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Some Recommendations for Characterization of Composite Panels by Means of Drop Tower Impact Testing

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Instrumented drop tower impact-test devices have been long used for inflicting impact damage onto test specimens for damage tolerance characterization of composite panels. However, there are many considerations that need to be made regarding the test setup to avoid the inconveniences related to the acquisition and interpretation of the impact data. Because there are many advantages associated with this type of experiment, to benefit fully from the amount of information available from an impact test, a multiparameter approach needs to be used, and the entire test history needs to be interpreted. The previously demonstrated similitude between impact and quasi-static indentation tests is used to gain even further understanding in the mechanics of the event and its associated damage mechanisms. The fundamental characteristics of damage resistance tests are illustrated for the engineer being initiated to this type of work, particularly with regards to the understanding of impact traces. A summary of lessons learned is reported, and guidelines for the setup of the test and the interpretation of the results are given. A set of recommendations for best practice is given with the intent of laying down the foundation for a standard approach to future research programs.

I. Introduction

A. Background

ALTHOUGH there are many impact-test practices found in the industry, government organizations, and research institutions, the normative regarding impact testing of composite materials has been extremely slow to appear in the community. Only in the last couple of years has consistent progress been made toward the finalization and prerelease of two ASTM International through its Committee D-30 on composite materials, concerned with test procedures for impact damage resistance and tolerance, respectively.[1,2] Impact tests may be used to screen materials for damage resistance, in terms of the resulting damage size and mechanism, or in conjunction with a damage tolerance investigation, as in the case of compression-after-impact (CAI) testing. The inherent difficulty of developing a true standard lies in that damage resistance properties usually generated in impact tests are highly dependent on several configuration-specific factors that include specimen geometry and material properties, as well as impactor characteristics.

This paper, resulting from research programs conducted over the years,[3–6] provides a guide for those becoming acquainted with instrumented impact testing, and faced with acquiring accurate data and subsequently evaluating it. The discussion is separated in to a first section that includes the determination of the major system parameters and some of the commonly occurring problems and a second section that includes the evaluation of the data collected, including the interpretation of typical impact curves. Because of the large amount of information that can be extracted from an adequately performed damage resistance investigation, it will also be shown that a multiparameter approach is recommended to interpret the available data fully.

In traditional low-velocity impact tests, such as the ones achieved by means of drop tower setups, a flat composite plate is subjected to an out-of-plane, concentrated load by means of a falling weight whose potential energy is specified.[1] Early damage tolerance studies used impact energy as the sole damage metric for characterizing the severity of an impact event and for its subsequent residual strength determination.[7,8] Later research programs indicated the importance of having a fully instrumented impact test device because the ability to obtain force–time histories can give great insight in the dynamics of the event and mechanisms of damage.[9–16] Because of its analogy with quasi-static indentation loads, force has proven over the years to be an extremely valuable tool to determine the onset of damage in dynamic tests.[13–16] However, great distinction needs to be made between the critical value of the contact force, which corresponds to the threshold for damage initiation, and other values of contact force, such as peak force, which might or might not have a real physical significance.[3–6] Currently, federal organizations and aircraft manufacturers still employ impact energy as damage metric in their certification efforts,[7,17] mostly because of the difficulties encountered with the use of contact force.[18]

With the instrumented drop tower having become the impact-test machine of choice for many researchers in evaluating the dynamic response of structural materials, there is a definite requirement for standard procedures. The three most important factors for achieving such task are calibration of the dynamic load cell, control of the instrumented tup signal, and reduction of data. Among the most commonly reported problems in the literature[3,9,10] is the incorrect interpretation of force–time histories, because of the inertial oscillations of the instrumented tup and target assembly, which may result in spikes in the signal of little physical meaning. Another frequent problem observed is that often researchers attempt to characterize directly the impact damage resistance of composite targets without previously assessing its elastic response or its quasi-static indentation performance. Other usual delays result from the application of inadequate impactor masses,[19] the incorrect assignment of boundary conditions, or the assumption of friction-free fall despite the potentially significant losses in kinetic energy within the system. To implement reliable test procedures, the engineer or researcher should have a general understanding of the inherent characteristics of instrumented impact testing.

B. Definitions

1) Damage is a structural anomaly in a material or structure created by manufacturing or service usage.

2) Damage resistance is a measure of the relationship between the force, energy, or other parameter(s) associated with an event or sequence of events and the resulting damage size and type.

3) Damage tolerance is a measure of the relationship between an existing damage size and type within a structure and the retention of

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specific functionality for that structure, such as the ability to sustain applied forces without failure.

4) As indicated in Ref. 17, damage resistance and damage tolerance are often confused. A material or structure with high damage resistance will incur less physical damage from a given event. Materials or structures with high damage tolerance may incur varying levels of physical damage but will retain high amounts of remaining functionality. A damage-resistant material or structure may, or may not, be considered damage tolerant.

5) Contact force (newtons or pounds) is the total force applied normal to the face of the specimen by the indenter during the impact event.

6) Peak force (newtons or pounds) is the maximum value of contact force recorded during an impact test.

7) Critical force (newtons or pounds) is the value of the contact force during an impact event at which the first noticeable change in out-of-plane stiffness of the material occurs, coincident with the onset of damage; it is also referred to as damage threshold.

8) Impact energy (joules or foot pounds) is the available potential energy or, equivalently, incident kinetic energy.

9) Critical energy (joules or foot pounds) is the level of kinetic energy required to introduce damage and corresponding to the critical force value.

10) Dissipated energy (joules or foot pounds) is the amount of energy absorbed mainly in damage mechanisms but also in other nonconservative phenomena, that is, vibrations, friction, and specimen/fixture slipping, and is, therefore, not restituted to the rebounding impactor.

11) Subcritical impact is the impact event conducted at energy values below the damage threshold, where the structure behaves in an elastic manner.

12) Supercritical impact is the impact event performed at impact energy values above the damage threshold.

13) Impact velocity (meters per second or feet per second) is the incident velocity of the impactor at the beginning of contact.

14) Rebound velocity (meters per second or feet per second) is the residual velocity of impactor at the end of contact.

15) Contact duration (milliseconds) is the total time of the impact event, or the impactor's resident time on the target.

16) Mean static failure load (newtons or pounds) is the value of the contact force during a quasi-static test at which the first noticeable change in out-of-plane stiffness of the material occurs; it is the equivalent of the critical force for a quasi-static test.

17) Mean static ultimate load (newtons or pounds) is the maximum load-bearing capability of a structure in a quasi-static test.

18) Contact stiffness (newtons per meter or pounds per inch) is the combination of impactor/target system material (elastic modulus and Poisson's ratio) and geometric (radius of curvature) properties.

19) Effective structural stiffness (newtons per meter or pounds per inch) is the combination of target material (elastic modulus and Poisson's ratio) and geometric (laminate thickness and support span) characteristics that influence the mechanical response of a structure.

