Comparative numerical evaluation for the low velocity impact behavior of T300 and T800 composite system

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Carbon fiber reinforced polymer (CFRP) composites have been used for many decades for extreme light weight design purposes in various areas, such as the aerospace industry, automobiles, sports goods and etc. because they provide the advantages of high specific strength and high rigidity [1]. In particular, the fuselage and wings of various aircraft, as well as the load bearing structures and components of mechanical and civil engineering systems are currently being manufactured with CFRP. However, even a low velocity impact on the carbon fiber reinforced composites can cause considerable damage, including matrix cracking, fiber failure and delamination [2-6]. These damages can result in the dramatic loss of strength and stiffness of the composites [7-9].

Nonetheless, only a few studies have been performed on methods to quantitatively estimate the effects of low velocity impacts on carbon composite laminates. In order to investigate the complex failure mechanisms in a composite material, it is helpful for researchers to use finite element (FE) simulation data, since a finite element analysis (FEA) can provide not only detailed stress information but also information about micro damage, such as damage that is invisible to the eye [10]. Given the wide range of applications, it is very important to understand the damage mechanics and mechanisms of low velocity impacts on composite laminates. This paper investigates the effect of low velocity impact behavior on the fibers of CFRP laminates by using the numerical data obtained from a finite element method (FEM) model, using LS-DYNA. First, an experimental impact test of cross ply laminate fabricated with T800 carbon fiber was performed. Then an FEM model was developed, and validated by comparison with the experimental data. Finally, an impact parameter study including lamina damage was carried out using the FEA, and was compared for two composite systems, using T300 and T800 fiber.

The fiber materials used for the study were Toray T300, which has a standard modulus and low strength, and T800 which has intermediate modulus and high strength compared with other fibers such as M40 and M46. The physical properties of the carbon fiber are listed in Table 1(a) [11]. The material used for the specimen in the experiment was a toughened epoxy resin, cured at 350 °F and pre-impregnated with unidirectional Toray T800/3900 carbon fibers, with a fiber volume fraction of 55.5% [12]. This material is currently being used in the construction of primary structures of the Boeing 787.

A mini drop-tower impact test setup was developed and used for the impact tests. The cylindrical impact striker has a hemispherical head with a radius of 6.5 mm, and was used to impose transverse loading on the center of the top surface of a 125×125×1.5 mm CFRP laminated plate with 8 plies, as shown in Fig. 1a. The four corners of the composite plate were fixed with four rubber clamps. The experimental setup is shown in Fig. 1b. A previously developed data acquisition system for low velocity impacts was used to obtain the
time-force curve, which was used to validate the FEM impact model. The impact striker with a mass of $m=3.44$ kg drops free from the height of $h=0.7$ m and the impact velocity is $v_0=3.71$ m/s. The total impact energy was calculated to be $E_0=23.67$ J.

An explicit FE code LS-DYNA was used to simulate the behavior of the low velocity impact on the cross ply CFRP composite plate. The developed FEM model is shown in Fig. 2a and b. The model of the CFRP composite plate includes the 3-D solid element. All of the components, including the composite plate, the impact striker, and the fixture and clamps comprising the experimental set up were included in the 3-D FE model.

The proper loading boundary and contact conditions were assigned and a 1/2 symmetry condition was adopted. The transverse impact loading was applied to the central portion of the specimen. In this model the infinitesimal element deformation occurring asymmetrically was ignored. The total numbers of elements for the composite plate and the impact striker in this model were 30,624 and 2014, respectively. The composite material model used in this study includes a MAT59 (MAT_COMPOSITE_FAILURE_SOLID) available in a solid element. This material model with the solid element for the orthotropic material was able to determine the failure of the composite material, such as delamination, due to impact loading.

