Damage Analysis on Woven Randomly Composite Plates

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Abstract. In this study, dynamic analysis of woven randomly composite plates with different impact damage patterns including pattern of post-low velocity impact and patterns of post-ballistic impact is considered. For this purpose, modal testing procedure is performed to present the vibration characteristics of the clamped-free square plates. Effects of bullet-tip geometry, projectile velocity, and impact damage location on the vibration characteristics are examined experimentally. Mass effect is also investigated for this purpose. Results are given in tabular and graphical form.

Introduction

Generally known that any impacted damage region part means weakness in any composite structure. This type of structural weakness can be easily determined by using vibration analysis. A response model may be the most suitable approach to understand what happens to the damage region on a composite structure. In the modal analysis (response model), first two natural frequencies of the impact damaged composite structure are particularly changed by geometrical properties (i.e. structure geometry, damage geometry), material properties and boundary conditions [1-4]. Whereas there are many studies on randomly oriented composite laminates [5-8], limited studies on impact performance of woven randomly composites are found in the literature.

Woven randomly composites possess high degree of integration of the yarns to improve impact strength in multi-axial point of view. For the damage in thin laminates, one may consider to investigate vibration characteristics of randomly composite square plates because of similar mechanical properties in two major axes [9].

Especially, due to the fact that there is a very limited amount of work in the literature about detailed experimental results of bullet-tip effects on vibration characteristics for woven randomly clamped-free composite square plates, this study addresses the problem of three different ballistic impacts on the composite square plate with respect to three different dynamics of the projectile. Effects of bullet-tip geometry, projectile velocity, and impact damage location on the vibration characteristics are examined experimentally. Mass effect is also investigated for this purpose. Results are given in tabular and graphical form.

Material and Methods

Five-layered woven randomly carbon fiber composite square plates provided by Turkish Aerospace Industry Inc. (TAI), Ankara, Turkey (yarn width= 8 mm, yarn thickness=0.3 mm, layer thickness=0.5 mm, ρ=1121 kg/m³, E_{xy}=20.1 GPa, ν_{xy}=0.24) are considered. Each of the four composite square plates is 155 mm in length. Test setup with clamped area, place of accelerometer and seven application points of impact hammer (namely nodes) is shown in Figure 1.

On one hand, low velocity impact test is carried on a set up including an air gun with a stainless steel bullet (11.7×19.6 mm in dimension, 13.3g in weight and 75° in nose angle as shown in Figure 2a). Velocity of the air gun’s projectile (namely air gun) is set 89 m/s. Flight line for the low-velocity impact test is 1 m in length. On the other hand, ballistics tests are conducted by using a G3-A3 machine gun with two different bullet-tip geometries presented in Figure 2b,c (called as blunt and sharp) at Mechanical and Chemical Industry Corporation (MKEK), Kirikkale, Turkey. Weights
of both blunt- and sharp-type projectiles (7.65×29 mm in dimension and 22.5° in nose angle) are 9.6 and 9.5 g respectively. Associated with the ballistics test configuration, velocity (muzzle velocity) is measured as 781 m/s which is in the range of G3 technical specification (780-800 m/s). In connected with the bullet’s yaw angle, flight line for all tests is set 15 m in length.

Figure 1. Clamped-free test setup for the randomly oriented composite square plate.

Figure 2. Representation of bullet types: (A) Air gun, (B) Sharp and (C) Blunt.

Image acquisition for all impact damage areas is completed by using a Boeco Stereo Microscope (Model BTB-3C, Germany).

Vibration measurements are conducted such a way that an impact hammer with a force transducer (Model No: 5800B2, Dytran Instruments, Inc., USA) is used to excite the undamaged/impact damaged composite plates through the selected nodes. Three impact excitations are applied on each of the nodes. After the excitations, the responses are obtained by an accelerometer (Model No: 327342, Dytran Instruments, Inc., USA). The vibration measurements are completed using a microprocessor-based data acquisition system, namely SoMat™ eDAQ-lite
and nCode GlyphWorks software (HBM, Inc., USA). Average impact hammer force of 25 N is applied to the specified impact hammer points (nodes).

Corresponding to the types of impact damage, experimental modal analyses consist of four parts: (I) Vibration analysis with the undamaged plate, (II) Vibration analysis with the air gun-damaged plate, (III) Vibration analysis with the blunt-damaged plate, (IV) Vibration analysis with the sharp-damaged plate. Then, results are compared with the results with following two equations [10];

\[
\frac{\lambda m}{\rho A} = \frac{1 + \cos(\lambda L) \cosh(\lambda L)}{\sin(\lambda L) \cos(\lambda L) - \cos(\lambda L) \sinh(\lambda L)}
\]  

(1a)

\[
\omega_1 = \frac{1}{2\pi} \lambda \sqrt{\frac{EI}{\rho A}}
\]

(1b)

where \(\lambda\), \(m\), \(\rho\), \(A\), \(L\), \(E\) and \(I\) are first eigenvalue, mass of accelerometer (kg), density of the plate (kg/m\(^3\)), cross section area (m\(^2\)), length of the plate (m), modulus of elasticity (Pa) and inertia of the plate (mm\(^4\)) respectively.

