Forceful Measures, Energetic Solutions

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ABSTRACT

This paper summarizes two key findings of the impact research on composite laminated structures conducted over the years by the author in collaboration with Dr. Keith Kedward [1-9]. First, the problems associated with the use of peak contact force as damage metric are reviewed. Second, the equivalence of quasi-static indentation (QSI) and low-velocity impact (LVI) testing, with regards to force, energy, and damage state is discussed. The sensitive nature of these findings is such that a consensus will hardly ever be reached, albeit the experimental evidence, yet this paper should assist the next generations of investigators in the formulation of their future experimental plans.

INTRODUCTION

In traditional low velocity impact tests, such as the ones achieved by means of drop tower setups, a composite plate is subjected to an out-of-plane, concentrated load by means of a falling weight, whose potential energy is specified. Historically, the first impact test performed on composite materials for residual strength determination were non-instrumented [10], and early damage tolerance studies used impact energy as the sole damage metric for characterizing the severity of the event [11]. The target structures were impacted at a nominal impact energy level, and the subsequent damage was measured with destructive and non-destructive inspection methods. Eventually, the goal of the test was to inflict barely visible impact damage (BVID) to the panel, and then to measure its residual properties for certification purposes [12]. 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 an extrinsic measure of the severity of the test (such as incident kinetic energy). Always associated with these plots are the compression after impact (CAI) curves, where the residual strength of the panel is plotted against the same extrinsic parameter.

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Later developments, which coincided with the commercialization of instrumented impact devices [13, 14], indicated an advantage in the use of dynamic load-cells. Fully instrumented devices, such as the Dynatup, 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 contact force has proved to be an extremely valuable tool to determine the onset of damage in dynamic tests [15, 16]. To the extent that over the years the practice of using contact force degenerated in the recording of only its peak value, not for determining the critical value for damage initiation. For this and other reasons associated with the use of contact force, federal organizations and aircraft manufacturers currently still employ impact energy as damage metric in their certification efforts [17].

2. MAY THE FORCE BE WITH YOU

A force-time trace is the typical tool used to interpret data from instrumented impact tests. 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 sub-critical test, which is "purely" elastic in nature, can be represented by half a sine wave (fig. 1), if the ratio of impactor to target mass is sufficiently high [18]. Employing a simple energy balance and a spring-mass model, under the assumption of linear elastic response, the data for the peak force can then be accurately fitted by a well-accepted power law curve [1, 4], which relates peak force to the square root of the effective structural stiffness of the plate and of the incident kinetic energy (fig. 2). In the elastic, or sub-critical [1-9], regime the prediction is in excellent agreement with the experimental data.

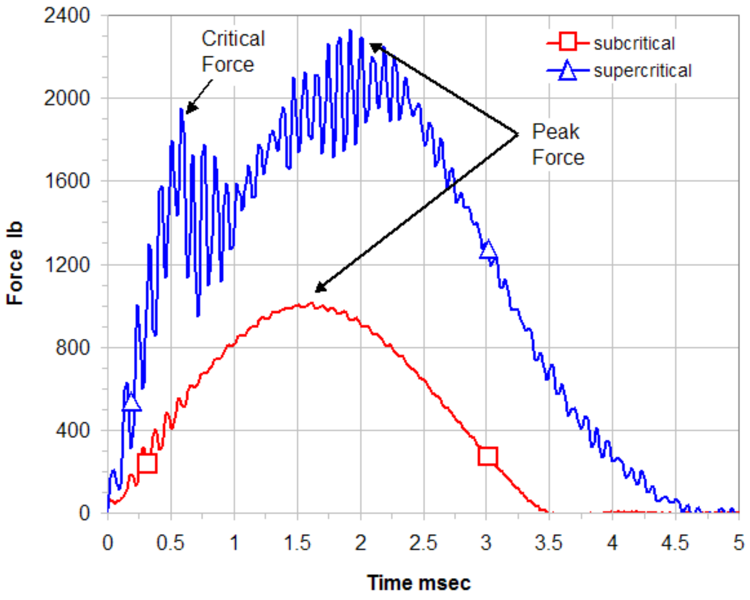

Figure 1. Sub- and super-critical force-time impact traces.

If the impact energy level at which the test is conducted is sufficiently high, the damage threshold is exceeded and the event falls in the super-critical regime (fig. 2). The contact force increases up to the point of failure, then suddenly drops, and is followed by the onset of the low-frequency oscillations (fig. 1). Eventually the force picks up again, and it may reach or exceed the value at which failure initiated. *Peak force may, or may not, be the same as critical force.* The onset of damage is associated to a specific value of contact force (the critical force) and kinetic energy (the critical energy), and this value remains constant throughout the entire supercritical regime, independently of the impact energy level. *While critical force is a property of the structure, and is independent of kinetic energy, peak force is a function of both.* Only when the kinetic energy is sufficiently high to reach the maximum load-bearing capability of the plate, the value of the peak force ceases to increase, and it remains constant around a mean ultimate dynamic plateau. For strain-rate insensitive materials, such as modern carbon/epoxy systems, the critical force and the ultimate dynamic plateau have been shown to virtually coincide with the Mean Static Failure Load (MSFL) and Mean Static Ultimate Load (MSUL) respectively [1].

