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Strain Localization During Crack Propagation at the Interface of Dissimilar Materials

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Abstract

Interface failure in a sandwich component is analyzed in detail by using the digital image correlation method. Virtual strain gages are emulated at the interface and beneath it, in the material of the core. The moment of damage initiation and its evolution are analyzed by measuring the local opening strains with the ARAMIS system in the monitored points. Strains at the initiation and finalization of the damage can be measured. The opening of the interface crack at propagation can be also established. Depending on the relative distance from the tip of the initial delamination, strain localization shows different patterns and is carefully monitored.

Key words: *sandwich composite, strain localization, digital image correlation, crack propagation*

Interface crack – presentation of the problem

A sandwich structure is a three-layer structure comprising a low density and low modulus core material between two high modulus face sheets. The core mainly acts as a spacer keeping the face sheets spaced apart and has a thickness 2–10 times the face sheet thickness. This arrangement provides a structure with a high bending stiffness. The problem of mode mixity of an interface crack in a sandwich is discussed by Østergaard and Sørensen in [1]. For sandwich structures, debonds (areas between the face sheet and core with no adhesion) constitute an important damage type that can lead to *debonding crack growth*, i.e. crack growth in the interface between face sheets and core. Interface cracking is generally mixed mode cracking, i.e. both normal and shear stresses develop just ahead of the crack tip. Several criteria for interface fracture were examined and compared to test results obtained from glass/epoxy specimens by Banks-Sills and Ashkenazi [2]. These include two energy release rate criteria, a critical hoop stress criterion and a critical shear stress criterion. Experimental data are compared to these criteria formulated on linear elastic bases. The problem is that in many situations phenomena are nonlinear and most analytical formulations cannot be valid anymore. Högberg [3] proposes a traction-separation relation to model the fracture interlaminar process. The cohesive law captures the linear elastic and softening behaviour prior to fracture. It also allows for different fracture parameters, such as fracture energy, strength and critical separation in different mode mixities. Thus, the fracture process in mode I (peel), in mode II (shear) or in mixed mode (a combination of peel and shear) can be modelled without the limitation of a common fracture energy in peel and shear.

The purpose of this research is to characterize damage and delamination in sandwich specimens, to observe the interlaminar damages and failures, and to try to understand most of the local processes. We continue the using of digital image correlation (DIC) for establishing the three-dimensional displacements of the tested composites and for monitoring the crack propagation [4,5]. This time we concentrate on the problem of strain localization in the interface and beneath it, in the material of the core.

Description of the tested sandwich composite

Present work continues a previous discussion on the issue of interface failure in a sandwich component with a glass fiber mat face sheet and a rigid polyurethane core. Digital image correlation is used in monitoring the evolution of failure from an initial interface crack by using two rows of virtually emulated strain gages of about 1.4 mm at the interface and beneath the interface. Their number for each test depends on the way in which the crack propagated. In this way many information on strain evolution and localization are acquired.

The tested sandwich composite has skins made from mat with a density of 300 g/m^2 and a core with density of 200 kg/m^3. The skins and the core are glued together by a bicomponent polyurethane adhesive. Tractions testing of both skin and core are done on a LLOYD LRX PLUS testing machine with the NEXYGEN software at a speed of loading of 3 mm/min. An extensometer Epsilon with a gage of 50 mm was also used to measure strains. On the other hand digital image correlation (DIC) with the ARAMIS 2M system were used to monitor strains on the tested specimens. A calibre of 25 x 38 mm was used. One frame per second was acquired.

For the face sheets specimens of about 20 mm width and 1.5 mm thickness were tested. Five tests were done and each time, in order to calculate also Poisson's ratio, two virtual strain gages of 15 mm were emulated in the middle of the specimen: one longitudinal and the other transversal. For further calculations we considered, in average, maximum (ultimate) strength as 106 MPa, elongation at failure of 1.33 %, longitudinal (Young's) modulus as 9000 MPa, and Poisson's ratio as 0.33.

Same procedure as before was used for the tensile testing of the polyurethane core with a density of 200 kg/m^3. The response of the material is nonlinear and more ductile after a stress of 3.5 MPa is reached, and failure is produced around 5.9 MPa. The level of strains is quite low, and no specific indication is noticed before breaking. In average, maximum (ultimate) strength is 5.96 MPa, elongation at failure of 12.13 %, longitudinal (Young's) modulus as 172.1 MPa, and Poisson's ratio as 0.37.

Evaluation of interface failure

The testing of the sandwich specimen in mode I is done in order to establish the opening strain at the initiation of the degradation and the evolution of the opening strain during crack propagation (Fig.1). Six specimens were tested till their final failure.

