Strain Monitoring and Detection of Barely Visible Damage in Foam-Core Sandwich Structures

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STRAIN MONITORING AND DETECTION OF BARELY VISIBLE DAMAGE IN FOAM-CORE SANDWICH STRUCTURES

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ABSTRACT

To detect indentation or low-velocity impact induced damage in foam-core sandwich structures, a fiber-optic distributed strain monitoring system is applied to the structures. An optical fiber is embedded into the sandwich structures and the strains are measured using a Rayleigh scattering based monitoring system which offers high resolution. Indentation loading tests with sandwich beam and panel structures are conducted to verify the monitoring ability of the system and compared with numerical analysis predictions. The monitoring system could measure the strain distribution with very high spatial resolution and allowed for observation of the strain formation throughout the whole indentation event. The detectability of the damage in panel structures with regards to the location and density of the optical fiber sensor network is also discussed. The used system could accurately detect slightest changes in residual strains indicating barely visible damage and thus allowed for good estimation of the location and size of damage in the core of the sandwich structures.

KEYWORDS : *Sandwich structures, fiber-optic sensor, damage detection.*

INTRODUCTION

Composite foam-core sandwich structures have high specific strength, stiffness, and bending stiffness properties while being extremely lightweight [1]. Consisting of thin carbon fiber reinforced plastic (CFRP) face sheets and lightweight foam core, they can provide enhanced bending stiffness properties without added complex stringer components and can therefore significantly decrease the part-count of complex structures. Due to their attractive properties, sandwich structures have been widely used in various applications ranging from automobile structures to wind energy applications. Increasing interest has also been shown in using foam core sandwiches in the primary structures of aircraft structures [2-5]. The relatively weak core and thin faces of foam core sandwich structures however make them rather vulnerable against transverse indentation or impact loadings. Indentation or low-velocity loading can leave only barely visible impact damage (BVID) in the face sheet while the core and adhesive layer can be significantly damaged. This can have notable degrading effect on the strength and stiffness properties of the structure [6-8]. Due to the barely visible residual dent remaining after loading visual inspection becomes difficult. Therefore a way to accurately detect these kinds of damages and to assess their severity is needed to evaluate the integrity and residual strength of the structure. Furthermore, environmental conditions can also affect the indentation response of the sandwich structures by degrading the properties of the core material leading to even more severe damage inside the structure. In this study, a fiber-optic distributed strain monitoring system is applied to detect barely visible indentation or low-velocity impact induced damages in foam-core sandwich structures. Indentation loading tests are conducted with sandwich beam and panel specimens to study the monitoring ability of the system and the results are compared with finite element analysis predictions for verification.

1 DAMAGE DETECTION IN SANDWICH STRUCTURES USING FIBER-OPTIC SENSORS

In this study strain monitoring and detection of indentation and low-velocity impact damage in foam core sandwich structures is achieved by using distributed optical fiber sensors. Detection of these kinds of damages is now done by detecting the residual dent remaining in the face sheet after indentation or impact event from the residual strain distribution. During indentation or low-velocity impact of foam core sandwich structures, the face sheet bends locally under the loading. This again causes compressive loading in the core material, which starts to crush and deform plastically as the cell walls buckle and collapse. After the loading is removed the face sheet, which remains mostly undamaged under low indentation or impact energies, tries to return to its initial state thus pulling the crushed core. The plastically deformed core however resists this pull from the face sheet up to some degree, leading to a barely visible residual dent to remain in the face sheet [9]. Optical fiber sensor is therefore embedded into the core-face sheet interface where the strains caused by the bending of the face sheet are the highest. Also damage in the interface and in the core next to the interface can lead to anomalies in the strain distribution at the interface and thus possibly be detected. In the BVID case, however, the deformations can be significantly small and local which requires high resolution and accuracy from the monitoring system. For this purpose a Rayleigh scattering based monitoring system is used, and is next explained briefly.

1.1 Strain measurement method

Strain over the embedded optical fibers is monitored using an optical backscatter reflectometry (OBR) based monitoring system by LUNA. The system uses swept frequency interferometry (SWI) and monitors the Rayleigh backscattered light over the optical fiber sensors [10-13]. The Rayleigh scattering is caused by random but static fluctuations in the index profile along the optical fiber, thus making the amplitude of the scattered signal also a random but static property unique for each fiber. Using Fourier transformation, the Rayleigh scattering spectrum at each sampling point along the fiber is obtained from the time domain data. Changes in temperature or strain change the local period of the Rayleigh scatter and can be seen as shift of the backscattered Rayleigh spectrum.