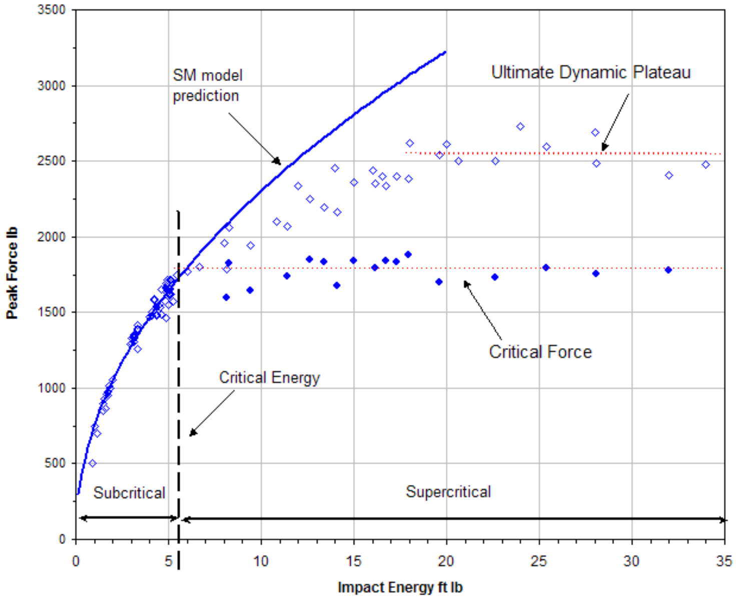

Figure 2. Experimental peak force data points, critical damage threshold, and spring-mass model prediction.

In the supercritical regime the value of peak force recorded in a super-critical event is quite lower than the one predicted by the spring-mass model for the same level of impact energy. The discrepancy between the experimental results and the model progressively intensifies for higher impact energy levels and, most notably, the spring-mass model doesn't predict any sort of asymptotic behavior. While the power law predicts an unbound increase of the peak force, the data shows that it rather quickly reaches a plateau (fig. 2), where it assesses around a constant value. The introduction of damage introduces a progressive change in transverse stiffness, according to the severity of the event. *Therefore higher impact energy levels introduce greater damage, which in turns reduces the stiffness of the plate, thereby producing a peak force lower than the one predicted by the linear-elastic model*.

