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Small Mass Impact Testing of Sandwich Structures

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Small mass impacts pose a threat to modern lightweight materials even at low velocities. In this study we describe a test method with a suitable setup to access the materials impact response to masses below 500 g and velocities up to 20 m/s. The setup uses a high-speed camera and adapted semi-automatic image processing algorithms to extract the time-force history of the indenter. The results show good agreement to analytical impact models for hollow core sandwich structures.

In the field of lightweight applications sandwich structures offers high stiffness to weight, strength to weight ratio and provide an efficient solution in increasing bending stiffness without increase in structural weight [1]. In this regard, sandwich structures have drawn much attention in material research and lightweight application in the last years [2], [3].

The integration of lightweight and non-metallic materials into vehicle design is subjected to restrictions related to external surface quality and impact safety. With regard to safety concerns the evaluation of material behaviour is not only critical in crash situations but also in low velocity impact behaviour [4-9] and small object impact events [10]. Such events include damage on train fronts or cars due to flying debris or gravel as well as dropped tools or equipment during maintenances (see [11]).

In the experimental practice the evaluation is concentrated on small mass - high velocity (projectile loading) as well as large mass - low velocity impact loading. For additional testing of a batch of intermediate velocities with small mass impact in composite sandwich structures a new testing setup has to be developed. The setup has to fulfill the following requirements: The acceleration of the impactor should be adjustable from 1 m/s to 20 m/s. The sandwich specimen has to be positioned and supported in a well-defined way. Repeatability and sufficient accuracy of the optical measurement process has to be guaranteed. The impactor radius and geometry should be adjustable. Finally the test equipment has to record the complete time vs. force history of the impact event.

The focus of the published work is on the presentation of the newly developed test method for small mass impact in sandwich structures for transportation purposes and to investigate the relations between material properties and impact response including load, contact duration and damage of the sandwich components. Additionally we used the models presented in various publications [17-19] to compare the experimental results with the analytic solution of the load history. The choice of those models follows the guidelines of Abrate [18] indicating good correspondence between impact experiments compared to energy balance and plastic foundation models.

Experimental

Specimen Fabrication. Sandwich structures have been manufactured by using the KraussMaffei polyurethane long fibre injection (LFI) technology [12, 13]. In the LFI process a cutting unit placed directly on the two components polyurethane mixing head cuts the glass rovings to the desired fibre length. The impregnation of the fibres takes place directly after the mixing of the two components. For sandwich manufacturing, the polyurethane-fibre bulk is introduced in the open cavity of the die by a robot. Then the core material is deposited followed by the insertion of the polyurethane-fibre bulk. Finally the lower polyurethane-fibre bulk, core material and upper polyurethane-fibre bulk are compressed to build up the sandwich structure.

Sandwich structures with two different core materials have been manufactured. On the one hand a sandwich structure with a 40 mm thick sinusoidal cardboard core out of testliner paper with a grammage of 115 g/m² and a wall thickness of 0.15 mm, on the other hand a sandwich structure with a 40 mm thick polypropylene tubular core with a wall thickness of 0.2 mm (Figure 1).