The strain distribution along the fiber can then be calculated by looking at the Rayleigh scattering spectrum at each sampling point along the fiber and by comparing it with reference data. Shift in the spectrum ($\Delta\lambda$ for wavelength or Δv for frequency), obtained by cross-correlating the measured spectrum with reference spectrum, is related to the change in temperature ΔT and strain $\Delta\varepsilon$ at the measurement point and can be defined as

$$\frac{\Delta\lambda}{\lambda} = -\frac{\Delta v}{v} = K_{\varepsilon}\Delta\varepsilon + K_{T}\Delta T \ . \tag{1}$$

where λ is the mean optical wavelength, v the mean optical frequency, and K_T and K_ε are the temperature and strain calibration constants which depend on the used fiber. Defining the reference state as zero strain and assuming there is no change in temperature, the strain can be calculated as

$$\varepsilon = -\frac{\bar{\lambda}}{cK_{\varepsilon}}\Delta v = \bar{K}_{\varepsilon}\Delta v \ . \tag{2}$$

where $\bar{\lambda}$ is the center wavelength of the measurement and c is the speed of light. These form the conversion factor $\bar{K}_\varepsilon$ which can be obtained experimentally by relating applied strain and frequency shift of the Rayleigh scatter spectrum in the used optical fiber.

2 EXPERIMENTAL STUDY

2.1 Sandwich configurations

In the experimental study, two kinds of sandwich configurations were used as depicted in Figure 1. The specimens consisted of T700S/2592 (Toray Co.) CFRP face sheets prepared in advance and Rohacell 51 WF (Evonik Rohm GmbH.) PMI foam core bonded together using AF 163-2K (3M Co.) adhesive film. Low-bending-loss optical fiber (Heatop 300, Totoku Electric Co., Ltd., outer diameter: 150 μm, cladding diameter: 125 μm) was embedded between the face sheet and adhesive layer during the adhesion phase. Underside of the specimens was adhered to a steel or aluminum jig to prevent global deformation. In the indentation tests, quasi-static indentation loading was applied at the middle of the test specimens. Constant indentation rate of 5 mm/min was used throughout the tests. Loading was applied until certain level of indentation displacement or loading was achieved, after which the loading was removed at the same rate. The strain data along the embedded optical fiber sensor was measured continuously during the tests.

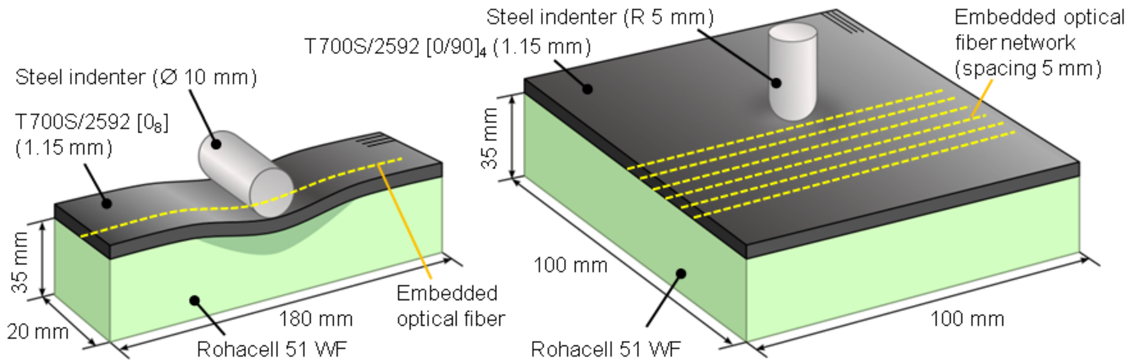

Figure 1: Sandwich beam and panel specimen configurations used in the experiments.