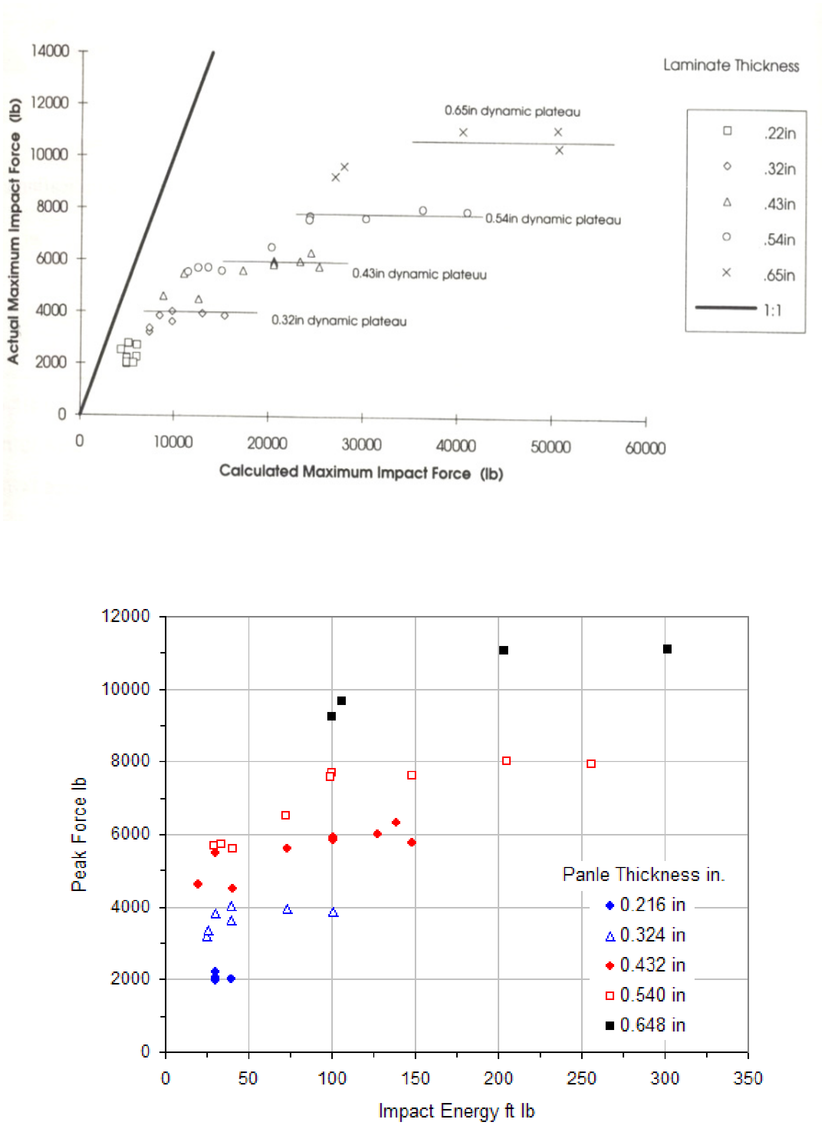

Figure 3. Top: Discrepancy between calculated and measured peak force data [19]. Bottom: re-plot of the calculated peak force data against impact energy, showing the majority of the data points lie in the dynamic plateau.

The plot shown in fig. 3 (top) by Hinrichs et al. [19] emphasizes the discrepancy in the measured vs. the predicted response, which the authors attributed to the creation and propagation of damage. The symbols represent the different values of panel thickness tested, while the solid line represents the spring-mass prediction. Re-plotting the peak force data against the nominal impact energy (fig. 5 bottom) shows that the majority of the tests conducted effectively falls in the region of dynamic plateau, thus explaining the lower-than-predicted peak force values. Inconsistent trends are also reported by Nettles and Douglas [20] for the projected delamination area using peak force as the damage metric. Re-plotting peak force against impact energy shows that the majority of the tests conducted fall in the region of the dynamic plateau, where higher states of damage are associated with higher impact energy levels, but constant peak force [7].

There are two conclusions that can be deduced by reviewing this plot. First, peak force is highly dependent on the level of impact energy up to the ultimate dynamic plateau, and therefore caution should be used if comparing events with such parameter. Peak force, unlike critical force, is not a structural property, but a function of both the structural configuration and impact test (through impact energy). Second, because of its asymptotic behavior after failure, peak force cannot be used to uniquely define the state of damage in the structure. Multiple damage states can be associated to the same peak force if the dynamic plateau is reached. This can be easily seen in fig. 4 [21], where the damage area is shown to increase with increasing impact energy (drop height). Initially the contact force (max load) is also shown to increase proportionally, but eventually the dynamic plateau is reached, and the force assesses itself around a constant level.

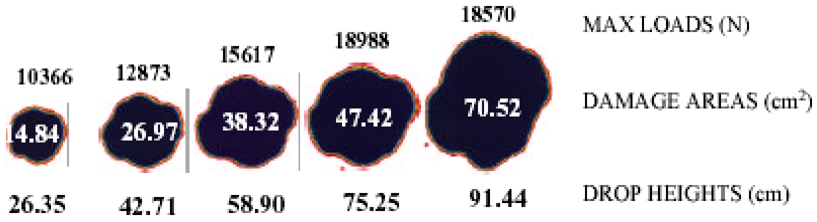

Figure 4. Increasing damage area is associated to an increasing drop height but not max load, which reaches a plateau [21].

Although contact force can be an extremely valuable tool, if properly used to identify the critical force associated with the onset of damage, its brute use to record the peak force is particularly dangerous, as it can lead to inconclusive results (fig. 5). As a general guideline, the entire force-time history has to be understood by the engineer assigned to determining the impact damage resistance characteristics of composite panels. Furthermore, parametric investigations such as the one in fig. 5 which use peak force alone as the only metric to compare the response of various structural configurations should be avoided, as each configuration may reach the dynamic plateau at different values of impact energy, thereby giving little insight on the actual damage resistance.

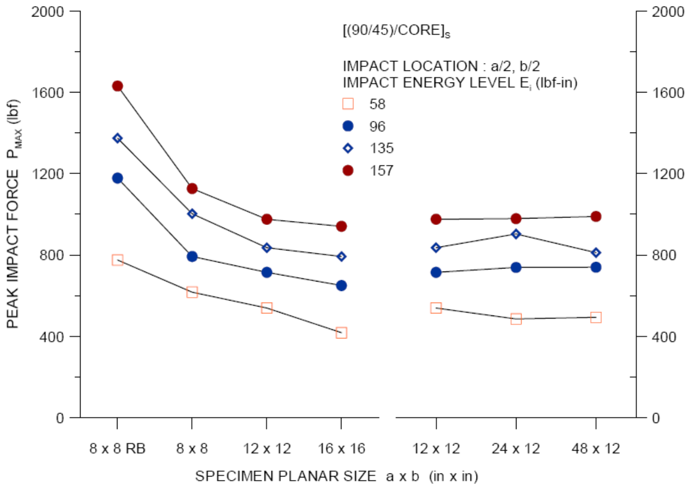

Figure 5. Peak impact force for sandwich panels at different energy levels [22].