The impact striker, the fixture and clamps all behave as a rigid body. A fixed boundary condition constraining all degrees of freedom except the proceeding direction. Hexahedron

### Table 1. (a) Physical properties of carbon fiber [11] (b) The material properties of two UD carbon/epoxy composites

<table>
<thead>
<tr>
<th>(a)</th>
<th>Tensile strength (MPa)</th>
<th>Tensile modulus (GPa)</th>
<th>Elongation (%)</th>
<th>Density (kg/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T300</td>
<td>3530</td>
<td>230</td>
<td>1.5</td>
<td>1760</td>
</tr>
<tr>
<td>T800</td>
<td>5490</td>
<td>294</td>
<td>1.9</td>
<td>1730</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>(b)</th>
<th>Properties</th>
<th>T800/3900 (Toray)</th>
<th>T300/PR319 (Toray)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiber volume fraction</td>
<td>0.555</td>
<td>0.60</td>
<td></td>
</tr>
<tr>
<td>Young’s modulus in the longitudinal direction ($E_1$)</td>
<td>142 GPa</td>
<td>129 GPa</td>
<td></td>
</tr>
<tr>
<td>Young’s modulus in the transverse direction ($E_2$)</td>
<td>7.79 GPa</td>
<td>5.71 GPa</td>
<td></td>
</tr>
<tr>
<td>Young’s modulus in the through-thickness direction ($E_3$)</td>
<td>7.79 GPa</td>
<td>5.71 GPa</td>
<td></td>
</tr>
<tr>
<td>Poisson’s ratio ($\nu_{12}$)</td>
<td>0.34</td>
<td>0.319</td>
<td></td>
</tr>
<tr>
<td>Poisson’s ratio ($\nu_{23}$)</td>
<td>0.59</td>
<td>0.55</td>
<td></td>
</tr>
<tr>
<td>Poisson’s ratio ($\nu_{13}$)</td>
<td>0.34</td>
<td>0.319</td>
<td></td>
</tr>
<tr>
<td>Shear modulus ($G_{12}$)</td>
<td>4.0 GPa</td>
<td>0.33 GPa</td>
<td></td>
</tr>
<tr>
<td>Shear modulus ($G_{23}$)</td>
<td>2.55 GPa</td>
<td>1.84 GPa</td>
<td></td>
</tr>
<tr>
<td>Shear modulus ($G_{13}$)</td>
<td>4.0 GPa</td>
<td>1.33 GPa</td>
<td></td>
</tr>
<tr>
<td>Young’s modulus in the longitudinal direction ($X_1$)</td>
<td>2251 MPa</td>
<td>1380 MPa</td>
<td></td>
</tr>
<tr>
<td>Compressive strength in the longitudinal direction ($X_C$)</td>
<td>1078 MPa</td>
<td>950 MPa</td>
<td></td>
</tr>
<tr>
<td>Young’s modulus in the transverse direction ($Y_1$)</td>
<td>58.47 MPa</td>
<td>40 MPa</td>
<td></td>
</tr>
<tr>
<td>Compressive strength in the transverse direction ($Y_C$)</td>
<td>58.47 MPa</td>
<td>40 MPa</td>
<td></td>
</tr>
<tr>
<td>Young’s modulus in the through-thickness direction ($Y_3$)</td>
<td>199.81 MPa</td>
<td>125 MPa</td>
<td></td>
</tr>
<tr>
<td>Compressive strength in the through-thickness direction ($Y_T$)</td>
<td>69.36 MPa</td>
<td>97 MPa</td>
<td></td>
</tr>
<tr>
<td>Mass density ($\rho$)</td>
<td>1550 kg/m$^3$</td>
<td>1560 kg/m$^3$</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 1. (a) Geometry and stacking sequence of the impact test specimen. (b) Experimental equipment.
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In the time-energy curve, the total energy \( E_a \) absorbed by the specimens was calculated as follows \[14\].

\[
E_a = E_0 \left(1 - \frac{E_f}{E_p}ight)
\]

\[
E_f = \frac{1}{2}mv_0^2
\]

where \( v_0 \) is the impact of the striker velocity, \( F \) is the force exerted by the impact striker on the specimen, and \( m \) is the mass of impact striker. \[14\]. The material model of MAT59 (MAT_COMPOSITE_FAILURE_SOLID) in LS-DYNA is usually used for impact simulations of solid composite materials with orthotropic characteristics. The different failure modes expressed in terms of stress and strength in Eq. 8 are listed below \[15,16\].