2.2 Sandwich beam indentation test

First the performance of the monitoring system during an indentation loading cycle of a sandwich beam specimen was observed. Figure 2 shows the measured strain distribution along the embedded optical fiber at the indicated selected points during indentation loading cycle. The high resolution of the monitoring system now allows for detailed observation of the strain distribution in the structure. During the indentation loading part a rather sharp tensile strain peak can be observed at the loading point with areas of tensile strain on both sides. These strains are caused by the bending of the face sheet and increase accordingly as the loading increases and the dent on the face sheet becomes deeper. After unloading a flat tensile strain peak remains visible. This indicating that a residual dent remains in the face sheet due to compressive plastic deformation in the core which then resists the pulling force from the face sheet trying return to its initial position. The strain measurement system can thus provide high resolution strain distribution data of millimeter order during the whole indentation loading cycle.

2.3 Effect of humidity conditions

Indentation loading tests were also conducted with specimens conditioned at various humidity conditions (Dry: 10%RH, Ambient: 55%RH, Wet: 95%RH) for 24 hours before testing. Measured strain distributions during maximum indentation loading (600 N) and immediately after are shown in Figure 3. Stiffness and strength of the foam core is degraded by increased humidity which then leads to increased plastic deformation in the core and formation of larger dent in the face sheet. This is also seen as higher maximum strains and wider strained area during maximum loading. Due to increased plastic deformation in the core of the wet specimens, wider strained area and larger residual strains are also observed as deeper residual dent remains.

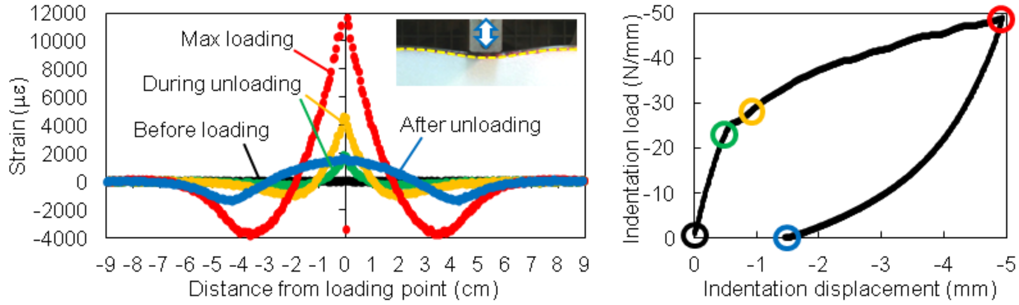

Figure 2: Measured strain distribution during different parts of indentation loading cycle.

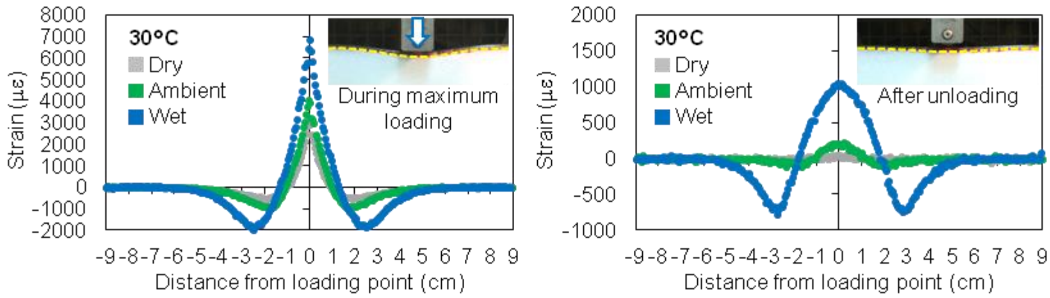

Figure 3: Measured strain distributions at tested humidity conditions.

2.4 Sandwich panel indentation test

In the sandwich panel specimen, indentation loading was applied at the center of the panel while gradually increasing the maximum loading after each cycle. Looking at the strain response in Figure 4 the response of the panel specimen seems to be similar with the beam specimen. As the dent profile at the locations of the embedded optical fibers changes depending on the distance from the loading point, the shape of the measured strain distribution at each location changes accordingly. The point loading however causes highly local deformation which results in high strains and possible damage of the adhesive layer and face sheet at the loading point. This causes correlation problems in the monitoring system and can be seen as notable noise in the strain response in the vicinity of the loading.

Furthermore, in the panel case, the damage detection ability of the system now depends also on the location of the indentation point with respect to the embedded optical fiber sensors. Detection is most difficult when the loading is exactly between two adjacent fibers. By observing when the indentation damage becomes detectable in the measured strain distribution at each fiber away from the loading point after each loading cycle, relationship between the residual dent and distance of the fiber from the loading point can be plotted as in Figure 5. Detection ability improves notably as the spacing is reduced until 20 mm. If for example 0.2 mm residual dent depth is taken as the limit for BVID, for this sandwich configuration a fiber spacing less than 35 mm should be capable to detect damages under the BVID limit.