3. SPEED ISN'T EVERYTHING

Double integration of the acceleration data from the impact test force-time history allows for the derivation of the force-displacements curve, which is comprised of the loading and unloading phases (Fig. 6). The area comprised between the two portions of the curve is the system hysteresis, which is an indication of the total energy dissipated in the process [1, 3].

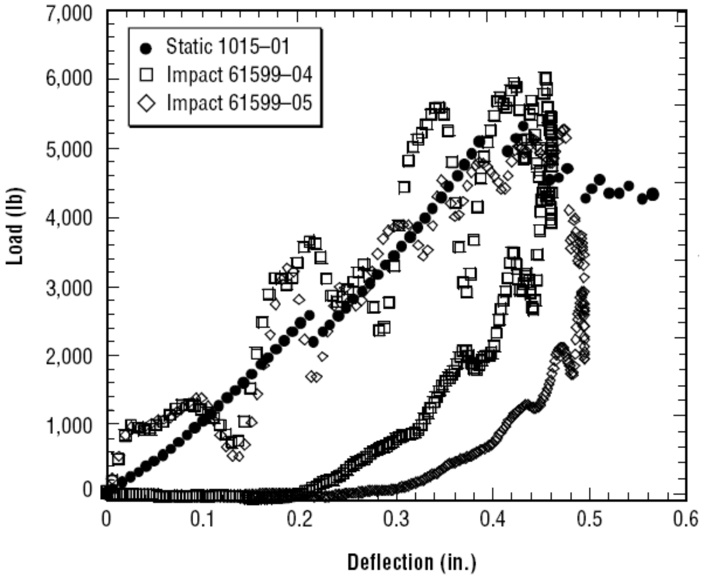

Figure 6. Superimposed load-deflection curves of solid laminates for a QSI and two LVI events [20].

The derivation of force-displacement curves allows for an immediate comparison with the results obtained from QSI. It can bee seen in fig. 6 [20] that the QSI and LVI curves are directly super-imposable, and that the QSI curve represents a mean around which the LVI trace oscillates. Many investigators have documented this phenomenon over the years [16, 20, 23], and yet there is a strong reluctance in accepting it. *According to the MIL-HDBK-17 [18], a LVI event is defined as an event where the response is essentially quasi-static in nature.* That is, the force displacement relationships for an impact and for quasi-static loading are the same. Furthermore, critical force and ultimate dynamic plateau have been found to be virtually identical, or at least very close to, the MSFL and MSUL [1].

The analogy between QSI and LVI, for the same impactor and target conditions, can be further visualized by looking at figures 7-9. The contact force required for introducing a certain degree of damage in a laminate is the same for QSI and LVI tests in fig. 7 [18, 24]. Furthermore, the existence of a well-defined damage threshold (critical force) is also clearly visible, as well as the presence of an asymptotic dynamic plateau. Once the plateau is reached, the damage size continues to increase but the contact force reaches a plateau, and that can lead to inconclusive comparisons, as mentioned earlier. For thin laminates such plateau corresponds to penetration, but for thicker laminates, where penetration may never occur, it corresponds to the MSUL. Similar considerations can be extrapolated from the plot of fig. 8, which shows the different damage resistance characteristics of toughened and untoughened systems [18, 25]. The damage tolerance characteristics of the same two material systems are shown in fig. 9, which reveals that the Compression After Impact strength of panels that were damaged through QSI is the same as those damaged through LVI testing [18, 25]. *By all means quasi-static and impact test of the kind discussed here produce identical damage states and residual performance.*

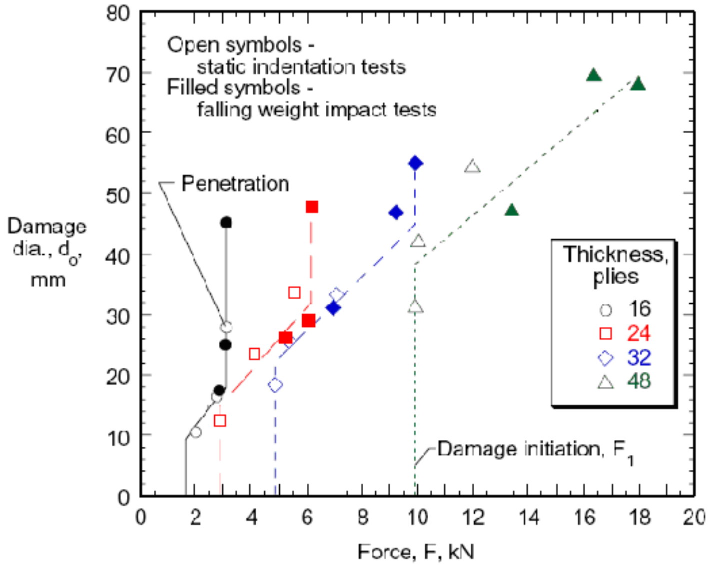

Figure 7. Damage size as function of contact force for QSI and LVI tests for different laminate thicknesses [18, 24].