II. Recommendations on the Preparation of the System for Data Collection

A. Definition of Low-Velocity Impact Test

Drop towers have long been used to assess the dynamic response of composite panels for damage resistance and tolerance investigations. Traditionally, this type of investigation has been referred to as low-velocity impact testing to differentiate it from the so-called high-velocity impact tests used, for example, in ballistic studies. However, this kind of definition may be misleading, and there are many cases in the literature where researchers have tried to generalize the existence of a fixed transition point between the two regimes. To further complicate the situation, the range of impact velocities used in the drop tower impact tests for damage resistance and tolerance considerations is the same as that of crush tests used in crashworthiness research, a field concerned with very different structural phenomena. A more accurate definition of impact event is obtained employing the impactor–laminate mass ratio.[20] For very small mass ratios, the event falls in the ballistic regime, where the impact event has a total duration of the same order as the transition time for through-the-thickness (three-dimensional) wave propagation, and the response is highly localized. For larger but still small mass ratios, the event falls in the high-velocity small-mass regime, and it is mainly governed by flexural and shear waves. For even greater mass ratio values, the total contact duration is much longer than the time needed by these waves to reach the plate boundaries, the response is mass dominated, and the lowest vibration mode of the impactor–target system predominates. The resulting response is essentially quasi-static in nature, in the sense that deflection and load have the same relation as in a static indentation test.[13–15] Although an impactor–target mass ratio of 2 is sufficient to set an impact test in the large-mass regime, for values even up to 4–5 it is possible that the recorded force–time trace might be hard to interpret because of the mutual excitation of the two masses and the resulting presence of inertial and harmonic oscillations, which will be discussed later. For that reason, when performing a low-velocity impact test it is desirable to employ impactor masses that are at least 10 times greater than those of the target laminates.

Historically, the first impact test performed on composite materials for aerospace applications were non-instrumented.[8] The target laminates or structures were impacted at a nominal impact energy level, and the subsequent damage was measured with destructive and nondestructive inspection methods. Eventually, the goal of the test was to inflict barely visible impact damage in the structure for certification purposes and then to measure the residual properties of the panel. This practice originated the tradition to build the so-called damage maps, which relate a measure of damage (such as dent depth or projected delamination area) to incident kinetic energy, and the CAI curves, where the residual compressive strength of the panel is also plotted against the incident kinetic energy.[17] Later developments, which coincided with the commercialization of instrumented impact devices,[9–11] indicated an advantage in the use of dynamic load cells. Fully instrumented devices, such as the Dynatup,[21] enabled the recording of force and time, which are directly measured, as well as energy, deflection, and velocity, which are calculated. It became then possible to characterize the elastic behavior, failure initiation, and failure propagation characteristics of a composite structure in terms of applied contact force. The use and understanding of the force–time traces enabled the researcher to individuate the damage threshold, and its similitude with quasi-static indentation tests allowed for classical mechanics criteria to be applied.[12,13]

For this very reason, it is recommended that the engineer, assigned to characterize experimentally or numerically the impact performance of composite panels, first perform an identical test under quasi-static conditions. It is usually possible to remove the entire fixture/target assembly from the drop tower and move it to a static loading machine. It is fundamental that an indenter of identical shape, size, and material as that of the impactor be used for the indentation test. It is now generally accepted in the literature that, for current composite systems, quasi-static and low-velocity impact tests should be superimposed within a very small margin.[22]

In recent years, the practice of employing the recorded contact force has sometimes degenerated in the one of recording only its peak value reached during a prescribed test, without an effective understanding of the meaning of that value. For example, the lack of consideration for the complete force–time history, in exchange for the pinpointing of the peak force value, has frequently led some researchers to select the erroneous value of the contact force due to the presence of instrumentation-related low-frequency oscillations in the signal. Sometimes the onset of damage itself can be attributed to a peak recorded force value, whereas in reality it may have occurred earlier in the force–time history. For all those reasons, a multiparameter approach should be employed in impact damage resistance characterization studies that involves the simultaneous understanding of multiple force and energy parameters, as well as other parameters indicative of structural stiffness, such as contact duration and the coefficient of restitution.[3] At a minimum, the entire force–energy history needs to be evaluated, making sure that its overall characteristic features are correct.

B. Adjustment of Impact Response

Calibration of an instrumented tup can be performed by performing a low-blow elastic impact test: The force–time curve (Fig. 1) is recorded and compared with a calculated (or otherwise measured) result. It is essential that the impact be entirely elastic because even small amounts of damage will produce noticeable reductions in the measured peak force. Key parameters in the force–time (F–T) trace for an elastic test are total contact duration and peak force. However, the understanding of the overall shape of the F–T history, including whether it resembles a sine or halvesine curve, the symmetry with respect to time to peak force, and the superimposed oscillations, is fundamental to gain confidence in the acceptance of more complex results. For that reason, it is fundamental that, before venturing in the realm of supercritical (damage-inducing) impact testing, the engineer has established sufficient confidence in the interpretation of the subcritical (elastic) results.

The relationship used to estimate the peak force in a purely elastic test is[9]

$$P_m = \sqrt{2E_i/C} = \sqrt{2KE_i} \tag{1}$$

where E_i is the available impact energy and C and K are the compliance and stiffness, respectively, of the specimen being impacted. When the interaction between the hammer and the specimen is considered to be a vibrating mass on a spring, these quantities can be determined using the relationship

$$t_c = \pi\sqrt{mC} = \pi\sqrt{m/K} \tag{2}$$

Where t is the contact duration for a purely elastic test that can be adequately approximated by a half-sine wave (Fig. 1) and m is the impactor mass.

When the tup makes contact with the test specimen, its kinetic energy is reduced by an amount E_D given by (Fig. 1)

$$E_D = E_I + E_V + E_{DD} \tag{3}$$

where

E_D = total energy dissipated or absorbed

E_I = inertial contribution, the increment of energy required to accelerate the specimen from rest to the velocity of the hammer

E_V = term due to vibration and other non conservative dissipation phenomena

E_{DD} = term associated with the total energy dissipated in the creation and propagation of damage, if applicable.

For elastic impact tests, where no damage is created, it is possible to extrapolate the overall amount of energy absorbed by the system in inertial and vibrational phenomena. Once that characteristic value is known, it is possible to extrapolate the actual amount of energy dissipated in damage formation for supercritical impact events.[19] Because it can be shown that[20]

$$E_D = v_0 \int_0^{\tau} P\,\mathrm{d}t \tag{4}$$

or, alternatively,

$$E_D(t) = (m_{\text{tup}}/2)\left[v_0^2 - v^2(t)\right] \tag{5}$$

it is possible to compute the total energy dissipated in the impact event by integrating the area under the F–T curve. However, the actual impact velocity near the point of contact needs to be known to account for frictional losses along the guiding rails. The hammer can be regarded as a free-falling object, and its potential energy should be converted entirely into kinetic energy, thus, yielding the known expression

$$v_0 = \sqrt{2gh} \tag{6}$$

where h is the drop height.