Longitudinal tensile failure mode:

\[
\left(\frac{\sigma_{11}}{X_1}\right)^2 + \left(\frac{\sigma_{12}}{S_{12}}\right)^2 + \left(\frac{\sigma_{13}}{S_{13}}\right)^2 = 1
\]

Transverse tensile failure mode:

\[
\left(\frac{\sigma_{22}}{Y_2}\right)^2 + \left(\frac{\sigma_{12}}{S_{12}}\right)^2 + \left(\frac{\sigma_{23}}{S_{23}}\right)^2 = 1
\]

Through-thickness shear failure mode (longitudinal):

\[
\left(\frac{\sigma_{11}}{X_1}\right)^2 + \left(\frac{\sigma_{12}}{S_{12}}\right)^2 = 1
\]

Through-thickness shear failure mode (transverse):

\[
\left(\frac{\sigma_{22}}{Y_2}\right)^2 + \left(\frac{\sigma_{23}}{S_{23}}\right)^2 = 1
\]

Delamination failure mode:

\[
\left(\frac{\sigma_{11}}{X_1}\right)^2 + \left(\frac{\sigma_{12}}{S_{12}}\right)^2 = 1
\]

Longitudinal compressive failure mode:

\[
\left(\frac{\sigma_{11}}{X_1}\right)^2 = 1
\]

Transverse compressive failure mode:

\[
\left(\frac{\sigma_{22}}{S_{22}}\right)^2 + \left[\left(\frac{Y_2}{S_{12} + S_{12}}\right)^2 - 1\right] \left(\frac{\sigma_{12}}{S_{12}}\right)^2 + \left(\frac{\sigma_{23}}{S_{23}}\right)^2 = 1
\]

Through-thickness compressive failure mode:

\[
\left(\frac{\sigma_{33}}{S_{33}}\right)^2 + \left[\left(\frac{Z_3}{S_{13} + S_{13}}\right)^2 - 1\right] \left(\frac{\sigma_{13}}{S_{13}}\right)^2 + \left(\frac{\sigma_{32}}{S_{32}}\right)^2 = 1
\]

When the equation corresponding to each failure mode reaches a critical value, the failure occurs in the particular directions. The failure criterion is generally governed by the lamina and loading directions. For a composite material with orthotropic characteristics, the failure mode depends on the longitudinal, transverse and the through-thickness directions and tension, compression loading states, respectively.

To compare the damage characteristics of the T300 and T800 systems under low velocity impact, longitudinal and transverse
time required for the specimen to have the maximum deflection during the impact.

Parameters such as the time-force, the time-velocity, the time-displacement, the displacement-energy, the time-energy were considered for this study. The force means the impact force, when there is contact between the impact striker and composite plate. In the time-force curve, the force value returned to zero represents the time when the contact ends, which is equivalent to the end of the impact time. The other impact parameters are the time-velocity and the time-displacement of the impact striker. The characteristic time is defined as the time when the velocity of the impact striker becomes zero \[13\]. This time represents the
tensile failure modes and delamination failure modes were considered in this study. These are the dominant failure modes associated with fiber, matrix stiffness and strength under low velocity impact. Three dominant failure modes associated with stress components are shown in Fig. 2c-e. The impact force versus time curve indicates the damage initiation, growth and stiffness change.

Fig. 3a shows a comparison between the experimental and FEM simulation results for the T800 composite system. In the simulation result, there is an increasing aspect with oscillation because of contact between the impact striker and the specimen, as well as the experimental result. The curve increases steeply and the force reaches the peak level because the impact striker generates deflection of the specimen.