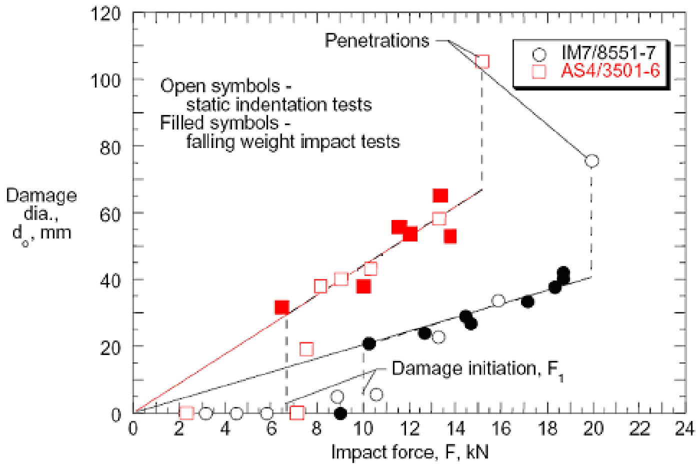

Figure 8. Damage size as function of contact force for QSI and LVI tests for different material systems [18, 25].

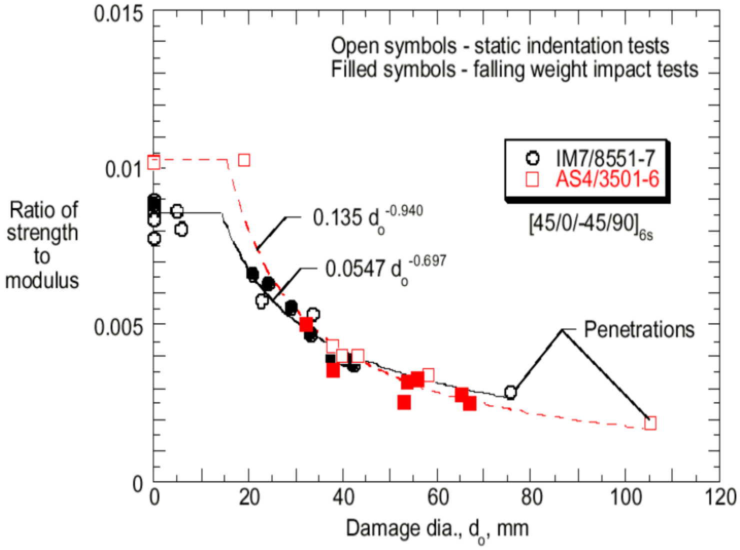

Figure 9. Residual strength as function of damage size for QSI and LVI tests for different material systems [18, 25].

From integration of the QSI load-displacement data [3], it is possible to calculate the deformation energy, and build a force-energy curve such as the one in fig. 10. For strain-rate insensitive materials, such as contemporary carbon/epoxy systems, the quasi-static force-energy curve virtually coincides with the peak force-energy plot of Fig. 2. The advantage of employing the force-energy curve of Fig. 10 is dual. First, it provides a valuable tool for understanding the global response of the specimen, and can therefore be used in the process of defining the test matrix. Second, it can be used to extrapolate the force values corresponding to 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.* While a limited number of impact tests are always necessary to validate the approach for every structural configuration, *the curve thus obtained by testing one panel in a quasi-static fashion yields the equivalent force/energy information as a large impact test database*.

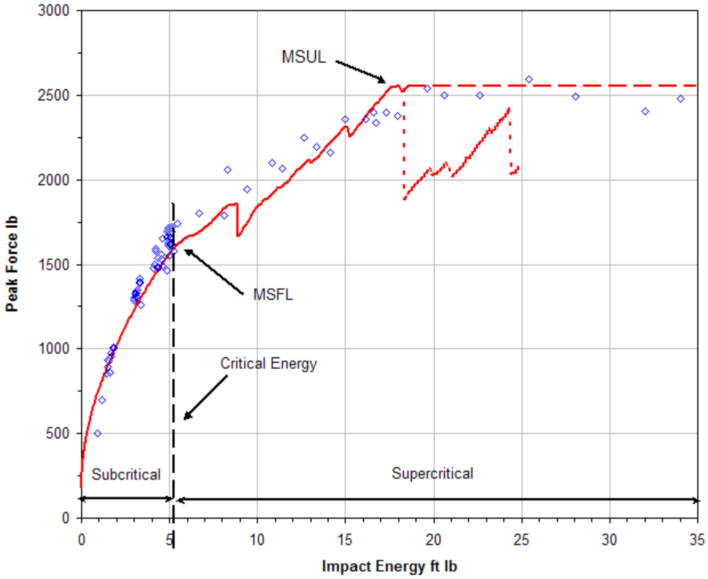

Figure 10. QSI force-energy curve with superimposed LVI data points.

