Low-speed impact test for foam supported composite laminates

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ABSTRACT

A test approach was developed to characterize the low-speed impact performance of foam-supported rigid composites for personnel protection applications. In particular, an instrumented impact test approach with a fixed specimen was employed that is simpler and more effective than tests involving a moving specimen. With the aid of the specifically-designed specimen fixture, multiple-impact tests can be performed for a number of test scenarios, including different combinations of composite material, laminate thickness, and support foam. As an application example, a low-speed impact test for E-glass/polypropylene laminates supported by a vinyl nitrile foam was presented. The test results demonstrated that the thickness of the laminates and the impact energy level have significant influences on the impact response.

INTRODUCTION

The improvised explosive devices (IEDs) frequently encountered during recent military operations continue to drive requirements for higher levels of personal protection for soldiers. In addition to ballistic penetration and blast threats, IEDs also induce low-speed impact threats to a soldier's head. Such impacts include the head hitting the ground or a barrier, getting hit by a relatively large mass accelerated by the explosion, and secondary impacts inside a vehicle subjected to an external IED explosion. Therefore in new designs of personal protection armour systems, such as a combat helmet, low-speed impact protection capability is an important consideration.

In order to achieve the desired protection levels while minimizing the weight burden on the wearer, many components of a personal protection system are made from state-of-the-art composite materials, including hybrid composite laminates consisting of different material systems or composites consisting of different fibres and resins in a single laminate. Successful design of a composite armour component/structure requires a full understanding of ballistic and mechanical behaviour at both laminate and structural levels. In many stages of the design process, experimental approaches are primarily employed to support and verify the design. The present investigation focuses on the test evaluation of low-speed impact response of composite laminates backed with foams.

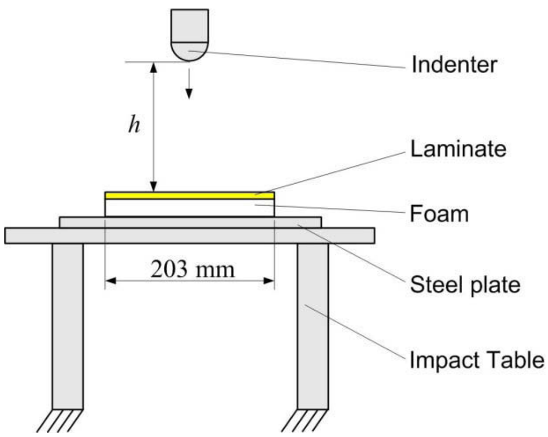
In this investigation a test approach was developed to characterize the low-speed impact performance of foam-supported fibrous composite laminates in personnel protection applications. A drop-weight impact machine with a fixed specimen was employed which is simpler and more effective than tests involving a moving specimen. To facilitate the test, an in-house impact specimen fixture was employed to hold a foam-supported laminate. From the impact force versus time data measured by the instrumented force transducer, the specimen deflection and absorbed energy during the impact can be determined. With the developed approach, impacts can be conducted for test scenarios representing different combinations of composite material, laminate thickness, support foam, and multiple impact energy levels. As an application example, low-speed impact tests for E-glass/polypropylene (PP) laminates supported by a viscoelastic vinyl nitrile foam are presented. Impact force versus time curves at various impact conditions indicate that the laminate thickness and impact energy level have significant influences on the dynamic impact response.

DROP-WEIGHT IMPACT TEST FOR FOAM SUPPORTED LAMINATES

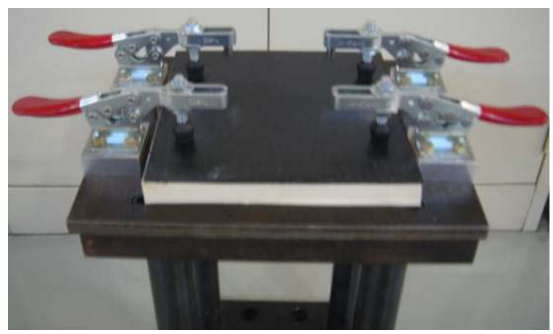
Instrumented impact testing [1, 2] provides an efficient approach to characterize the impact performance of composite laminates in laboratory controlled conditions, in which both the damage resistance and the stiffness performance of the composites can be quantitatively determined and compared. With an instrumented force transducer (load tup) and the associated data acquisition system [3], impact load on the specimen is continuously recorded as a function of time and specimen deflection, which gives an adequate description of the stiffness response and a representation of the entire impact event [3]. In this investigation, an instrumented drop-weight impact testing approach for composite laminates was extended to the testing of foam supported rigid laminates widely used in personal protection applications against low-speed impact threats.