In most cases, however, there is a considerable amount of energy dissipated during the descent of the carriage, particularly in custom-built drop tower assemblies, and it is mainly associated with the friction occurring along the rails of the single- or double-column device. Whereas in supercritical impact tests, at higher values of impact energy, such dissipation can consist in only 3–5% and may appear to be negligible, in subcritical tests, such as the elastic tests used to determine the effective structural stiffness of the system, it can reach values of 12–14% and, hence, become the source of gross miscalculations. There is a need for the impact device to be instrumented to measure the velocity of the indenter at a given point before impact, such that the instantaneous value of the impact velocity may be calculated. Furthermore, the value of the exit velocity can also be calculated and yield other useful information, such as the coefficient of restitution, discussed later. Commonly, these velocity-measuring systems use a double-pronged flag, which obstructs a light beam between a photodiode emitter and detector. The impact velocity is then calculated using the measured time in which the light beam is obstructed by each prong.[21]

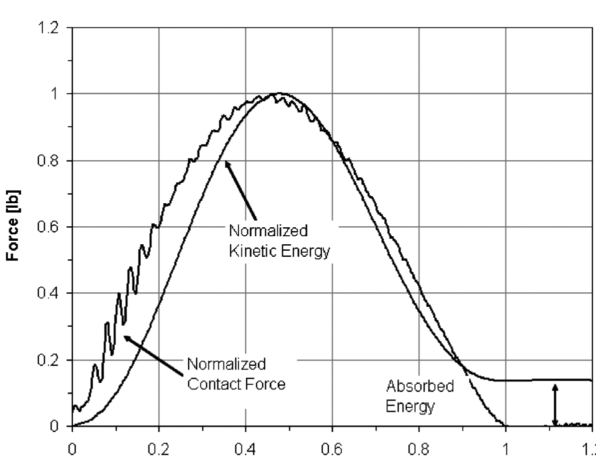

Fig. 1 Contact force and kinetic energy vs time history for purely elastic test.

C. Oscillations and Dynamic Signal Control

The most commonly employed technique for the determination of the load-time response of a specimen during impact utilizes strain gauges attached to the tup or striker portion of the carriage. The signal generated and recorded by the data acquisition system is a complex combination of the following components, as shown later[9,10]: 1) the true mechanical response of the specimen, 2) inertial loading of the tup, 3) low-frequency fluctuations, and 4) high-frequency noise. The first component is the obvious objective of the investigation, yet often the second and third components can overshadow the actual results. The last component, which is mainly attributable to the amplification system, can generally be minimized with appropriate strain-gauge selection, or by employing electronic filtering.

Note that the true mechanical response of the target includes some of the oscillatory phenomena visible in the force–time trace. In particular, the oscillations that can be seen as fluctuating around the mean value of the signal before the onset of damage are a physical indication of the flexural wave propagation within the specimen itself; hence, they should not be confused with a signal error.

The inertial loading (Fig. 2) on the tup may be viewed as the force caused by rigid-body acceleration of the specimen from a rest position to the velocity of the impacting assembly. The discontinuity itself results from the interaction of a rapidly changing inertial load and the finite ability of the instrumented tup to react to very rapid load transients. The period for which this component dominates the tup signal is again a function of acoustic impedances of the tup and target and of the geometry of the specimen. Generally, it dominates the first 10–100 μs portion of the signal and is represented by the first load fluctuation of the F–T profile. Its magnitude is related to the acoustic impedances of the tup and specimen, as well as the

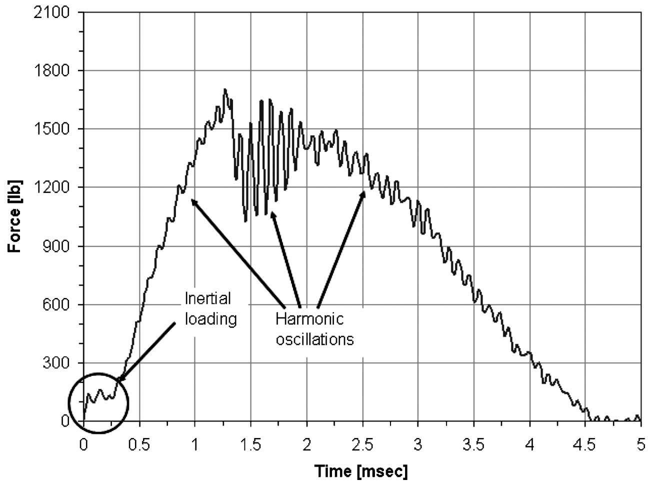

Fig. 2 Contact force vs time history showing inertial and harmonic oscillations.

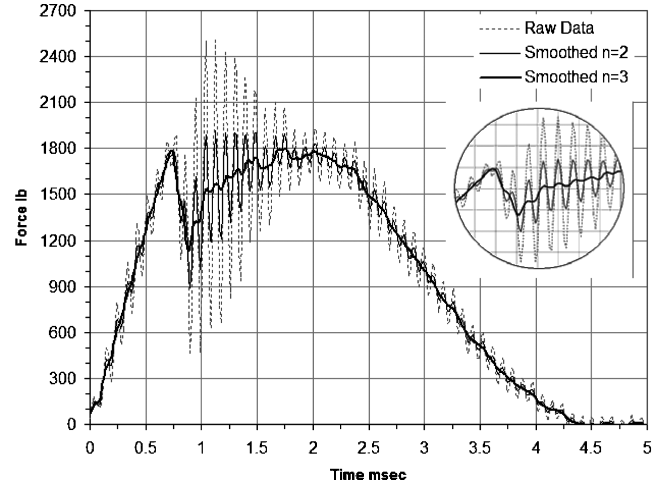

Fig. 3 Force vs time trace showing effect of averaging signal over 5 and 7 points, respectively.