The facesheets of the sandwich structures consist of an E-glass fibre weight-

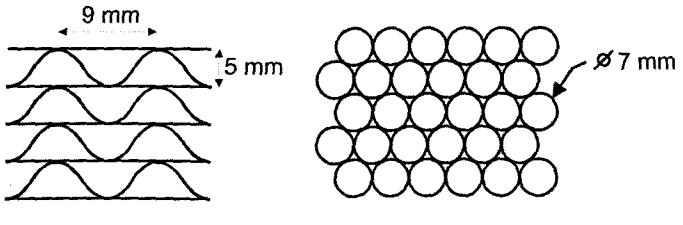
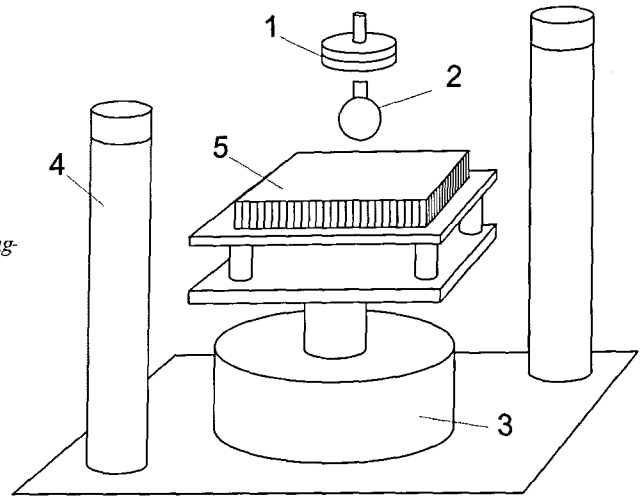


Figure 1. Geometry of the sinusoidal (left) and tubular core structure (right)



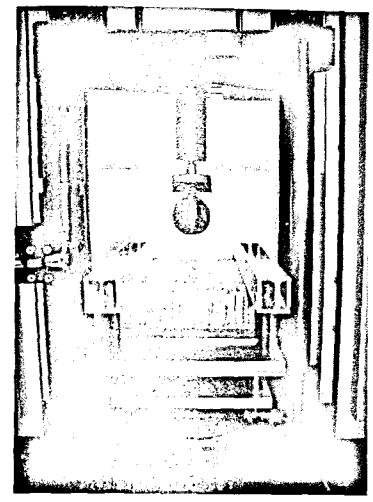


Figure 2. Photograph and schematic of the sample stage for impact testing: (1) plate magnet, (2) impactor, (3) load cell, (4) cage brakes, (5) sandwich specimen

fraction of 30 % and fibre lengths of 12.5 mm and 25 mm respectively (mixing ratio 2:1).

Mechanical Characterization

Bending Properties. Bending tests were performed at room temperature in accordance with DIN 53293 [14] on a quasi-static material testing machine equipped with a 10 kN load cell and an inductive position measuring system.

Shear Properties. The shear characteristics of the core material were determined at room temperature in accordance with DIN 53294 [15] using the same machine, load-cell, and strain measurement system as for the bending tests.

Tensile and Compression properties. Tensile tests were performed at room temperature and a crosshead velocity of 2 mm/min in accordance with ISO 527-1 [16].

Method

Drop Tower and Magnetic Holder. The described velocity range up to 20 m/s was provided using an Instron Dynatup droptower with a standard drop cage of 5.24 kg. The piezo load-cell was mounted on the cage as support for the magnetic holder. The drop height of the screw-driven cage and therefore the drop height of the impactor was adjusted to achieve the implied testing velocity. The cage was released from the frame and fell consequently onto two steel bars providing the resistance for an immediate stopping of the cage. The impact velocity can be derived from the drop height as follows:

$$V_i = \sqrt{2gh} \quad (1)$$

A pot magnet was mounted on the load cell to be used as a pod for the steel impactor. The active magnetic surface of the plate was 78.5 mm², and the attraction force per mm² was 0.17 N. On top of the magnet a plastic ring was fixed to provide guidance for the piston of the impactor. This ring was sprayed with polytetrafluorethylene to minimize any friction loss of the velocity (Figure 2).

Sample Stage. The sandwich sample was supported through a metal plate with a circular hole of 100 mm diameter. Additionally the sample could be clamped on both sides to accurately centre the specimen and prohibit transverse motion of the specimen during and after the impact event. The entire stage was mounted on a 10 kN load cell which worked as an additional measurement device for the impact force. The measured load was recorded with a sampling rate of 96 kHz which allowed a measurement of the acting forces with a four times higher time resolution than the optical system.