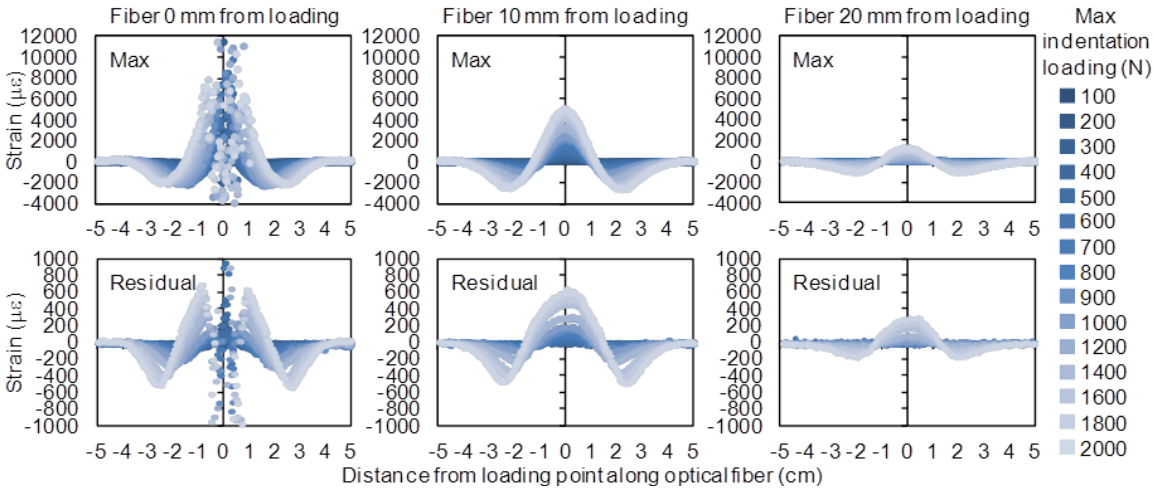

Figure 4: Measured strain distribution in the panel specimen at maximum loading and after unloading.

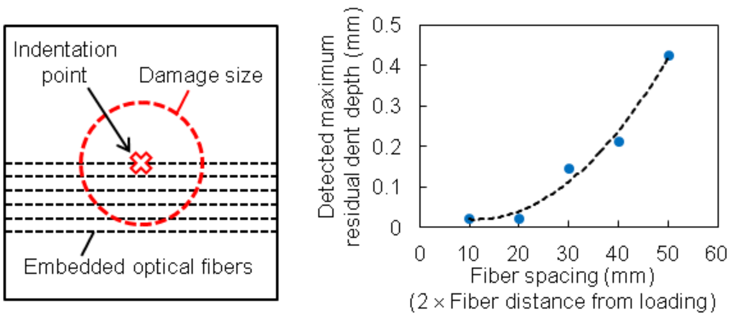

Figure 5: Detectability of indentation damage based on fiber spacing in optical fiber network.

3 FINITE ELEMENT ANALYSIS

3.1 Modeling of indentation tests

The indentation response of the tested sandwich structures was also studied by finite element analysis. Two dimensional model for the sandwich beam, and three dimensional model for the sandwich panel were constructed in the ABAQUS 6.11 software. The face sheet and adhesive layer were modeled as elastic and the core as elasto-plastic using the Crushable foam material model available in ABAQUS. Material properties for the face sheet and adhesive film were obtained from manufacturer datasheets [14,15]. Material properties and uniaxial compressive-tensile behavior of the foam material was obtained experimentally. Due to symmetry only half of the beam and one quarter of the panel was modeled with appropriate symmetry boundary conditions. Indentation loading was applied similar to the experiments by controlling the displacement of the rigid indenter.

3.2 Comparison of predicted and experimental results

Predicted strain distribution in the adhesive layer at the location of the embedded optical fiber was compared with the measured strains at maximum indentation loading and immediately after unloading. As can be seen from Figure 6 (a), the predicted strains correspond well with the measured data. Some difference is seen in the residual strains due to the simplified response of the core material model during unloading. The predicted indentation response should therefore be quite accurate and can be used for estimation of the damage in the sandwich structures.