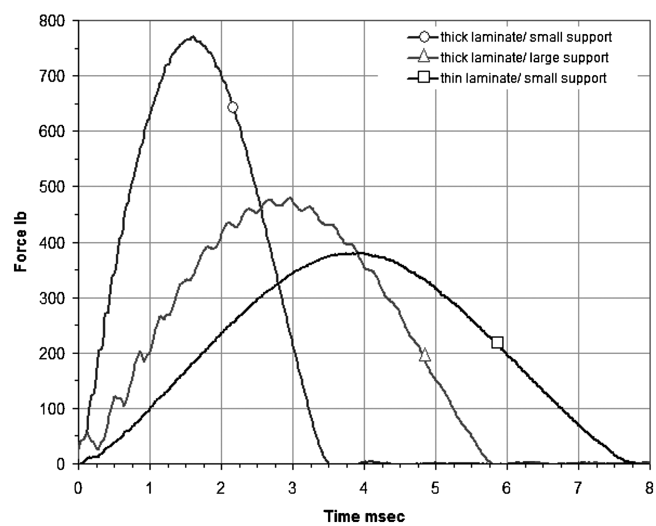

Fig. 4 Three impact tests performed at the same energy level (1 ft · lb) on three different laminate thickness/support span combinations: a) 32 ply *t* on 2.5- in.-diam aperture *D*, b) 32-ply *t* on 5-in.-diam aperture 2*D*, and c) 16-ply *t*/2 over 2.5-in.-diam aperture *D*.

initial impact velocity. The acoustic impedance of a material is the product of the sound speed in that material and its density.

The low-frequency fluctuations (Fig. 2) typical of impact tests are superimposed oscillations primarily caused by stored elastic energy, inertial effects, and reflected stress waves. Hence, the F–T signal obtained by the strain gauges mounted on the tup is not necessarily indicative of the reaction of the specimen. To extrapolate the desired specimen response, the experimenter can act in the following way:

1) Compare the signal obtained with that of strain gages mounted directly on the specimen.

2) Test at a reduced velocity.

3) Electronically filter the signal.

The first technique has distinctive advantages for limited scientific studies, but is inherently cost and time ineffective.

The second technique is based on the observation that the inertial oscillations are directly related to impact velocity, but the obvious disadvantage of such a procedure is the potential loss of strain-rate effects, which is often the driving force for the impact test itself. In that regard, it is important to remind the researchers that common quasi-static tests are performed in the range from 0.2 to 20 in./min (0.5 to 50.8 cm/min) and that a comparison with a common impact test velocity of 4.5 ft/s (1.37 m/s) reveals a strain-rate difference from 10^2 to 10^4. On the other hand, an increase to 100 ft/s (30.44 m/s) gives a potential increment in strain-rate difference of only 10^1.

The third technique is sometimes employed for reducing the adverse effects of tup signal oscillations; however, the investigator should have a strong understanding of the overall effects of the process, because filtering can be as much of a problem as the superimposed oscillations because of possible signal distortion. The importance of understanding the significance of these phenomena lies in that an operator or automated data analysis routine, as in the case of the Dynatup 930 software, may incorrectly select the peak force if the inertial peak or any of the following oscillations is the highest load value recorded (Fig. 3) unlike filtering, smoothing does not affect the data acquisition process. Because the oscillations, also referred to as ringing, are harmonic about the mean or true signal value, the energy value should be accurate, but the maximum load data can potentially be incorrect.

A diagnostic test, which can be performed to determine whether a given signal spike is caused by mechanical specimen response or by inertial loads and low-frequency oscillations, consists in repeating the desired test using lower impact velocities because it has been shown that the magnitude of an inertial load is essentially proportional to the impact velocity. If the data in question are indeed caused by inertial loads, a lower impact velocity will reduce its magnitude, whereas the material is commonly not nearly so strain-rate sensitive. As a last resort, a layer of tape or other elastomer will effectively reduce the ringing by providing a dampener between the tup and specimen. However, the energy absorption of the tape has to be considered, and its use should be limited to material comparison tests.

Many data collection systems incorporate analog filters to reduce the noise introduced by the specimen and tup and other external sources. As mentioned earlier, whereas these filters can improve the interpretation of test data, their use should be restricted to situations in which the source of the noise is known and its effect on the data is understood. In most cases it is recommended to employ a posteriori data smoothing techniques, as shown in Fig. 3, that do not affect the recorded data but are only mathematical expedients used to reduce the amount of unwanted oscillations in the signal. One of the simplest smoothing techniques, as the one employed in the Dynatup 930 software,[21] takes a running average of the recorded signal over $2n + 1$ points. In most cases a value of $n = 1$–3 will produce satisfactory results, as shown in Fig. 3, but if the signal is very noisy, values of n up to 14 have been used.[4] One of the simplest smoothing techniques, as the one employed in the Dynatup 930 software,[21] takes a running average of the recorded signal over $2n + 1$ points. In most cases, a value of $n = 1$–3 will produce satisfactory results,[11] as shown in Fig. 3, but if the signal is very "noisy," values of n up to 14 have been used.[4]

D. Target Parameters Influencing Impact Response

The response of a laminated plate specimen to out-of-plane dynamic impact is dependent on many impactor and target characteristics, as well as impact test setups Fig. 4. Consequently, comparisons cannot be made between materials unless identical test configurations, test conditions, and laminate configurations are used.

The thickness, out-of-plane curvature, stacking sequence (and degree of orthotropy), and material form (tapes, weaves, and textiles) of the target laminate greatly affect the impact response and damage formation behavior of the specimens.

The amount of laminate material comprised between the base- and faceplates, outside the unsupported region (effective support span), is referred to as overhang material, and it too can influence the shape and magnitude of the impact trace.

The impact location can affect the impact performance of the specimens significantly; hence, accuracy in the axial positioning of the impactor needs to be guaranteed. Guiding pins shall be located

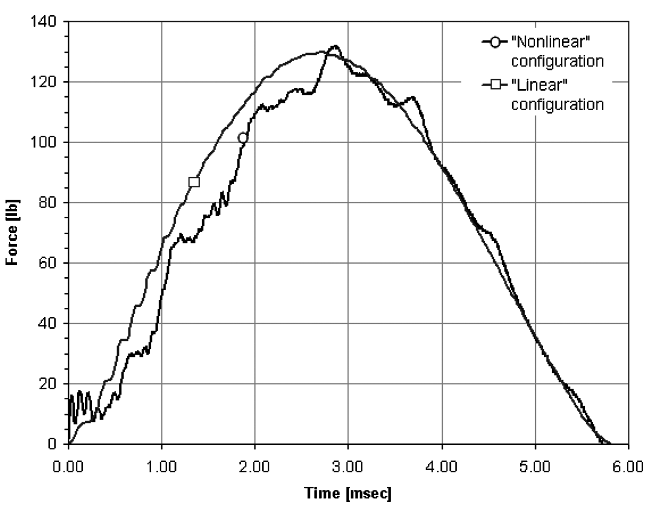

Fig. 5 Signals obtained by impacting compliant rectangular target and stiffer square one.