These results shown so far do not apply only to a small range of panel configurations, but extend to a broad range of stacking sequences, laminate and sandwich geometries, small and large panel sizes. During a damage resistance investigation on the candidate crown panels for the NASA Blended Wing Body [9], very-thick-honeycomb panels are tested under QSI and LVI regimes. The QSI test enables the observation of a “knee” in the load-deflection curve (fig. 11), occurring at very low values of applied force, which indicates the onset of damage. This behavior is not readily observable in the impact traces because of the presence of other vibratory phenomena. Beside the mentioned knee, a series of secondary failures before occurring prior to ultimate load are visible in the QSI curve, but are not discernable in the LVI trace.

The force-energy curves for three different facesheet thicknesses are shown in fig. 12. Superimposed on the QSI curves are the peak force-energy data points recorded during impact testing of a limited number of panels per facesheet thickness. It can be observed how accurately the impact data superimposes onto the quasi-static curve. The knee present in the load-displacement trace is also visible in the force-energy curve, and it indicates that the onset of core crushing occurs at impact energy levels lower than 1.0 ft lb for two of the three curves. Therefore thick-honeycomb panels are particularly susceptible to foreign object damage, an observation that would have been particularly hard to be made with impact test setups. The impactor assembly, which usually weighs at least 1.0-1.5 lb, would require drop heights of only a few inches in order to highlight such a low threshold.

As a last consideration, the curve shows that for even for the thicker facesheet panel, ultimate load is reached at an impact energy level of 65 ft lb, thus testing at higher impact energy levels would not result in greater contact force, but would yield increasing amounts of damage [1].

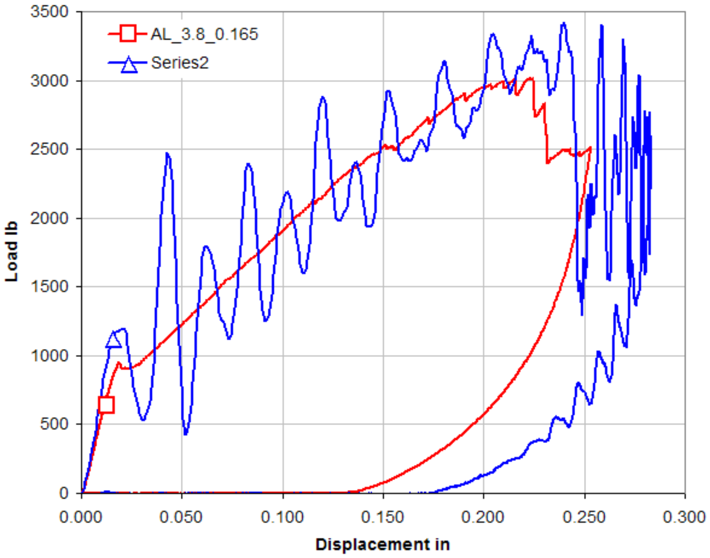

Figure 11. Superposition of indentation and impact curves for thick-honeycomb panels [9].

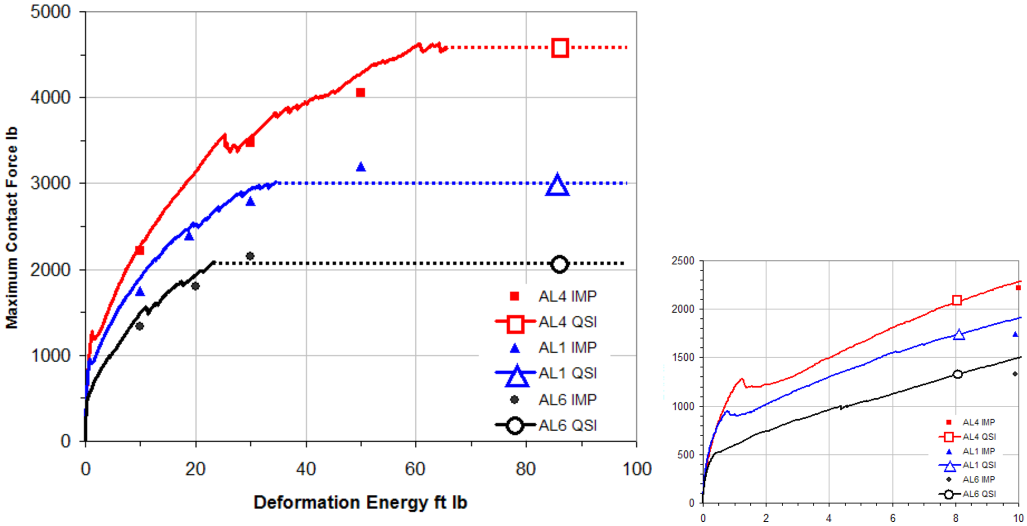

Figure 12. Left: QSI Force-Energy curves for three configurations, and juxtaposed maximum impact force values for discrete impact energy levels. Right: close-up on initial region of the curves [9].