Test Setup

Figure 1(a) shows a schematic of the proposed drop-weight impact test setup [3]. A low-speed impact event is introduced in the specimen by dropping an impact indenter (energy carrier) from a pre-defined height, *h*. In addition, by measuring the impact force and motion of the impact indenter during the dynamic contact with the foam supported composite laminates, the impact response of the specimen is characterized. Moreover, the damage (if any) in the specimen can be observed after the impact test.



(a) Impact test set-up



(b) Fixture with specimen

Figure 1 The setup and fixture of the drop-weight impact test

The specimen fixture recommended in ASTM D7136 [1] could not be used in this study because the current specimen has larger dimensions and a wider range of thickness. An in-house fixture was therefore designed and fabricated [3]. The design of the fixture incorporated the following considerations. Firstly, the specimen is placed on a solid steel plate (about 10 mm in thickness), which is bolted to the steel impact table, providing a rigid support to the test specimen. Secondly, the specimen should be accurately located during multiple impacts to ensure the same striking point. This is achieved by using three dowel pins which locate a specimen by constraining two adjacent edges. The specimen is also clamped by four toggle clamps with rubber tips (see Figure 1b). Since the actual composite laminates were not perfectly flat (especially the thinner sheets), clamping was used to ensure contact between the composite laminate and the support foam.

Considering that different specimens (composite laminates with backed foams) can be conveniently located in the fixture and good contact maintained between the composite laminates, the foam and the steel plate, this approach is simpler and more effective than tests involving a moving specimen.

A spherical indenter is frequently used as the impact striker in helmet impact tests. In this work, a stainless steel impact indenter with a hemispherical tip of diameter 96 mm, as suggested in Ref. [4], was designed and fabricated. This indenter was used for all impact testing in this investigation.

The proposed test approach was implemented in a Dynatup® Model 8200 drop-weight impact machine. Designed for use with Dynatup Impulse™ data acquisition systems, the 8200 impact test system is equipped with load and velocity transducers to provide data collection, analysis and reporting. The impactor assembly is composed of a crosshead weight and an indenter and is instrumented with a piezoelectric force transducer specifically designed for use in the short duration impact test. Impactor velocity at the point of impact contact is determined by a flag passing through an infrared detector. The infrared detector also triggers the acquisition of the force transducer data. The impact machine also has a latching mechanism for the impactor to prevent repeated impacts due to rebound. Figure 2 is a schematic drawing of the drop-weight impact machine where major components of the system are denoted.