For the investigation of mass effect, each dead weight of 0.2, 0.4, 0.6, 0.8 and 1 kg is placed on the impact damaged region (see Figure 1).

And, the study ends up with completing three-point-bending tests after impact. To determine modulus of elasticity of each of the damaged samples, the equation below is considered;

\[
E = \frac{1}{48} \frac{FL^3}{\Delta I}
\]

(2)

where \(F\), \(L\), \(\Delta\) and \(I\) are applied load in elastic limit (N), span length of the plate (mm), deflection at the applied load (mm) and inertia of the plate (mm\(^4\)) respectively. Finally, comparison of elastic modulus between undamaged and damaged samples is evaluated by using a damage formula [11];

\[
E_{\text{damaged}} = (1 - d)E_{\text{undamaged}}
\]

(3)

where \(d\) is the damage variable.

**Results and Conclusion**

Type of projection penetration and photographical representations of damage areas including air gun, blunt and sharp are given in Table 1 and Figure 3. Damage areas of air gun, blunt and sharp specimens are measured as 0.8, 3.8 and 7.1 mm\(^2\) respectively.

| Test      | Impact velocity (m/s) | Projectile type | Projection penetration |
|-----------|-----------------------|-----------------|------------------------|
| Air gun   | 90                    | Blunt           | Partial                |
| Machine gun | 780                 | Blunt           | Full                   |
| Machine gun | 780                 | Sharp           | Full                   |
Table 2. Mechanical characteristics of the undamaged and damaged specimens.

| Test             | $E$ (GPa) | $d$  | $\omega_1$ experimental (Hz) | $\omega_1$ analytical (Hz) |
|------------------|-----------|------|-----------------------------|-----------------------------|
| Undamaged        | 20.07     | -    | 63.57                       | 62.74                       |
| Blunt (air gun)  | 17.22     | 0.14 | 66.94                       | 67.15                       |
| Blunt (machine gun) | 16.35     | 0.41 | 76.91                       | 74.25                       |
| Sharp (machine gun) | 16.67     | 0.40 | 84.38                       | 83.89                       |

Table 2 says that (i) there is no exact difference of damage effect between the machine gun projectiles and (ii) the analytical and experimental results of fundamental frequency with no mass coincide with each other.

Figure 4 shows the variation of fundamental frequency at the nodes of the composite square plate with a mass of 0.2 kg. It is noted that (i) putting a mass on the damage region changes the linear nodal behavior into undulation one, (ii) At node 3, fluctuation pattern of damaged and undamaged groups are similar. That is, increasing the damage area increases the fundamental frequency, (iii) there may be minimum interlaminar damage in the line between the accelerometer and node 3. Consequently, groups undamaged, air gun, blunt and sharp are able to be compared at node 3.
Figures 5-7 give variations of fundamental frequency, fundamental damping ratio and fundamental displacement response function with different load of mass at node 3. Figure 5 says that (i) increasing mass effect decreases the frequency difference among the damaged plates, (ii) decreasing damage region (low velocity impact) gives similar behavior between the undamaged and the damaged plates.

![Figure 5](image)

Figure 5. Variation of fundamental frequency with different load of mass at node 3.

One may conclude from Figure 6 that (i) increasing damage region (ballistic impact with sharp projectile) with increasing mass effect increases fundamental damping rate linearly, (ii) fundamental damping ratios of blunt specimens become closer while increasing mass effect more than 0.6 kg where the damping ratio of blunt (air gun) is constant.

![Figure 6](image)

Figure 6. Variation of fundamental damping ratio with different load of mass at node 3.
In Figure 7, (i) except blunt (machine gun), all groups represent similar exponential behavior. In other words, interlaminar shear effect may be high for the specimen with blunt (machine gun), (ii) fundamental displacement response function of blunt specimens becomes closer while increasing mass effect more than 0.6 kg.

Figure 8. Variation of second natural frequency at the nodes of the composite square plate with a mass of 0.2 kg.
Moreover, in order to clarify the mass effect, Figure 8 presents the variation of second natural frequency at the nodes of the composite square plate with a mass of 0.2 kg. It is observed that because of starting undulation behavior, fluctuation pattern of damaged groups are similar at node 4.

Figure 9 says that (i) although increasing mass effect decreases second natural frequency exponentially for the undamaged specimen, increasing mass effect increases the frequency for the damaged ones, (ii) For the specimens with machine gun damages, increasing mass effect increases second natural frequency with an identical path.

One may conclude from Figure 10 that (i) except the blunt (air gun), increasing mass effect more than 0.5 kg decreases fundamental damping rate, (ii) second damping ratios of all damaged specimens except the blunt (air gun) one become closer to that of undamaged specimen while increasing mass effect more than 0.6 kg where the damping ratio of undamaged one is approximately constant.
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