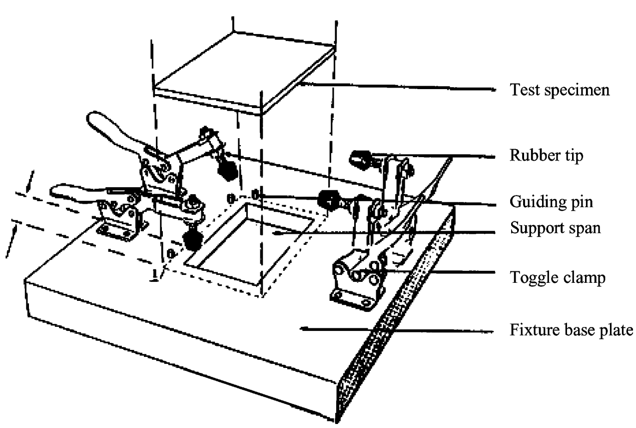

Fig. 6a Impact support fixture with four clamps.

such that the specimen shall be centrally positioned over the cutout. Care needs to be taken to ensure that the target/support fixture assembly is centered with respect to the impact device.

For identical target laminate shape, aperture shape can greatly influence the overall response of the target. Symmetric cutouts, such as circular or square apertures, yield smoother curves (containing less oscillations) than rectangular apertures (Fig. 5). This is mostly associated with the unsymmetric bending of the unequal length sides, as well as an unequal stress wave reflection along the two axes. The support fixture's aperture shape, as well as dimensions, may also introduce nonlinear effects in the response, which also can contribute in a noisier signal.

A minimum of four clamps (Fig. 6a) shall be used to restrain the specimen during impact and restrict out-of-plane motion. Alternatively, a minimum of four peripheral screws can be used to restrain the target laminate between the support fixture and the matching faceplate (Fig. 6b). The location of the clamps, and the overall degree of out-of-plane edge support provided, can influence the magnitude of the contact force and the total duration of contact. If the amount of torque applied to the screws is unknown and arbitrary, the resulting boundary conditions are very close to the simply supported case, where the laminate rests unrestrained on the unsupported area. The resulting peak force for this pseudoclamped condition is only 3–5% greater, whereas the contact duration is around 8–10% shorter than the purely simply supported condition.[6] If proper torque is applied and is measured by means of a torque wrench, and if the clamping is performed by means of multiple through-thickness holes in the laminate, whereby the faceplate is fastened to the support plate,[4,6] it is possible to achieve peak force values up to 20% greater than simply supported ones.[13] In general, however, the amount of clamping achievable with these methods is not nearly as high as the one predicted by plate theory.

To identify the critical energy level, which translates into defining the drop height required to introduce detectable damage in the structure, ASTM suggests the use of a "staircase approach."[23] First a low and a high boundary (defined by the respective impact energy levels) are identified, resulting in an elastic and in a full-damage response. Then the impact energy difference is divided in two, and an impact test is performed at each such energy level. If the damage is still very extensive, or if no damage occurs, such energy level becomes the new upper or lower boundary. Therefore, the following impact test is performed at an energy level that is one-half of the difference between the preceding and the new boundaries and so on, until a threshold is detected. Note that during this staircase process, the specimen needs to be replaced after each test, even if elastic in nature, to prevent any sort of impact-fatigue issue.[23] The repeated impact of the same specimen can translate into an apparently lower damage threshold. Whereas this practice can lead to a large waste of material and specimens, experience usually allows for a reduction in the range of tests required to identify such a threshold. As indicated earlier, performing a preliminary quasi-static test and extrapolating the deformation energy to first failure will also give an adequate indication of the kinetic energy required to introduce damage in the impact test.

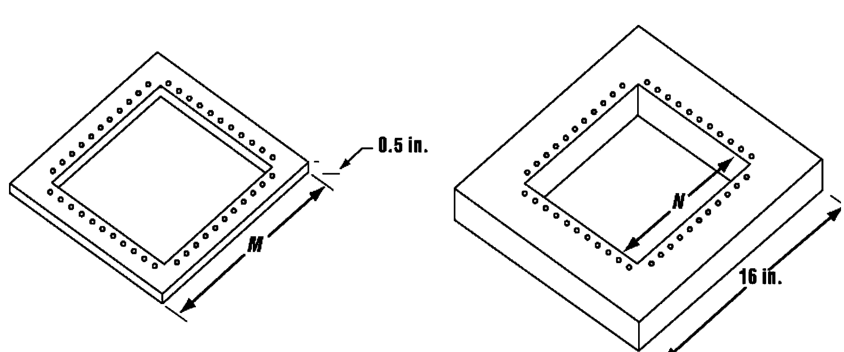

Fig. 6b Impact support fixture with faceplate and peripheral screws.

E. Impactor Parameters Influencing Impact Response

Results are affected by the characteristics of the impactor, such as mass and velocity, and, hence, drop height and impact energy. As stated earlier, the greater the difference between the masses of impactor and target, the smoother the curve: A ratio of $m_{\mathrm{tup}}/m_{\mathrm{lam}} = 10–20$ is suggested. When the mass ratio of the impactor approaches values of 2–5, it is possible that the signal becomes highly distorted and noisy (Fig. 5). A dependence of contact force with impactor mass has been reported in the literature, and, for the same value of impact energy, impactors with lower mass but higher velocity are found to originate greater contact forces but more localized damage. For common drop tower impact devices, where impactor mass falls in the range of 2.2–44 lb (1–20 kg), the difference in observed falls is negligible.[6] As the mass of the impactor falls below a value twice that of the laminate, there is a dramatic change in the overall mechanism of the impact event from mass dominated to wave controlled.

It has also been found that the signal becomes less noisy and hard to interpret if the size of the impactor is increased, and the linear system approximation becomes less accurate.[4,6] As a generic guideline, the ratio between the in-plane cutout dimension to impactor diameter should not be greater than 10. On the other hand it has been found that a larger impactor diameter has the effect of producing greater contact forces and introduces greater damage within the laminate, and so care needs to be taken in choosing the adequate size for the study.

The load cell built into an instrumented impactor measures the force between the two portions that constitute the impactor itself, the main mass m_1 and the tip mass m_2. Traditionally, the main mass is much greater, so that the dynamics of the tip mass are neglected. However, unless the tup mass ratio is $(m_1 + m_2)/m_1 = 1$, neglecting the tip mass effects can lead to significant errors.[19] For example, the force oscillations discussed earlier, that is, the ones following a significant drop in stiffness, can be significantly influenced by the instrumentation dynamic response and should not be attributed to the specimen response. Note that it is the tup mass ratio, and not the tip mass per se, that dictates the strength of tup dynamics and associated force noise. Another example is concerned with the calculation of absorbed energy, which depends on the accuracy of the measured velocity, force, and tup mass. If the tup mass ratio is too large, integration of the acceleration signal will lead to erroneous calculations of the displacement and absorbed energy values.

F. Other Recommendations on Data Collection Parameters

The time and load range settings act as window into which the data must fit. This window must be large enough to capture all data required, yet small enough to provide good resolution.

Most instrumented impact-test systems can detect the beginning of the impact event and trigger data collection in two ways. The first consists in a rise in the load signal above a preset threshold value; the second generally uses the passage of a flag, rigidly attached to the carriage, through a light beam/photo-detector.