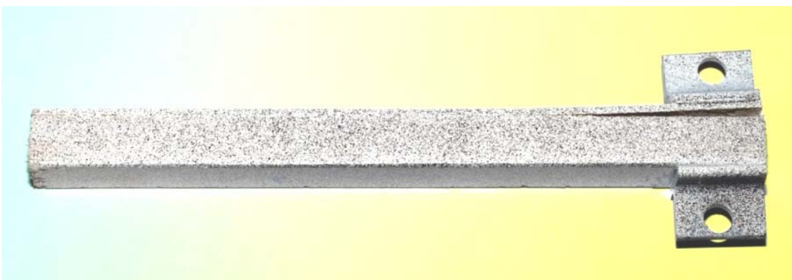


Fig. 1. Sandwich composite specimen prepared for testing

The force-displacement curves for each test are shown in figure 2. In test no. 4 only one unstable crack propagation occurred

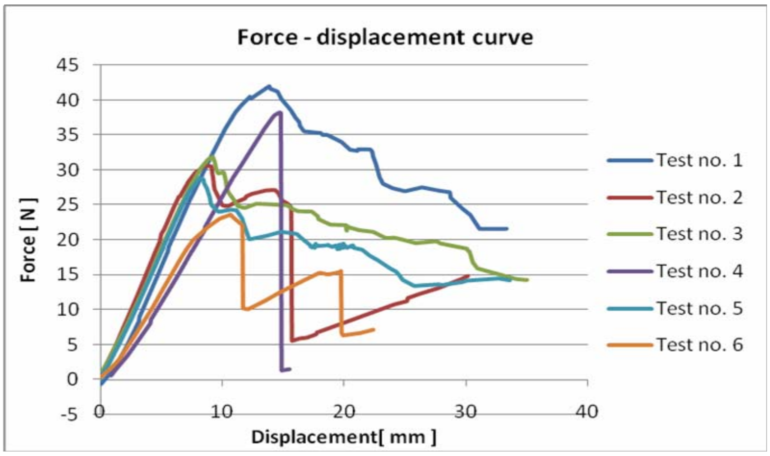


Fig. 2. Force-displacement curves till the failure of the sandwich specimens

Speed of loading is also 3 mm/min, and the same calibre 25 x 38 mm is used. Due to the asymmetric position of the interface crack in the specimen (only one interface has an initial delamination) the specimens have also a rotation while the test is completed. In some tests the crack propagated with a pop-in for longer distances. If the interface crack propagates too much it may get out the monitored field by the ARAMIS system which is about the same size as the used calibre. Therefore not for all tests we obtained the same amount of data.

Experimental analysis reveal that the force-displacement response of the material, before damage initiation, is linear elastic, and in most cases interlaminar stable crack growth is observed after reaching the critical parameters. Critical parameters that are describing the initiation of stable crack growth are influenced by the geometry of the sample and of the initial delamination. It looks like the integrity of the interface zone at the initial crack tip influences the maximum force value. During the experimental analysis the crack always propagated only on the interface region and no direction changes in the core of the material were noticed.

Several unstable crack growths were recorded throughout the experimental analysis, probably due to interfacial imperfections. The values of the maximum force and displacement at failure obtained for each tested sample are presented in table 1 and figure 3.

Table 1. Maximum values of force and displacement at the failure of the specimens

Test no.	**Force** [N]	**Displacement** [mm]	**Test no.**	**Force** [N]	**Displacement** [mm]
1	42.041	13.904	4	38.191	14.744
2	30.569	8.7224	5	28.841	8.1578
3	31.857	9.1333	6	23.58	10.695

For tests 1, 2, 3 and 5 crack propagation is stable, and for tests 4 and 6 stable crack growth before and after the unstable crack propagation is recorded. It can be seen that there are three tests having a similar pattern, as being tests 2, 3 and 5, all of the three force-displacement curves having the same slope for the linear response zone, and about the same maximum force. The differences between the maximum force-displacement values obtained during the tests are caused, most probably, by initial delamination length difference.