Size of the plastically deformed area in the core is compared with the strain distributions in Figure 6 (b). A compressive peak is observed at the outer edge of the dented area as the face sheet bends over the crushed core while being supported by the adjacent undamaged core. During unloading the compressive peak moves further away from the loading point as the dent becomes shallower. From Figure 6 (b) it can be seen that the compressive strain peak in the residual strain distribution seems to settle near edge of the damaged core area. Therefore, size of the damage in the core can be estimated from the strain distribution data by observing the location of the compressive strain peaks. This applies also for sandwich panels as areas of compressive strain are formed near the edges of the damage core area. Addition of optical fiber sensors also in the perpendicular direction can further improve detection and estimation of the size and shape of the damaged area in sandwich panels.

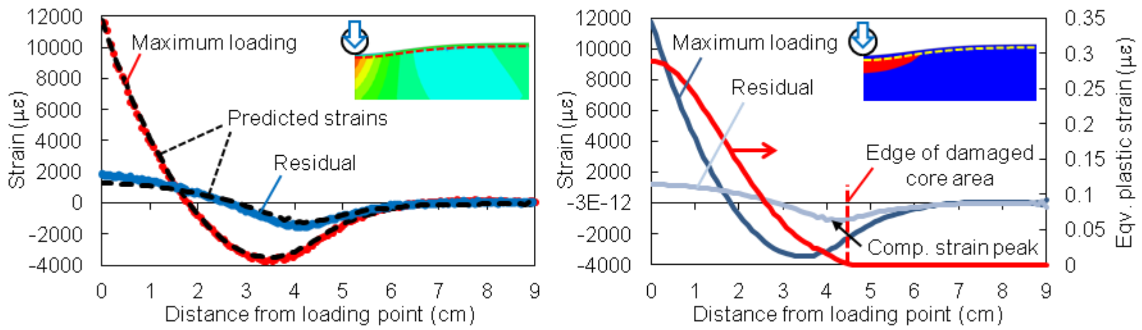

Figure 6: (a) Comparison of measured and predicted strains. (b) Estimation of core damage size from residual strain distribution.

4 LOW-VELOCITY IMPACT DAMAGE DETECTION TEST

4.1 Test configuration

To demonstrate the monitoring ability of the system under conditions closer to real life applications, low-velocity impact tests were conducted using a large scale sandwich panel as depicted in Figure 7. An optical fiber sensor was embedded between the core and face sheet to form a network where the spacing between adjacent parallel fibers was 20 mm. The panel edges were clamped to a test support and impact tests were conducted at the taper and mid regions of the panel. A 12.5 mm diameter hemispherical impactor was used with small impact energies so that the resulted damage in the faces was barely visible.

4.2 Impact test results

Figure 8 shows strain distributions measured at the taper and mid regions after multiple consecutive impact events. In the mid region, 8.2 J impact energy caused a clearly visible damage in the face-sheet, and therefore only lower impact energy events are considered. Even with the lowest used impact energies, a clear tensile peak is observed at the impact location in the strain distribution data. Also in the current case, the previous impact damages remain detectable even after multiple impacts. Maximum strains are lower in the taper region where the face sheet is thicker and the core thinner than in the mid region. This however did not affect the detectability of the impact damages at the used impact energy levels.

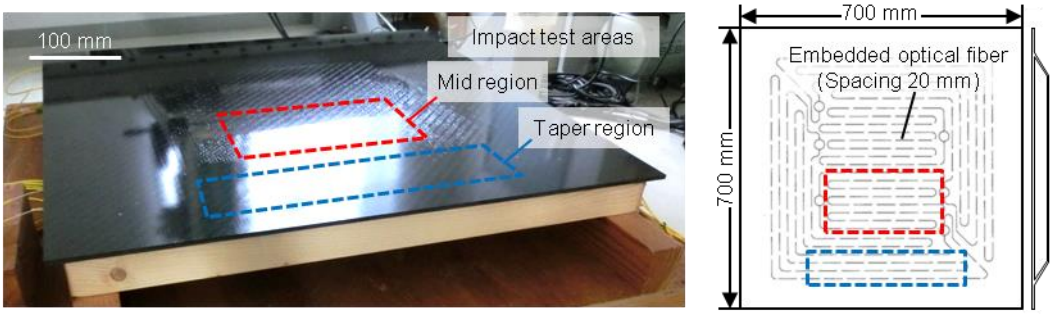

Figure 7: Sandwich panel specimen used in low-velocity impact tests.