Impactor. As impactor a magnetic steel sphere was used. To achieve an attractive force which can reliably hold the impactor during the acceleration phase as well as weak enough to release the impactor as soon as the breaking force impulse is triggered, a cylindrical extension with a diameter of 10 mm was fit to the steel sphere. The radius of the sphere and the length of the extension were then adjusted to reach the given impactor weight of 250 g.

Image Data Acquisition. During acceleration and deceleration periods the movement of the sphere was recorded using an IDT Motion Pro X4 high speed camera with a maximum frame-rate of 30 kHz depending on the region of interest of the setup. This produced a time series of 400 to 600 images where the camera properties were optimized to maximize the contrast between sphere and background. To avoid a low contrast image being valueless for image processing and data analysis the scene had to be illuminated using 2 high frequency LED lights.

Evaluation Software. The evaluation of the image time series was done in Matlab. The image processing thereby was divided into the following steps:

- Contrast enhancement and noise reduction using image filters (median)
- Extraction of the centre-position of the sphere during image acquisition
- Correction for transverse motion of the sphere
- Generation and interpolation of the position-time curve of the sphere's centre using polynomials of order 8-12 and least-square fitting
- Differentiation of the position-time curve with respect to time to determine the velocity and acceleration history of the impactor
- Linear fitting of the position history to determine the incoming and escape velocity v_{in} and v_{out}

A detailed description of the respective steps is given in the following.

Image Pre-processing. Due to the high sampling-rate of the camera system an equal illumination of the scene is crucial. Every inhomogeneity in the illumination will decrease the contrast between the sphere and the background and will degrade the precision of the position measurement. Prior to the ex-

traction of the position data the image noise has to be removed using an edge-preserving smoothing filter. For this task the use of a 3 × 3 median filter was found to be adequate. After illumination equalization and noise removal the images were stacked in a 2D vs. time image stack and one time slice in the transverse position of the sphere was picked incorporating user interaction and evaluation. The transverse position of this slice had to be shifted with respect to the centre to avoid the asymmetric part of the sphere's pod to enter the evaluation. After the final time-position image has been created the redundant information in the image which does not contribute to the position data is clipped.

Extraction and Correction of the Position-Time History. After pre-processing the image, the centre position of the sphere can be determined by finding the medial axis of the sphere section's path. Therefore it is necessary to segment the image into the region belonging to the sphere motion and the background (Figure 3). Due to the careful adjustment and choice of contrast parameters a simple threshold allows the separation of the region of interest. With the accelerating and decelerating force acting primarily along the orthogonal direction and the transverse movement resulting only from friction and inhomogeneous impact dynamics the sections show a linear behaviour with respect to transverse motion. This allows interpolating the change of the central point in the strip due to transverse motion of the sphere in the region where the indenter penetrates into the sample between the incoming velocity and the escape velocity of the impactor in a linear way.

Interpolation and Determination of the Force-Time History. The force-time history of the sphere can be derived using the first and second order derivative of the position with respect to time. Therefore it is best to fit analytic functions to the extracted data points. This can be easily done using the Matlab fitting and interpolation framework. It can be seen that polynomials of 8-12 degree provide sufficient results to produce a smooth and well fitted curve if adjusted using least-square fitting procedure. Thus having produced an analytic expression for the orthogonal motion $y(t)$ the velocity $v_y(t)$ and acceleration $a_y(t)$ of the impactor can be determined as:

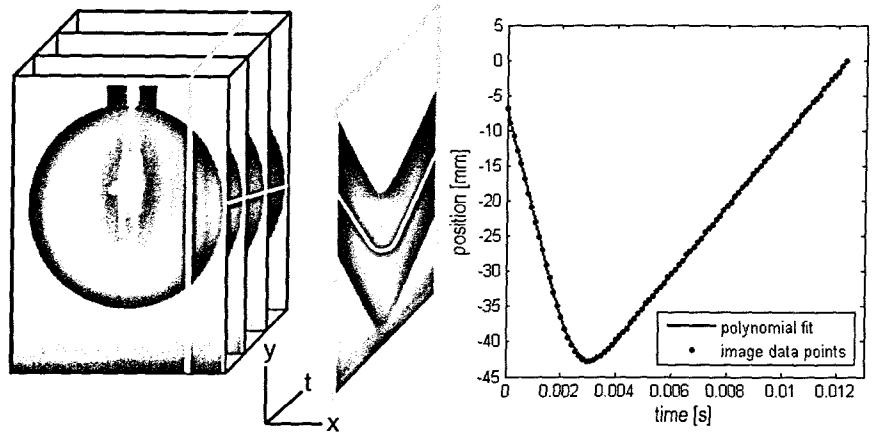


Figure 3. Image stack of sphere sequential motion (left) and extraction of the center position along one time section (right)

$$v_y(t) = \frac{d}{dt} y(t) \quad (2)$$

and

$$a_y(t) = \frac{d^2}{dt^2} y(t). \quad (3)$$

Finally the calculation of the force acting on the impactor can be carried out using the known mass of the impactor m_i and scaling the results with the pixel size and time step-size according to the frame-rate:

$$F(t) = a_y(t) \cdot m \quad (4)$$

In addition to the measurement of the velocity using differentiation of the position history an alternative measurement can be integrated through a linear fit in the regions of constant velocity. This provides a mean value for the impact and escape velocity which is defined unambiguously during the motion tracking process.

Results

Static Tests. The relevant material properties determined by static bending, shear and tensile/compression test can be seen in Table 1.

Impact Tests. The impact velocity was varied in four steps from 6 m/s to 16 m/s to show the expected relation between velocity and peak load and contact duration respectively.

As can be seen from Figure 3 the data point from the images representing the centre position of the sphere can be fit accurately with the polynomial. This allows for the calculation of the derivatives to obtain the load history. This sequence of calculations can be seen from Figure 4 where the data window is restricted to the actual contact region to suppress side effects of the polynomial fit.

	Tubular Core	Cardboard Core	GFRP Facesheet
Youngs modulus	112 MPa	221 MPa	4.5 GPa
Crushing resistance	1.3 MPa	1.4 MPa	-
Yield stress (compression)	1.7 MPa	1.5 MPa	40 MPa
Yield stress (tension)	-	-	62.9 MPa
Shear modulus	15.0 MPa	10.3 MPa	-
Contact stiffness k [eqn. (5)]	1.2 E7 $N/m^{1.5}$	1.1E7 $N/m^{1.5}$	-

Table 1. Material properties of the sandwich beam with different core structures and of the sprayed GFRP facesheet

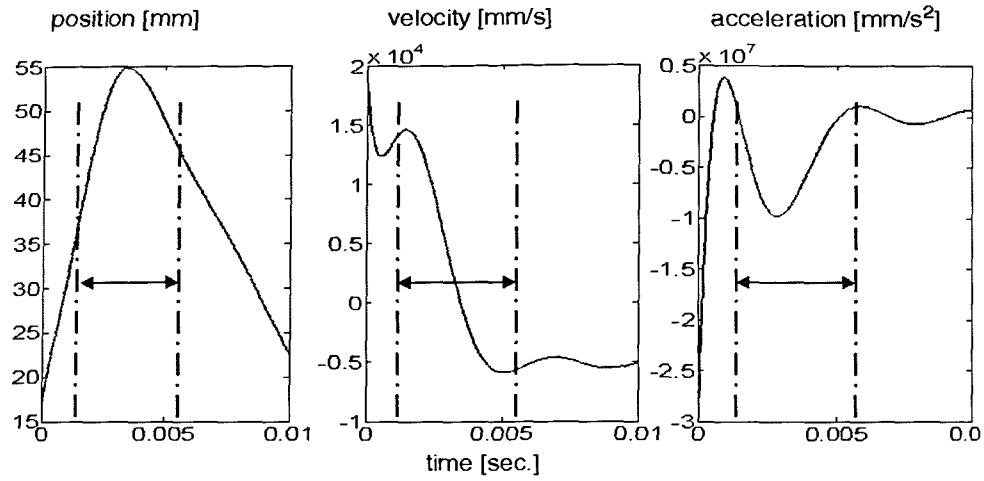


Figure 4. Consecutive calculation of position (left), velocity (centre) and acceleration history (right) with according contact zone