If the signal appears chopped off (Fig. 7), it is an indication that the load range or capacity may be set too high or too low. A solution can be to increase the sensitivity and the frequency of data acquisition.

It is imperative to avoid multiple impacts (rebound hits) of the target specimen, hence, it is suggested that latching and hoist mechanisms, stop blocks, or shock absorbers be mounted.

In the data acquisition process certain electrical anomalies may manifest, such as undesired spikes and signal transients or cutoffs due to inadequate system settings. (See Figs. V1–V4 in Ref. 24.) Sometimes digital filtering of the data can remove these anomalies; however, the procedure might mask an anomaly making it appear as real physical data. On the other hand, the underlying problem that originated the anomaly in the first place and is potentially associated to a faulty instrumentation might still be present and may corrupt future results.

III. Considerations on Evaluation of Data Collected

A. Force– and Energy–Time Histories

As noted earlier, one of the exclusive advantages of dynamic tests is the possibility of obtaining force–time traces, such as the one of Fig. 1. The onset of specimen–indenter contact is noted by the detection of a non-zero contact force: As the indenter presses into the specimen, the contact force increases. A subcritical test, which is purely elastic in nature, can be represented by a one-half sine wave if the relative effective stiffness of the target and relative size and mass of the impactor are sufficiently high. The relative effective stiffness of the target is a combination of in-plane aperture size and shape (rectangular vs square), laminate thickness, and a material's elastic modulus. If, however, those conditions are not satisfied, the resulting pulse will deviate from a pure sine wave (Fig. 5). Provided that the assumption of sine wave is correct, the total contact duration of the impact event is a direct indication of the effective structural stiffness of the target, as shown in Eq. (2). The contact duration is independent of the impact energy level at which the test is performed, provided no damage is introduced. The peak value of the contact force is also directly related to the effective stiffness of the structure for a purely elastic test, but it has the great disadvantage of being directly related to the available kinetic energy via Eq. (1). It is, therefore, hard to compare impact performance on the basis of the peak force in elastic test, and it is for that reason that instrumented coin-tap test devices, which are portable impulse hammers, employ contact duration rather than peak force to detect damage within a structure.[3,25]

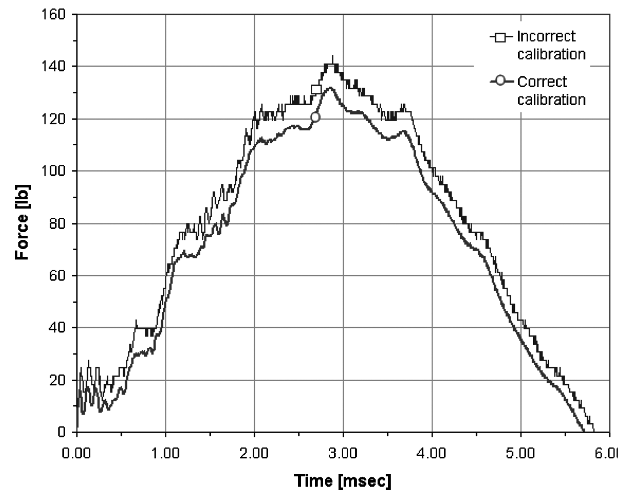

Fig. 7 Incorrect load trace and corrected after adjusting sensitivity and rate of data acquisition.

It is customary to present the energytime curve in the same time plot as the force, and, for a correct setup, the energy curve should peak at the same time as the force curve. At the end of contact part of the incident kinetic energy has been dissipated, even in elastic tests, in nonconservative phenomena such as friction along the rails [Eq. (3)]. The peak value of the energy coincides with the available kinetic energy, and it is theoretically reached when the velocity of the impactor approaches zero at the point of maximum deflection and contact force.

For supercritical events, such as that in Fig. 8, the impact energy is sufficient to initiate damage in the target. The onset of damage is typically associated with sharp drops in the contact force trace, and it is usually followed by the rapid oscillations (about the actual mean value) in the contact force signal, as mentioned earlier. The occurrence of damage is associated with a specific value of contact force and kinetic energy, known as critical force and energy, respectively. It has been shown frequently in the literature that their value is independent of impact energy, and it stays constant for increasing values of available kinetic energy.[3–6,11] Furthermore, for modern composite systems, which are relatively strain-rate insensitive in this low-velocity regime, it has been found that the value of the critical force is very close to the mean static failure load (MSFL) of the laminate, obtained by means of quasi-static indentation tests.

The exact point of failure initiation is sometimes hard to detect due to the presence of harmonic oscillations characteristic of the test and, at times, because the initial damage might have nearly

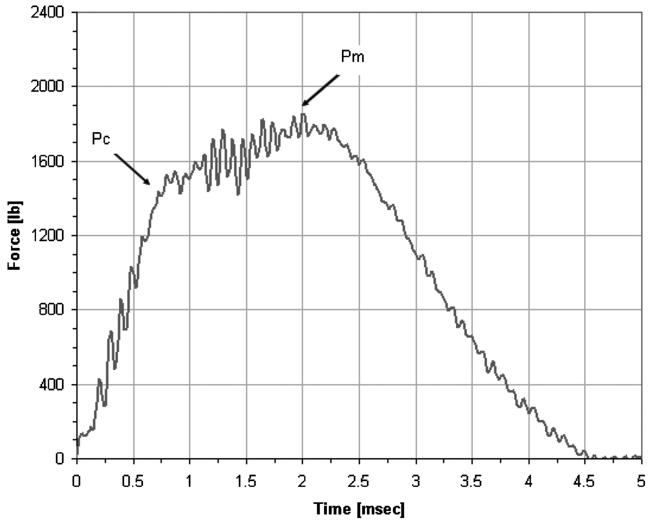

Fig. 8 Contact force and kinetic energy vs time history for supercritical test.

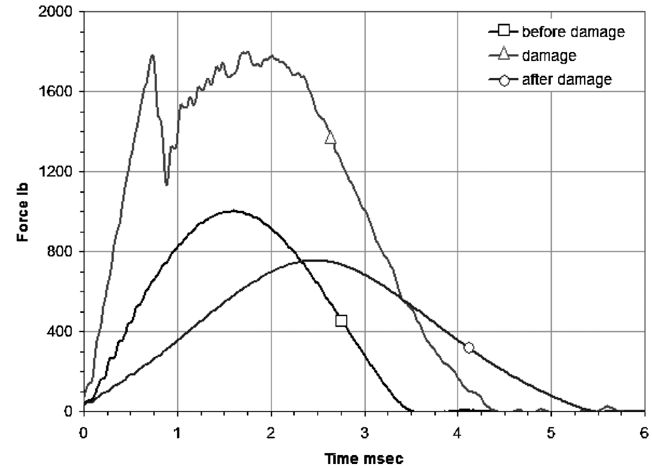

Fig. 9 Three consecutive F–T histories for impact tests performed consecutively on same specimen: a) before introducing damage (purely elastic), b) introducing damage (nonelastic), and c) after introduction of damage (purely elastic).

negligible effects on the target's stiffness. Thus, nondestructive inspections may become essential if the operator is uncertain about the presence of damage within the specimen. Alternatively, performing a preliminary quasi-static indentation test, where the signal is not distorted by harmonic oscillations, might give the operator invaluable insight in the subsequent impact tests.

