In this present study, GFRP composites were tested for their flexural strength, through 3 point bending test in standard 20 kN Tensometer. This Tensometer gives the maximum load at failure and the load – deflection curve for the particular specimen. The load deflection curve obtained from tensometer for a specimen subjected to 600 cycles of impact loading is shown in fig.2, as sample.

By using the following formulae the flexural strength and flexural modulus were calculated.

$$\sigma_{UF} = \frac{3 \times P_{max} \times L}{2 \times b \times h^2}$$

$$E_F = \frac{(m \times L^3)}{(4 \times b \times h^3)}$$

Where,

$P_{max}$ - maximum load at failure in N

$L$ - distance between centers of support in m

$b$ - width of the specimen in m

$h$ - thickness of the specimen in m

$m$ - initial slope of the load–deflection curve
Data on flexural strength was acquired for different specimens subjected to different cycles of impact loading and the same is presented below. Typical observed flexural strength of GFRP composites is illustrated in Fig.3. Without any exposure to cyclic impact loading, obviously plain specimens exhibit some higher flexural strength. Like metallic materials, up to 2500 cycles of impact loading, the flexural strength reduces, but after 2500 cycles of loading the strength was gradually raised. The reason for these decrease and then increase in flexural strength may be the introduction of cyclic load and strain toughening of fibers. The introduction of cyclic impact on the specimens reduces the flexural strength initially and then stiffening taking place in the interface between fibers and matrix with the continuation of cyclic loading. Hence, exposure to cyclic impact loading for certain duration has enhanced the flexural strength of polymeric composites. This can be attributed to possible strain toughening of fibers. Beyond a specific duration, due to accumulation of damage within the composites, the flexural strength reduces with number of cycles.

B. Observation on flexural modulus

Flexural modulus of GFRP composites is illustrated in Fig.4. Similar to that of flexural strength, it is seen that up to 2500 cycles, there is a progressive reduction in flexural modulus beyond which it is fairly raises with a mild tip up to 3500 cycles.

The polymeric composites subjected to low frequency impact loading, exhibited a reduction / small rise / marginal change in normalized stiffness, depending upon the frequency or magnitude of loading. And it was observed that during low cyclic impact loading, a transition in the response occurring between 2500 and 3500 cycles. This can be termed as a critical duration of exposure to cyclic impact for the type of composite tested, about which the structural response to cyclic impact loading changes, depending upon the loading environment. And also increase in flexural modulus was observed beyond 5000 cycles of impact loading due to the steep load-deflection curve obtained from the specimens subjected to higher cycles of loading.

Exposure to low cyclic impact loading, the flexural strength was reduces and then increases up to certain period of exposure, beyond which a reduction was observed; this can be attributed to possible strain toughening of polymeric composites. The importance in flexural bending characteristics can be attributed to relatively higher order strength induced toughening, due to bidirectional orientation of the glass fibers in the laminate.
IV. CONCLUSIONS

The flexural bending reduces like metallic materials during introduction of low cyclic impact loading due to lower initial impact energy absorbing capacity of GFRP laminate. And then the flexural strength increases with applied cyclic impact load up to certain limit. Due to accumulation of damage within the composite, the flexural strength reduces with increase in number of cycles after specific duration. Marginal reduction in bending property was observed with increase in cycles of impact load. Possibility of defect annihilation can be reason for the observed marginal changes in the flexural property with cyclic impact load. This calls for careful handling of the polymeric composite for model application.

REFERENCES