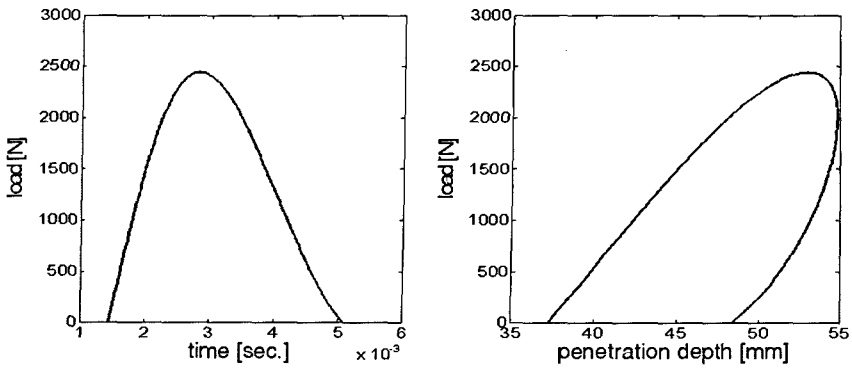


Figure 5. Evaluation in load history (left) and load-penetration dependence (right)

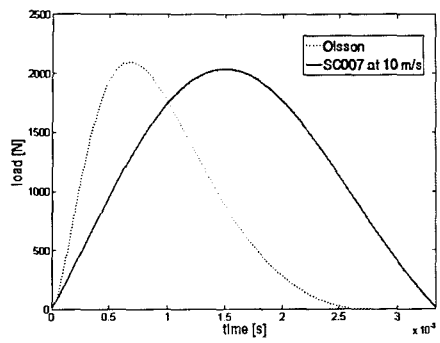


Figure 6. Comparison of analytic and experimental data of an impact test with m = 250 g and v_i = 10 m/s

As a result from the analysis of the acceleration polynomial it is possible to give a detailed and continuous representation of the load and deformation history (Figure 5).

The experimental results for the two sandwich configurations were compared to an analytical solution using an impact on an infinite plate approach [17], and an energy balance approach [18, 19]. The fundamental data for the models has been taken from different static tests as compression test, four-point-bending, shear test, and static indentation tests. The analytic model of Olsson can be combined with a Hertzian as well as a linear contact law. The Hertzian contact law can be applied to various contact problems of composite materials. The sandwich panels in this investigation exhibited a load-indentation relation according to the Hertz law [20, 21]:

$$P = k\alpha^{3/2}. \quad (5)$$

where the stiffness factor k was determined in a quasi-static indentation test. The analytic results for the peak load compare well with the experimentally determined data.

Subsequently the data from the load cell did show noise effects resulting from the oscillation of the machine and the overlapping oscillation from the indenter which are both travelling as stress waves from the impact point of the cage and the sandwich towards the load cell. It is not possible to apply an unambiguous and solid decomposition to the signal to exploit only the sandwich impact event (Figure 9 left).

Finally the sandwich surface had been gauged using a measuring sensor to detect the residual indentation. Due to the circular symmetry the mean value in four perpendicular directions was used to reconstruct a surface depth (Figure 10) and to visualize the impact damage (Figure 9 right).