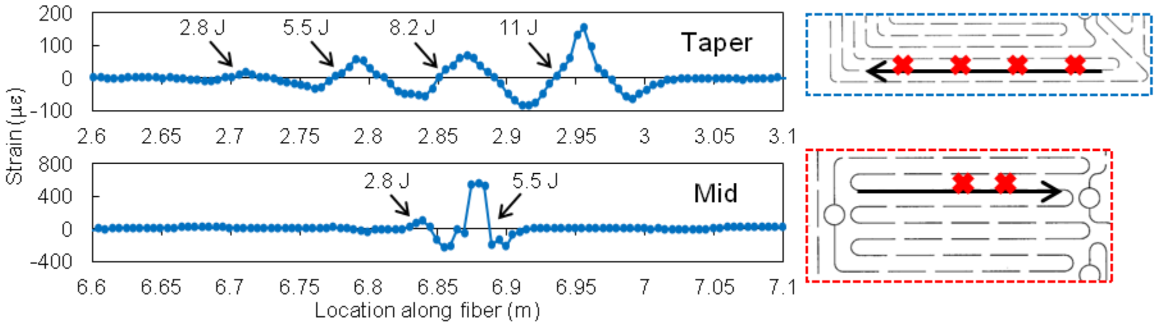

Figure 8: Measured strain data at taper and mid region after multiple low-velocity impact events.

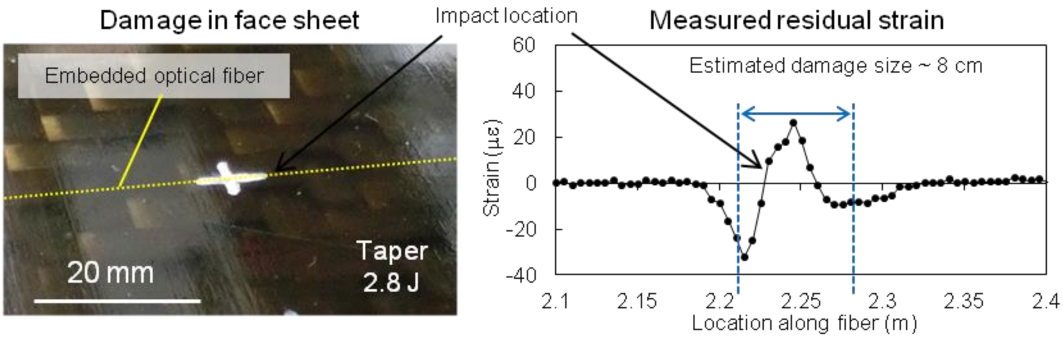

Figure 9: Damage in the face sheet compared with the measured strain distribution.

The measured strain distribution along a fiber near a low energy impact location is compared with the visible damage in the face sheet in Figure 9. It can be seen that the deformation in the face sheet is barely visible to the naked eye, while the strain data shows a clear indication of impact damage. The location and size can now be estimated rather easily from the strain data by using the principles explained in previous chapters.

CONCLUSION

Strain monitoring and indentation/impact damage detection in foam core sandwich structures using distributed fiber-optic sensors was studied experimentally and numerically. Indentation loading tests with sandwich beam and panel specimens showed that the monitoring system could measure the strain distribution in the interface with very high spatial resolution and allowed observation of the strain formation throughout the whole indentation event. Detectability of the damage with regards to the location of the indentation or impact loading and density of the optical fiber sensor network were also discussed for the sandwich panel specimens.

With the used monitoring system, damage in the sandwich specimens was easily located by the high strain peak at the indentation or impact location. The size of the damaged core area could also be estimated by utilizing information from the finite element analysis considering the correlation between damaged area in the core and residual strain distribution. Even for low-velocity impact induced damage in foam-core sandwich panel with only barely visible dent remaining in the face sheet the location and size of the damage can be estimated rather well from the measured strain distribution data.

The experiments and numerical analysis thus showed how the used system can accurately measure the strain distribution in the sandwich structures at various environmental conditions and detect changes in residual strains that can be used to estimate the location and size of even barely visible damage

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