After first failure *Pc*, the contact force might continue to increase and reach a peak value *Pm* above the critical force value. Ultimately, for impact energy levels sufficiently high, this value reaches the plate's ultimate load bearing capability and ceases to increase.[3,11] This ultimate peak force value, which has also been shown to be independent of kinetic energy once it is reached, has been found to coincide with the laminate's mean static ultimate load (MSUL). According to the relative effective stiffness of target, the critical force value might coincide with the peak force value (thin, large, flexure-dominated panels), or it might precede it by a substantial amount (thick, small, shear-dominated panels). The value of the force at the point of penetration, if it occurs, always coincides with the value of the ultimate peak force.

As a general guideline, the use of maximum sustained contact force to compare impact events is a very useful but also dangerous practice, because apparently similar force–time curves can hide very different underlying states of damage.[3,4] The amount of energy dissipated in a supercritical event, given by Eqs. (3) and (4), is much larger than that of an elastic test, and it can provide a useful indication of the amount of damage introduced in the specimen. It is, however, fundamental to qualify the type of damage associated with the energy dissipated in its creation by means of tradition destructive or nondestructive techniques.

In general, a lower peak force and greater contact duration is expected to occur for more compliant configurations of impactor–target combinations (Fig. 4). That is the case for thinner laminates, larger support spans, and lower-modulus composite systems, as well as smaller, heavier, and softer impactors. A longer signal period is also typical of delaminated or otherwise damaged specimens (Fig. 9), as long as no penetration occurs, in which case the overall event consists in a shorter duration. Furthermore, if specimens are simply supported or not adequately clamped, a similar trend should be expected. However, the preceding parameters influence the signal at different levels, and often the relationship is neither linear nor easy to predict a priori. A greater peak force and shorter contact duration is the resultant of stiffer combinations of impactor–target parameters. If an advanced clamping mechanism is present, or if it is accurately controlled, the setup may result in a stiffer configuration.

It cannot be overemphasized that when trying to assess the damage threshold of a prescribed structural configuration it is imperative to first perform a low-blow elastic test to gather an adequate understanding of the structure's stiffness and its signature trace, without the discontinuities and oscillations associated with the onset of damage. Similarly, it has been found that performing a low-blow test on a previously impact-damaged specimen can yield useful information on the presence and extent of damage and, possibly, the residual stiffness of the target.[3,26] For that reason, a three-test sequence per specimen to be impact damaged is suggested, and it enables the engineer to obtain in situ information similar to that of a coin-tap test.[25]

In the case of large and thin panels,[4] strong geometric nonlinearities may manifest. As a consequence, increasing values of drop height (hence, impact energy) will result in progressively shorter contact durations. The deviation from the linear response assumption, which is the basis for Eqs. (1) and (2), is caused by the stiffening mechanism associated to membrane effects. In such cases, it is necessary to exercise extreme caution in comparing impact events. For example, the contact duration for an impact test with incipient damage (but no penetration) is shorter than the elastic test at much lower-impact energy levels. Furthermore, whereas damage might be introduced within the matrix in the form of cracking or delamination, as detected by ultrasonic inspections, it might not result in a visible drop in the impact F–T or force–displacement traces.[4] This behavior is likely to be associated with the flexural-dominated nature of these nonlinear configurations, and its interpretation is further hindered by the presence of a large number of secondary inertial oscillations (Fig. 5). Last, if the geometry is highly nonlinear and maximum displacement is of the order of 10–15 times the laminate thickness, an unexpected phenomenon may occur that is often overlooked. The nominal kinetic energy for a specific impact test is determined by assigning a specific drop height, as measured from the contact surface. For linear behaving specimens, where the maximum deflection is less or equal to the wall thickness, this is an accurate procedure. However, for the highly nonlinear geometries, the impactor will continue its fall beyond the theoretical value by an amount equal to the maximum deflection of the target. The associated hidden energy can reach nonnegligible levels and affect the test results. Only if the engineer is aware of these phenomena the procedures used in linear-behaving structural configurations can be applied correctly.

B. Force-Displacement Curve

A useful trace available from impact test data is the force-displacement curve, which is readily available if an advanced data acquisition and analysis software is employed or otherwise needs to be derived a posteriori. The integration of the acceleration and velocity curves with appropriate initial conditions[9] allows for the derivation of the force-displacements curve, which comprises the loading and unloading phases (Fig. 10). The area comprised between the two portions of the curve is the system hysteresis,

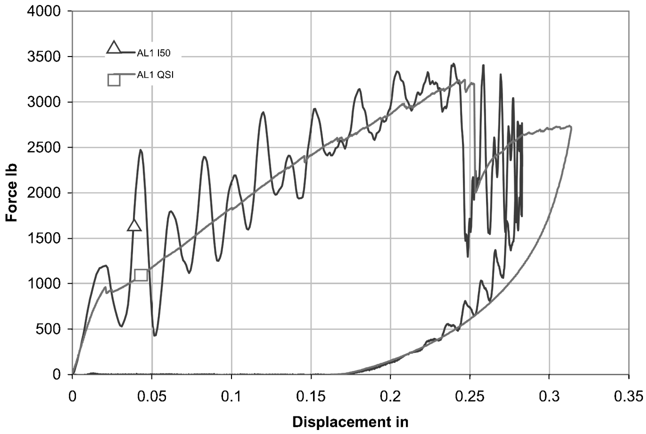

Fig. 10 Superimposable dynamic and quasi-static force-displacement curves.

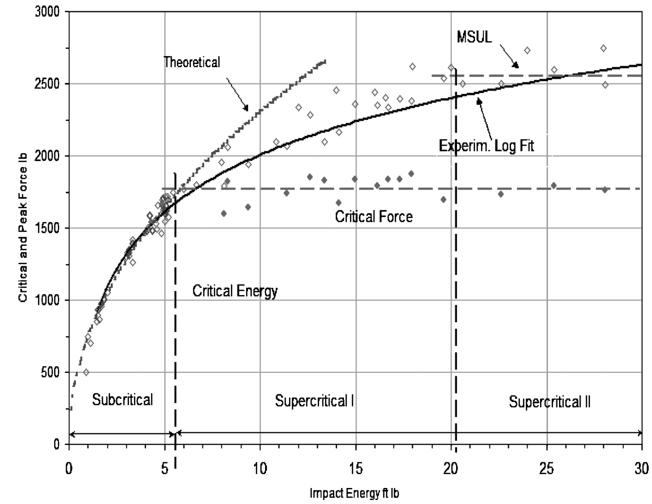

Fig. 11 Impact force–energy highlighting critical force and energy values and sub- and supercritical regimes.