The possibility to extrapolate the impact response of laboratory-sized specimens to larger panels is investigated by performing QSI and LVI tests on thin-gauge flat and curved panels for next-generation composite fuselage [8]. One half-size panel is impacted with scaled impactor size and energy to generate a response proportional to the full size panel. The ability to scale the elastic response was previously demonstrated by other investigators, so this study explores the scaling characteristics of damage-inducing impact events. The comparison is based on the recorded force-time histories and the resulting damage state, as measured by ultrasonic damage area. Three panels are impacted at increasing energy levels, and one panel is reserved for QSI testing. Typical force-energy curves obtained by QSI for flat and curved full-scale panels are shown in fig. 13. As previously indicated, this type of curve in great agreement with the LVI data points, and it allows for extrapolation information on impact energy levels beyond the ones tested.

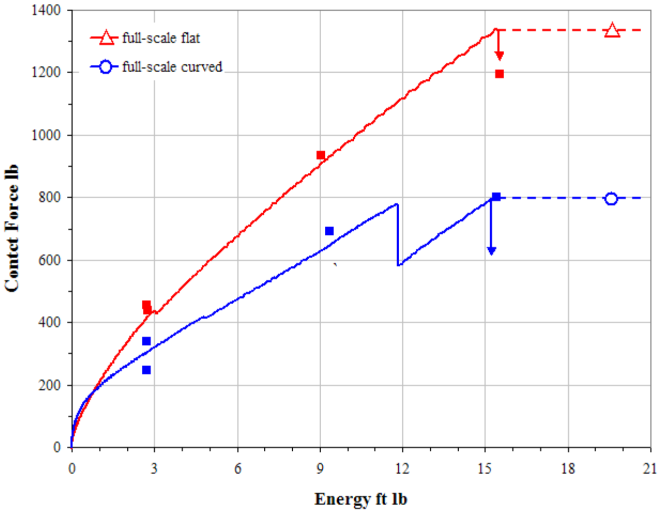

Figure 13. Force-energy curves for flat and curved, large, thin laminates [8].

The force-time histories for the three impact energy levels tested are shown in fig. 14 for the flat panels. At the lowest level, in the elastic regime, half- and full-scale responses superimpose very well if the correct scaling factor is employed [8]. At higher impact energy levels, the peak force scales very well, but there is a 10% difference in contact duration, which is indicative of the onset of damage [1]. Further inspection reveals indeed that the half-scale specimens show negligible damage (fig. 15A), while the full-scale ones exhibit a distinct delamination area (fig. 15B). The onset of damage in the full-scale panel is also witnessed by the presence of low-frequency oscillations in the trace itself, while the half-scale panel shows a much smoother curve. At the highest impact energy level, peak force continues to scale quite well, but now the discrepancy in contact duration is around 40%, and the damage area greatly exceeds the one predicted by scaling laws (fig. 15C and D). Again, the presence of greater damage in the full- than in the half-scale panel is visible from the force-time history, where a much sharper drop and more low-frequency oscillations characterize the trace of the full-scale panel. *These results bring further support to the conclusion that peak force is not a valid metric to compare structural configurations, and that the entire force-time history should be considered when comparing events.*

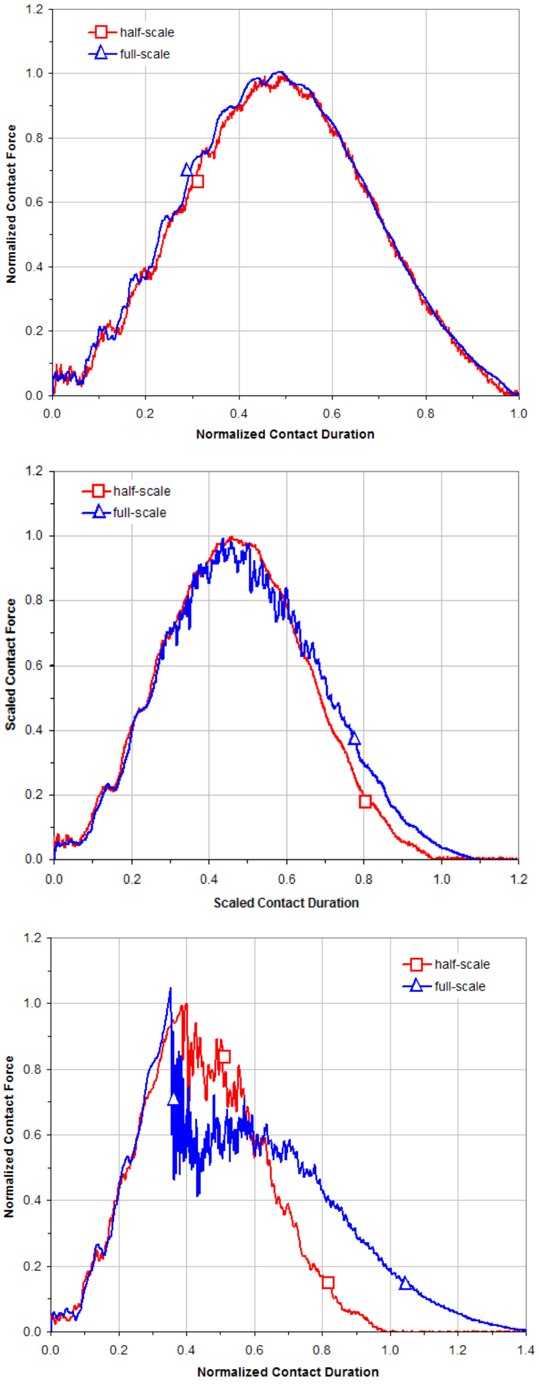

Figure 14. From top to bottom, half- and full-scale impact force-time traces for the three impact energy levels [8].