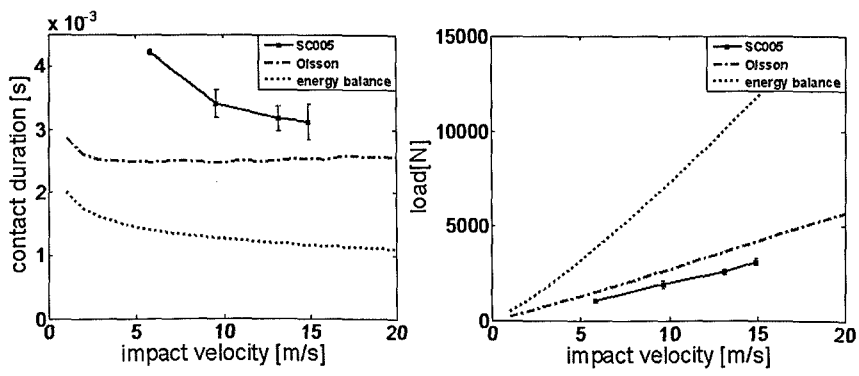


Figure 7. Contact time and peak load of fluted paperboard core sandwich and model prediction [17]

Discussion

The novel impact measurement setup described in the previous sections allows for the determination of the complete load history of an impact event. Bearing in mind that the prior knowledge of the impact velocity is essential to assess the necessary measurement parameters of the optical system, the image acquisition is the bottleneck with respect to the precision of the evaluated load history. The temporal and spatial resolution of the camera system has been Δt = 5.0 E-5 seconds and Δy = 0.266 mm which leads to an undistorted spatio-temporal image within the velocity range of our experiments. The polynomial fit required to access the derivatives of the motion history can be tailored precisely to the image data so that the analysis can be applied to more precisely sampled data (Figure 3). Nonetheless it is necessary to use a sufficient large window to track the motion, so that marginal effects of the fitting process can be excluded from the relevant data. Any oscillation induced into the sandwich or coupled back into the indenter could not be recorded either because the amplitude is too small to be detected or the time-scale of those events beyond the sampling rate of the imaging system. The alternative measurement using a load cell underneath the sample stage (see Figure 9 left) with a measurement rate of 96 kHz could not provide further exploitable results. This is because of the superposition of the damped oscillation of the acceleration cage impact on the brake columns and the sphere impact event on the sandwich.

The measured results for the imaging method using four different velocities in the range between 1 and 16 m/s indicate the expected behaviour and relation for a sandwich impact event as compared to simple analytic models. In addition to the analytic results the experiments show the effects of core yielding and sandwich bending which reduce the overall panel stiffness and therefore affect the peak load and contact time in the way outlined by the experiments. As can be seen from the peak load to velocity relations the models (Figures 7 and 8) show a tendency to higher loads because they neglect bending and shear effects of the sandwich. The results of static compression tests indicate a very early core failure for displacements as small as 1 mm. The portion of bending has not been accessed in our experiments but it can be assumed that the circular support of the panel specimen allows for a bending deflection in the central region up to 3 mm, derived from classical plate theory, for the different sandwich configurations [22, 23]. Therefore the bending and shear deflection carry a substantial portion of the overall measured motion of the indenter. This aspect also arises on investigation of the residual indentation on the sample surface (see Figure 9 right) which adds up to the overall maximum indentation when used in combination with the bending deflection as discussed above.

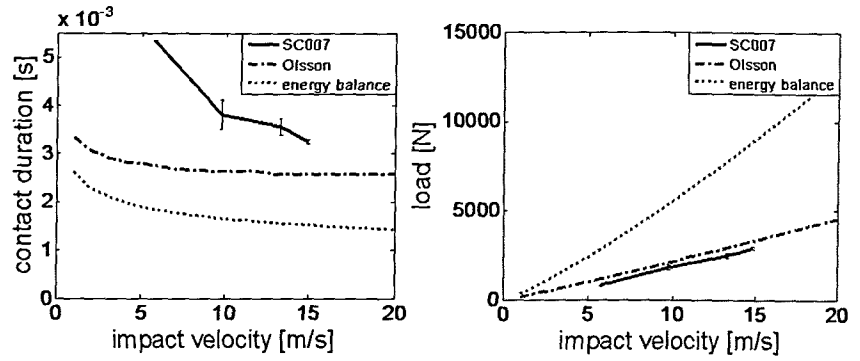


Figure 8. Contact time and peak load of tubular core sandwich and model prediction