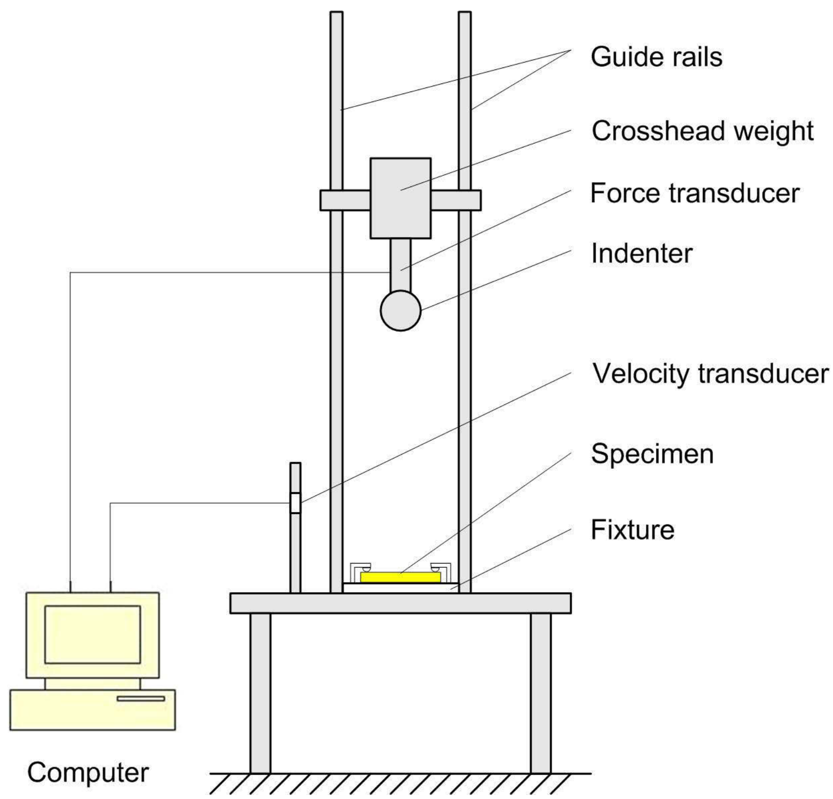


Figure 2 Instron drop-weight impact machine

Measurements and Data Manipulation

The required drop height (h) of the impactor for a given scenario is determined using the impactor mass (m), which can be measured by a laboratory scale and from the nominal impact energy specified (E). Using local gravitational acceleration g (= 9.81 m/s^2), we have

$$h = \frac{E}{mg} \tag{1}$$

Due to friction losses during the drop event, the measured impact energy will differ slightly from the nominal impact energy. The measured impact energy is determined by the impactor mass and the impact velocity measured by the velocity detector (see Figure 2):

$$E_i = mv_i^2 / 2 \tag{2}$$

Where E_i and v_i are the measured impact energy (J) and impact velocity (m/s), respectively. Note that E_i and v_i represent values at time t = 0 when the impact contact starts. The contact between the impact striker and the specimen is identified when a greater-than-zero force is detected by the force transducer.

With the impact force versus time history $F(t)$ measured during the impact test, we can determine important values such as the maximum impact force ($F_{\max}$), time duration of the impact, and so on. Furthermore, impactor velocity (v) and deflection (s) versus time relations can be determined by [1]:

$$v(t) = v_i + gt - \int_0^t \frac{F(t)}{m} dt \tag{3}$$

$$s(t) = v_i t + \frac{1}{2} gt^2 - \int_0^t dt \int_0^t \frac{F(\tau)}{m} d\tau \tag{4}$$

The integrations in Eqns. (3) and (4) are usually evaluated numerically using the measured $F(t)$ data. Note that the positive direction of $s(t)$ is downward for a drop-weight test and the reference point is defined at the instant when the impact contact starts, see Figure 3.

During impact, the specimen absorbed energy versus time relation can be obtained as,

$$E_a(t) = \frac{1}{2} m[v_i^2 - v^2(t)] + mgs(t) \tag{5}$$

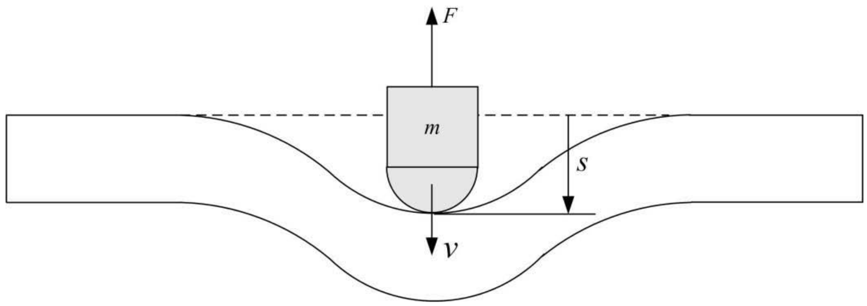


Figure 3 Deflection of the specimen

Note that the absorbed energy of the specimen can also be expressed as the area under the force versus deflection curve, i.e.,

$$E'_a(s) = \int_0^{s(t)} F(s)ds \qquad (6)$$

In the case that the specimen deflection $s(t)$ is directly measured by a displacement transducer, Eqn. (6) is more convenient than Eqn. (5) since only one numerical integration is required. On the other hand, for the foam supported specimen, the absorbed energy is the energy absorbed by both the composite laminate and foam. The fractions of energy absorbed by each component, however, cannot be directly determined by the test.

APPLICATION EXAMPLE--IMPACT TESTING OF E-GLASS/PP LAMINATES

Materials and Test Conditions

As an application example, impact test of foam-supported E-glass laminates at multiple impact energy levels was performed. Commercial E-glass fabric/PP laminates and a viscoelastic vinyl nitrile foam with a density of 108 kg/m^3 were used throughout the test. The nominal thickness of the viscoelastic foam is 19 mm. Composite laminates with areal densities (AD) of 1570 and 3020 g/m^2 were used. The nominal thicknesses of these two laminates were 1 mm and 2 mm, respectively.