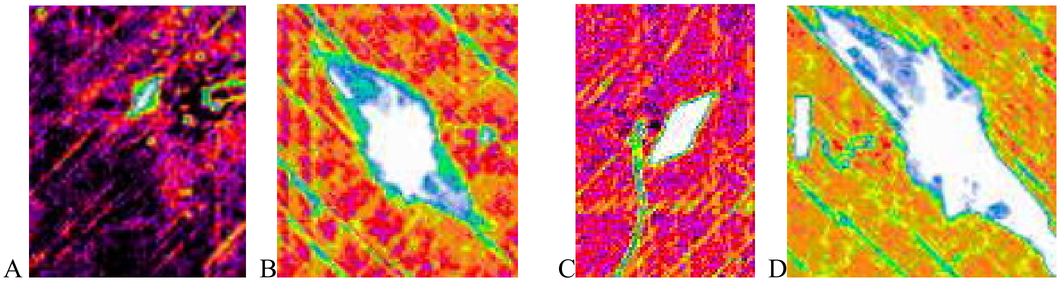

Figure 15. Actual size of ultrasonic damage area for the half-scale (A, C) and full-scale (B, D) panels at the intermediate (A, B) and high (C, D) impact energy levels [8].

CONCLUSIONS

Contact force is a useful parameter to interpret impact tests. The critical force at which damage occurs is a property of the structure, and is independent of impact energy beyond the damage threshold. However, peak force is a function of both the structural characteristics of the target and the severity of the impact test used to generate it. Therefore peak force should not be used as damage metric, or to compare impact performance of different structural configurations. Furthermore, when performing an impact test, it is important to understand the entire force-time history rather than to focus on just one parameter, such as peak force.

Quasi-static and impact tests have shown to yield virtually identical traces and damage states. While low-velocity impact tests can be used to gain unique insight in the response of a composite structure, through the generation of parameters such as contact duration, their dynamic nature is such that it can mask underlying phenomena. For this reason, it is imperative to characterize the quasi-static performance of a particular impactor/target configuration as an alternative to, or at least before considering, impact testing.

ACKNOWLEGMENTS

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During an extensive career in industrial research and development involving advanced composite structures and low observable systems, Dr. Kedward worked for Rolls Royce, General Dynamics, ALCOA Defense Systems, and McDonnell Douglas Technologies (San Diego), where he ultimately became Vice President of Integrated Product Development. In 1990 he joined the Faculty of the Mechanical Engineering Department at the University of California, Santa Barbara. Since then he has been dividing his life between San Diego and Santa Barbara, so much that it is easier to spot him on the 101 than in either one of his residences. Among Dr.

Kedward's multiple achievements, are the AIAA, ASC, and SAMPE fellowships, the 1997 Distinguished Teaching Award of the College of Engineering, and the Departmental Outstanding Teaching Award for 8 of the 15 years he served as faculty member at UCSB. One of the original pioneers of carbon fiber (fibre?) while still at the University of Wales when here in the US it was still considered "low-modulus junk" compared to the more sophisticated boron fibers, he quickly became known for his design-oriented approach to composites, witnessed by the creation of the Designer's Corner in the Journal Composites while serving as its North American editor 1990-96. Perhaps because of the composite fan blade "incident" for the RB211 while still at Rolls Royce, Dr. Kedward dedicated the majority of his work to matrix-dominated phenomena. His published research focuses on interlaminar shear testing, through-thickness stitching, foreign object damage resistance and tolerance, bonded joint analysis and design. A strong advocate of the composite material building block philosophy, his dedication to the standardization efforts of various organizations is witnessed by chairing two ASTM Special Technical Publications (STP), as well as the Delamination and Debonding Task Group of the MIL-HDBK-17 with Dr. Kevin O'Brien. I have known Keith since 2000, when I joined his group at UCSB, back then comprising Gregory D. Tracy, Jason D. Bardis, and Hyonny Kim, who preceded me on the path to doctoral glory. Beside the technical knowledge that he imparted to me as advisor and mentor, Keith introduced my to a whole professional family, of which I am particularly honored to be a member. Oh, I almost forgot, he was my best man too!

Lastly, the title and headings are inspired by the work of T. Kevin O'Brien [25, 26], to whom I am grateful for sharing some uniquely humorous remarks over time.

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