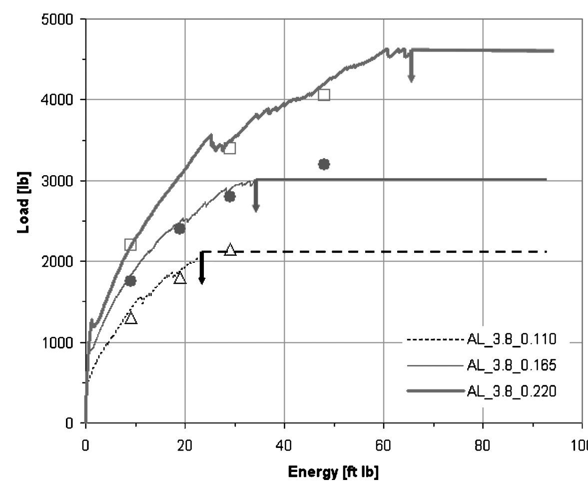

Fig. 12 Force–energy curves obtained by quasi-static indentation and superimposed force–energy impact test data points showing analogy between quasi-static and low-velocity events for carbon/epoxy systems.

which is an indication of the total energy dissipated in the process. As stated earlier, this area should be negligible for purely elastic tests and increases noticeably for supercritical events.

The derivation of impact force–displacement curves allows for an immediate comparison with the results obtained from quasi-static indentation, and in most low-velocity impact situations, the curves are directly superimposable.[22] Furthermore, critical force and ultimate peak force have been found to be closely related, and at times coincide, with the MSFL and MSUL of the quasi-static test.[3] The presence of the harmonic oscillations in the dynamic signal, even after postexperiment data smoothing, contributes to make the individuation of an exact point along the curve more difficult than in a static test. For that reason, the practice of performing (let alone the modeling) a quasi-static test is highly recommended before venturing into the understanding of more complex dynamic events.

C. Force–Energy Curves and Analogy Between Quasi-Static and Impact Response

The force–energy curve can provide a useful tool to understand the global response of a structure because it offers a clear indication of the transition between sub- and supercritical regimes, as delimited by the critical force and energy values (Fig. 11). The theoretical value of peak impact force given by Eq. (1) is valid in the elastic regime, but greatly overestimates the test results beyond initiation of damage. It is for such a reason that the use of contact force as governing parameter should be limited to damage threshold investigations where it is of fundamental importance. On the other hand, its use is not recommended without a thorough understanding of the entire force trace and structure behavior as a damage metric or to compare events on different configurations.[3] However, the great advantage of using contact force in the evaluation of impact performance is that it provides a direct translation to quasi-static indentation (QSI) tests, which are traditionally more familiar to structural engineers.

From integration of the QSI load-displacement data, it is possible to obtain the deformation energy. When the trapezoidal integration rule is used, it is then possible to build a force (or load) vs energy curve,

$$E_{\mathrm{QSI}} = \sum_k \left\{ (d_j - d_i) \left[\frac{(F_i + F_j)}{2} \right] \right\}_k \tag{7}$$

where d_i and d_j are the values of the displacement and F_i and F_j are the values of the contact force in a quasi-static load-displacement curve.

For strain-rate insensitive materials, such as contemporary carbon/epoxy systems, the quasi-static force–energy curve, such as the one in Fig. 12, virtually coincides with the peak force–energy in Fig. 11. This trend has been verified for solid laminates of various span/thickness ratios,[3–6] panel curvature,[4] stacking sequences,[3] as well as honeycomb-core sandwich panels.[5] The advantages of employing the force–energy curve of Fig. 12, obtained by preliminary QSI testing, are dual. First, it provides a valuable tool for understanding the global response of the specimen, similar to the impact force–energy curve of Fig. 11 and can, therefore, be used in the process of defining the design of experiment (DOE). Performing a QSI test on one panel before venturing into the impact testing of numerous panels can provide the engineer with great knowledge on the behavior of the structure. Second, the QSI force–energy curve can be used, similarly to the impact force–energy curve, to extrapolate the force values corresponding to impact energy levels other than the tested ones. The quasi-static nature of low-velocity impact events is such that it allows a direct translation of indentation tests into impact data.

As an example, Fig. 12 shows the quasi-static force–energy curves obtained by indentation of thick-core, thick-face sheet honeycomb panels for a candidate blended-wing–body (BWB) crown panel.[5] The three curves refer to three different face sheet thicknesses. Superimposed on the curve are the peak force–energy data points recorded during subsequent impact testing of three and four panels per face sheet thickness. Note how the impact data superimposes onto the quasi-static curve. Whereas a limited number of impact tests is always necessary to validate the approach for every structural configuration, the curve thus obtained by testing one panel yields the equivalent force–energy information as a large impact-test database. Simply put, the plot allows for extrapolating the impact force that would be generated, for example, if the applied impact energy were 5, 40, 60, or 100 ft · lb (6.8, 54.2, 81.3, or 135.6 J). Even more important, during the quasi-static investigation, it was possible to discover a phenomenon that was overseen during the impact testing. The QSI curve exhibits a linear elastic response only up to very low values of energy, around 2 ft · lb (2.71 J), beyond which core crushing initiates and the loading curve assumes a lower slope. This transition, detectable from C-scan analyses, is, however, not visible in F–T histories, and the initial test matrix called for elastic impact tests to be performed at approximately 10 ft · lb (13.56 J) of impact energy. Had the QSI been performed a priori, it would have been possible to design a more focused test matrix.

IV. Conclusions

This paper is a collection of lessons learned over a wide range of impact research projects and contains some recommendations for those becoming acquainted with instrumented impact testing. The present work is not supposed to either replace the test machine's reference manual, or to be a comprehensive review of impact phenomena. The discussion has been separated into a first section that deals with the preparation of the system for data collection, including the determination of the major system parameters and the most commonly occurring problems, and a second section, that covers the evaluation of the data collected, including the interpretation of the engineering curves commonly employed in this type of investigation.

To implement reliable test procedures, the engineer/researcher should have a general understanding of the inherent characteristics of instrumented impact testing. The importance of analyzing the entire F–T history rather than focusing on just one parameter, whether the critical or peak force values, has been highlighted. Last, the fundamental need to characterize the quasi-static and low-blow (elastic) impact performance of a particular impactor–target configuration before attempting to characterize a structure's damage threshold and supercritical behavior has been emphasized.

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