Each test specimen received multiple-impacts consisting of 3 “pre-conditioning” impacts of 20 J, followed by an impact of either 55 J or 90 J.

Results of 20 J Impact

Figure 4 displays the impact force versus time curves for the three 20 J impacts for specimens of AD1570 laminates backed by the viscoelastic foam. Note that the three impacts were performed using a sufficient time interval between consecutive impacts to allow full recovery of any viscoelastic deformation of the foam. As shown in the figure, the impact force versus time curves of the multiple impacts of the specimen are very similar. In this example, the maximum difference among the maximum forces of the three impacts is below 2 %.

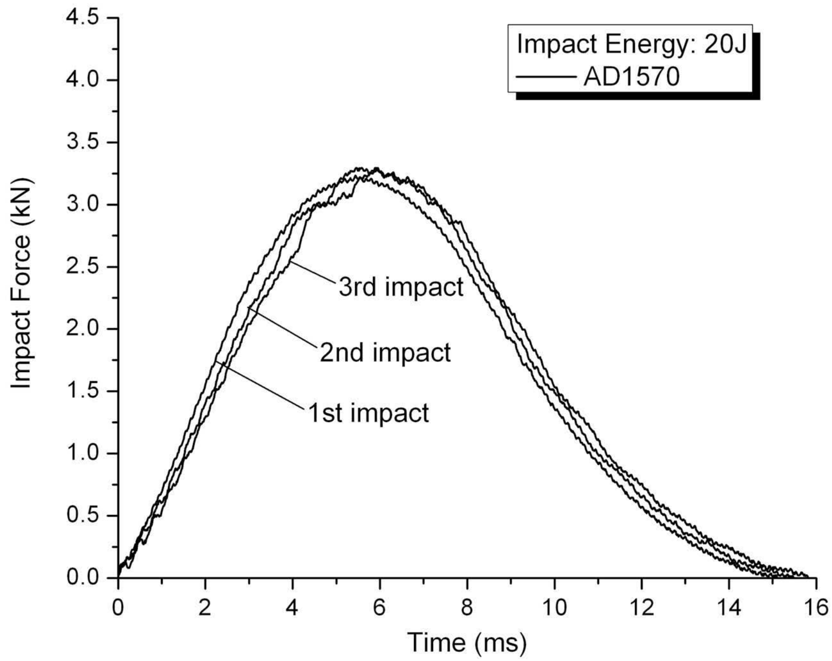


Figure 4 Three 20J impacts of specimen AD1570

Results of 55 J Impact

Figure 5 depicts and compares the impact force versus time curves of two specimens with laminate areal densities of AD 1570 and AD 3020 g/m^2. Note that the impact energy level for these two specimens is 55J and that the specimens have already been impacted by three 20 J "pre-conditioning" impacts. As can be seen from the figure, at a 55J impact energy level, the specimens AD1570 and AD3020 have quite different impact responses.

At the initial stage, the two curves are straight lines with different slopes. These different slopes imply that the initial stiffnesses of the two specimens are different, as expected. At approximately the mid-point of the curve segment before the maximum peak, there is a "step" for specimen AD1570. The mechanism for this phenomenon is as yet unknown. However it is expected that the deformation mode of the foam between the bending laminate (under a spherical striker) and the rigid support steel plate is one critical factor. Further efforts including analytical and/or numerical modelling are required to characterize the deformation of the foam. As can be seen from the curves, the maximum impact forces of the AD1570 and AD3020 specimens are about 8.5 kN and 7.3 kN, respectively; while the total impact duration times of the two specimens are about 15 ms and 11.5 ms, respectively. Unlike impacts at lower energies such as in the cases shown in Figure 4, a longer impact duration in this case does not implies a lower impact force.