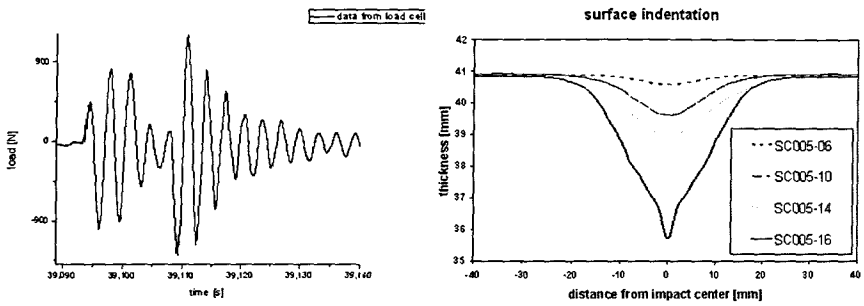


Figure 9. Load data from the load cell underneath the sample stage (sampling rate 96 kHz) (left) and surface damage of impacted samples (right)

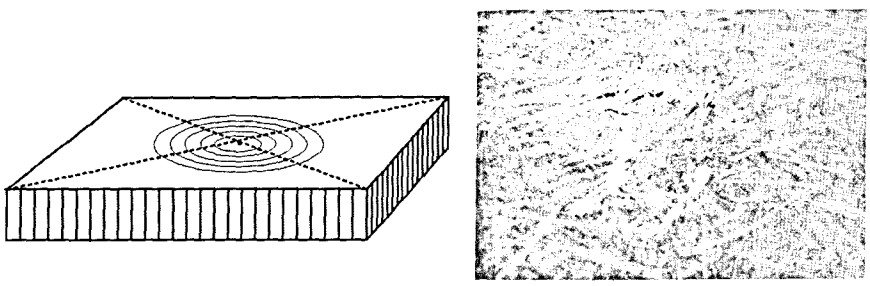


Figure 10. Surface measurement along diagonals in radial direction from impact center (left), image of damaged tubular core sandwich surface with face sheet failure at 14 m/s (right)

Conclusions

By using fundamental image processing methods and a high speed image acquisition system it is possible to chart the motion in an impact event. For the special case of a steel sphere impact we have implemented a testing setup into an existing impact testing machine. Using standard scientific visualisation software we implemented evaluation software to determine the load history from the tracked impactor motion. The comparison of experimental results with modelled data from simple impact models indicates a good correlation between experimental and analytic results.

Abstract

Kugeleinschlagversuche an Sandwich-Strukturen bei geringen Stoßkörpermassen. Auch bei niedrigen Geschwindigkeiten stellt der Einschlag von geringen Massen eine hohe Belastung für Bauteile aus modernen Leichtbauwerkstoffen dar. In der diesem Beitrag zugrunde liegenden Studie werden eine Prüfmethode und Prüfeinrichtung beschrieben, mit der das Werkstoffverhalten beim Einschlag von Massen unter 500 g mit einer Geschwindigkeit von bis zu 20 m/s charakterisiert werden kann. Im Prüfaufbau kommen eine Hochgeschwindigkeitskamera sowie Bildverarbeitungsalgorithmen zum Einsatz, die es erlauben den Zeit-Kraft-Verlauf des Eindringkörpers zu ermitteln. Die Ergebnisse weisen eine gute Übereinstimmung mit analytischen Modellen zur Simulation des Einschlages in Sandwich-Strukturen aus Honeycomb-Materialien auf.

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