Up to peak level of force, the specimen damage involves the initiation of matrix cracking, fiber breakage and delamination. After that peak level, when the motion of the impact striker changes to the opposite direction, the force decreases and the

**Fig. 3.** (a) Comparison of the experimental and simulation results for the time-force behaviors of the T800 carbon fiber reinforced polymer system, (b) time-velocity curve, (c) time-displacement curve, (d) displacement-energy curve, and (e) time-energy curve.
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The elastic energy of the specimen is released. During this stage, the local damage causes an oscillation on the graph, and the specimen damage continues to propagate. Finally, the force becomes zero when contact between the impact striker and specimen is over.

When the experimental and simulation results were compared, there was good agreement between the two results. The peak force values are very similar to each other and there is little difference in the two contact end times. Although a slight deviation exists in the time-force curves, they are well matched to each other. Therefore, it can be concluded that the FEM model is validated and well established. A 3-D FEM model using the solid element was developed to compare the behaviors of the T300 and T800 carbon fiber composites under low velocity impacts. The numerical results for various time-velocity, time-displacement, displacement-energy and time-energy curves were investigated, as follows.

The initial impact velocity was 3.71 m/s, and its time-velocity curve is shown in Fig. 3b. The impact striker drops in the direction normal to the specimen, and after contact with the specimen its velocity decreases progressively, reaching zero at the maximum deflection of the specimen. Both T800 and T300 specimens show similar variations in velocity, however, the time to reach zero velocity for T800 is a little shorter than that of the T300 specimen.

This is related to the difference in stiffness between the two fiber systems. The time in which the velocity becomes zero during the contact can be defined as the characteristic time of the T800 ($t_{C,800}$) and T300 ($t_{C,300}$) samples. After the characteristic time the velocity increases negatively, due to the rebound of the impact striker. The rebounding velocity of the impact striker for the T800 sample is faster than T300 due to the higher stiffness of T800. That effect could be related to the difference in elastic energy of the two systems. Finally, the rebounding velocity of the impact striker for both systems becomes constant, which means that the impact striker and specimen are not in contact anymore. The time-displacement curve in Fig. 3c shows the displacement behavior of the impact striker. At first the displacement progressively increases with time during the initial impact stage. When the impact striker reaches the maximum central deflection of the specimen, the velocity of the impact striker becomes zero. At this characteristic time the specimen shows maximum deflection.

The 7.6715 mm of maximum deflection of the T300 specimen is larger than the 7.4763 mm of T800 because it has lower stiffness than T800. This means that the T800 is more rigid and stiffer. The characteristic time of 3.49 ms for T800 ($t_{C,800}$) is shorter than the 3.90 ms of T300 ($t_{C,300}$).

After the characteristic time the impact striker rebounds in the opposite direction for both systems. During this rebound, there is some difference in the displacement of the impact striker with time for the T800 and T300 specimens. Because the T300 has a lower flexural stiffness than that of T800, the T300 has a larger deflection and slower rebounding velocity than T800. In Fig. 3d, the rebounding characteristics of the impact striker are shown. The energy absorbed by the specimen increases as the displacement of the striker increases. And the absorbed energy decreases as the striker bounces back after the maximum deflection of the specimen. A constant value of energy is maintained after rebounding from the initial contact position to the position where the impact event is over. The specimen has the maximum absorbed energy at the maximum displacement of the striker. There is a similarity in the peak energy value between the T300 and T800 systems. However, the energy absorbed by T800 decreases more steeply than T300, which means that the kinetic energy transferred from the specimen to the impact striker for T800 is bigger than for the T300 during the impact event.

The energy absorbed by the specimen with time is shown in Fig. 3e. The total energy for the specimen is the sum of the absorbed energy and elastic energy. There is a steeply increasing region in the slope up to the maximum energy level. The internal damage to the specimen is known to take place within this region. After the maximum energy, the curve decreases progressively until the impact striker is detached from the composite specimen.

After the impact striker is separated from the specimen, there is no change in slope and the curve becomes flat, as seen in Fig. 3e, since the specimen does not absorb any more energy. The maximum level of absorbed energy is almost the same for both the T300 and T800. During the damage initiation process, up to the peak energy level, the T300 system has similar internal damage to the T800. However, the slope of energy for T800 decreases more steeply than that of the T300 after the maximum energy. This means that the energy absorbed by T800 ($E_{a,800}$) is smaller than that absorbed by T300 ($E_{a,100}$).