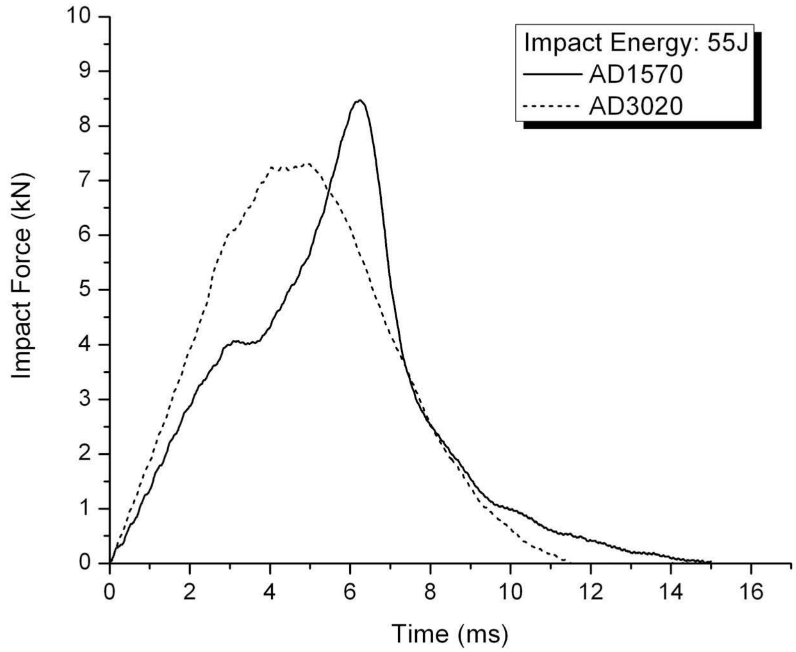


Figure 5 Comparison of two specimens impacted at 55J

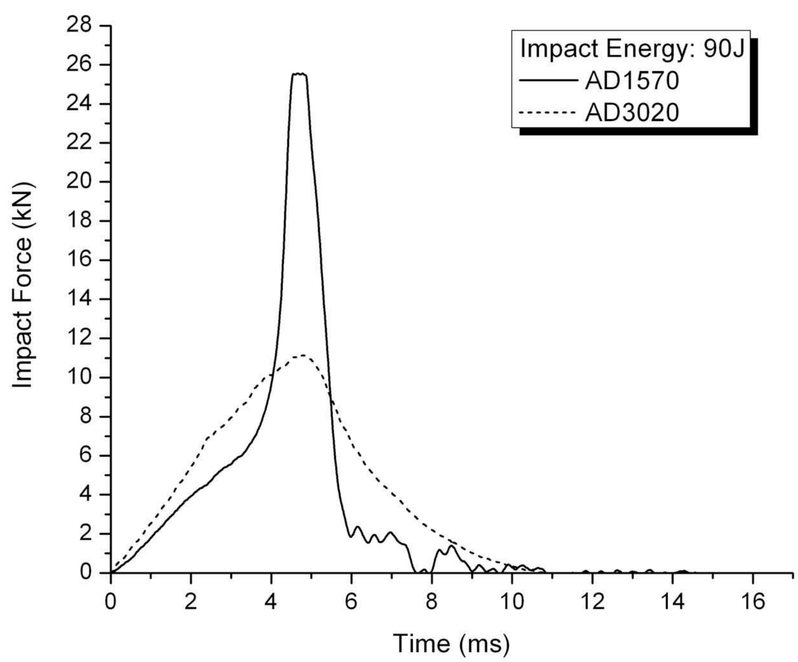


Figure 6 Comparison of two specimens impacted at 90J

Results of 90 J Impact

Figure 6 illustrates and compares the impact force versus time curves of two specimens with laminates of areal densities of AD 1570 and AD 3020 g/m^2, tested at an impact energy level of 90 J. Again the specimens have already been impacted by three "pre-conditioning" 20 J impacts. As can be seen from the figure, the AD1570 specimen have a very high impact peak force, which implies that the supported foam does not fully functioned to reduce the maximum load. This is usually detrimental to low-speed impact protection and should be avoided in design. This phenomenon was also observed in a similar impact test for Kevlar composite laminates [3]. It should be noted that the apparent maximum force for AD1570 specimen is about 25 kN, which exceeds the limit of the force transducer [3]. Thus the maximum impact force as shown in the figure is a truncated value by the force transducer.

CONCLUSIONS

An impact test approach was proposed to characterize the performance of foam supported laminates in personnel protection applications. A test scheme with a fixed specimen was employed which is simpler and more effective than tests involving a moving specimen. With the specially designed specimen fixture and impact indenter, instrumented impact tests for various combinations of composite material, laminate thickness, support foam, and multiple impact energy levels can be conveniently performed. Test results for E-glass/polypropylene laminates supported by vinyl nitrile foams were reported. It is demonstrated that the proposed approach captured the multiple impact behaviour of foam-backed composites and the extreme response at a high impact energy level.

REFERENCES

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