On the other hand, the elastic energy of T300 ($E_{el}$) is lower than that of T800 ($E_{el0}$). In this process, the damage is propagated in the composite plate. The T800 specimen absorbs 6.9 J versus the 12.25 J of T300 specimen.

When the composite plate is subjected to the impact loading, elastic deformation is produced by the impact energy. This energy is called elastic energy. If the impact energy exceeds the elastic energy, the energy is dissipated by intra-lamina failure and inter-lamina failure after the energy is absorbed by the composite plate.

Therefore, the absorbed energy is the index to the degree of damage. In this case, the T300 specimen more absorbs energy than the T800 specimen, based on the time-energy curve results. However, evaluating intra-lamina and inter-lamina failures in detail by experiment is difficult. Fortunately, there is a relatively easy method to investigate intra-lamina and inter-lamina failure. The composite failure simulation using LS-DYNA is able to show both the intra-lamina failure region and inter-lamina failure [17]. The directional stresses were obtained by LS-DYNA from the FEM model, and the damage evaluation was performed using various failure criteria within the material card of LS-DYNA. A matrix failure mainly depends on the stress values of $\sigma_{22}$, $\sigma_{12}$, $\sigma_{33}$ which are calculated in Eq. 5 [18]. Under transverse loading, the region which exceeds the critical value of the matrix failure criterion is considered to be the area experiencing matrix cracking. The matrix cracking regions, which are indicated by the ellipses on the top surfaces of the T800 and T300 specimens, are shown in Fig. 4a and b, respectively.

The matrix cracking regions on the top surfaces of both the T800 and T300 specimens occurred near the impact location. The matrix cracking area of the T300 was found to be wider than that of the T800.

The matrix cracking areas on the bottom surfaces of the T800 and T300 specimens are shown in the Fig. 4c and d, respectively.
The damage to the T300 specimen on both its top and bottom surfaces are observed to be more widely spread than the damaged area of the T800 specimen. The reason why the damaged area of T300 is wider than that of T800 might be related to differences in strength in the normal, shear direction of the composite, and the active stresses caused by the transverse impact loading. Fiber failure usually arises after the generation of matrix cracking and delamination. This fiber breakage is generated by the impact striker when the high stress concentration and shear stress cause an indentation effect. Stresses on the other regions besides the top surface are generated by high bending stress.

Fiber failure is governed by the stresses in $\sigma_{11}$, $\sigma_{12}$, $\sigma_{13}$ in Eq. 4 [18]. The top surface of T800 in Fig. 4e has a small fiber failure area except for the region near the impact loading. On the other hand, the bottom surface of T800, as shown in Fig. 4g, has a larger fiber failure region than the top surface because of the plate bending effect.

It can also be observed that the fiber failure region for both systems is smaller than the matrix failure region. The fiber failures in the top and bottom surfaces of the T300 specimen are shown in Fig. 4f and h, respectively. The T800 system has less fiber failure damage than T300 due to generated stresses under impact loading since the tensile strength of T800 is higher than T300. Delamination occurs because of the discordance in the bending stiffness between adjacent layers. In other words, the delamination at the interface of two adjacent lamina is caused by the mismatch in their stiffness as a result of their different orientations [19]. Delamination is mainly governed by the stresses $\sigma_{13}$, $\sigma_{13}$, $\sigma_{23}$ in Eq. 8 [18]. These acting stresses in order to separate the interface are related to the through-thickness direction.

The top surface of T800, as shown in Fig. 4i, has a large delamination area around the region of impact loading. The bottom surface of T800 in Fig. 4k has many small delamination areas locally. In contrast to T800, the delamination area of T300 is widely distributed over the whole area. This may have occurred because delamination generally grows where matrix cracking exists. Since the T300 specimen has a larger matrix cracking area than T800, the T300 composite system has a wider delamination area than T800.

Conflict of Interest

No potential conflict of interest relevant to this article was reported.
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References