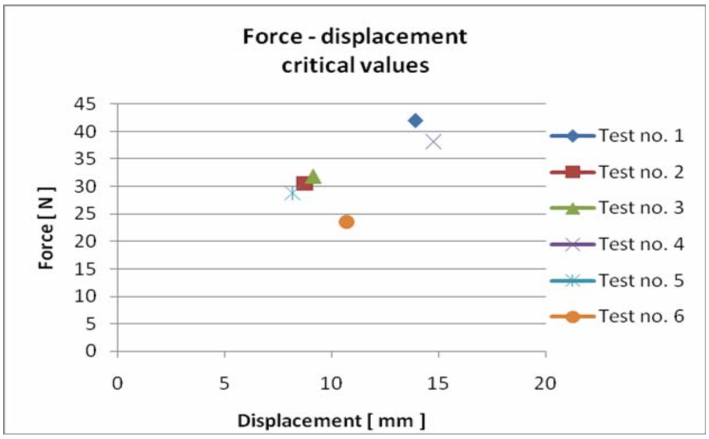


Fig. 3. Maximum values of forces and displacements at failure of sandwich specimens

During test no. 1 a force-displacement curve having the same slope was recorded, but failure occurred at a much greater value of the force. Despite this, the damage initialization and finalization parameters are in good agreement with the average ones, which suggests that the interface adhesive was of better quality. Test no. 4 also has the same slope for the force-displacement curve but failure occurs at a lower value of the force. This is caused by the initial delamination length (53.4 mm instead of 45 mm). Unstable propagation occurs during the test. Damage stage completes at a value of 18.46%, which is much smaller than the average values for other tests. On the other hand, for test no. 6 records a similar response to test no. 4 regarding the linear response was recorded. After reaching the critical point the crack starts to develop steadily, but soon after two successive unstable crack propagation are recorded.

The initial and final parameters of damage are given by the opening strain and relative displacement of the crack flanks – crack opening; these are measured with the locally emulated strain gage and directly with the ARAMIS system. It was tried to keep a distance of about 5 mm in between two consecutive monitored points. This was not always possible as we were interested to establish exactly the position on the specimen in which damage was finalized, that is there was no material in that location. The last analyzed point for each test was chosen as close as possible to the crack position at the end of the analysis.

The moment of damage initiation was chosen as the one at which we obtain the maximum tensile strain in the core of the sandwich, measured with virtual strain gage *S*. After attaining this maximum the material of the core relaxes, and the damage is considered as finalized. Meanwhile we measure significant local strains at the interface and failure is produced by the crack propagation. When strain in core diminishes the tip of the crack moves beyond the monitored point.

In figure 4 is presented the typical variation of strains in the interface in a monitored point which is initially further away from the tip of the initial delamination. There are four distinctive domains of strain variations which are obtained:

- *domain I* in which the interface and the core are in compression due to the loading of the specimen; meanwhile the crack propagates in a stable manner towards the monitored point;
- *domain II* in which both interface and core are loaded in tension; the tip of the crack reaches the monitored point;
- *domain III* while damage is produced with increasing strains in the interface and relaxation of strains in the core;
- *domain IV* registers the strains in the material of the core; meanwhile the crack exceeds the point of measurement and, although strains in interface still increase there is no physical significance for such a trend as there is no material left at the interface.

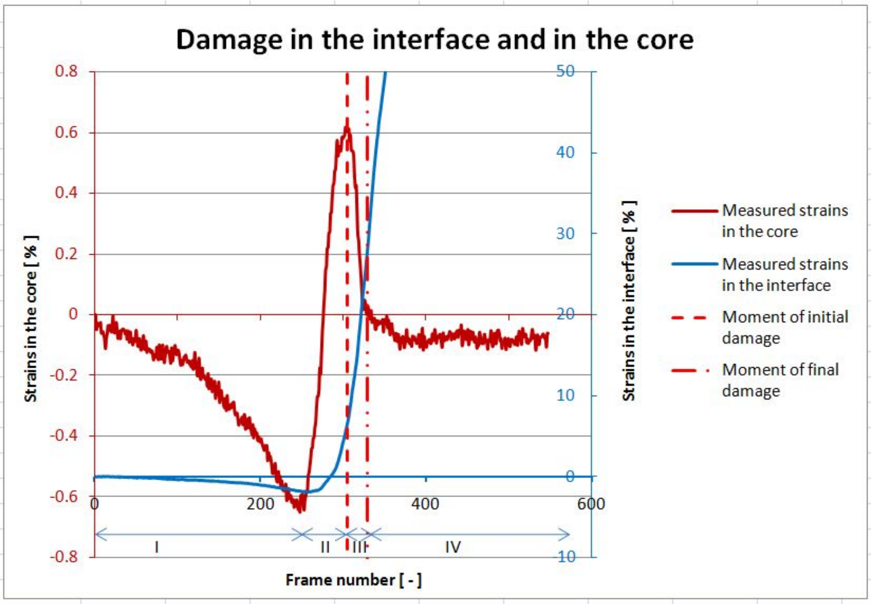


Fig. 4. Variation of strains at the interface and in the core in a monitored point while damage is produced

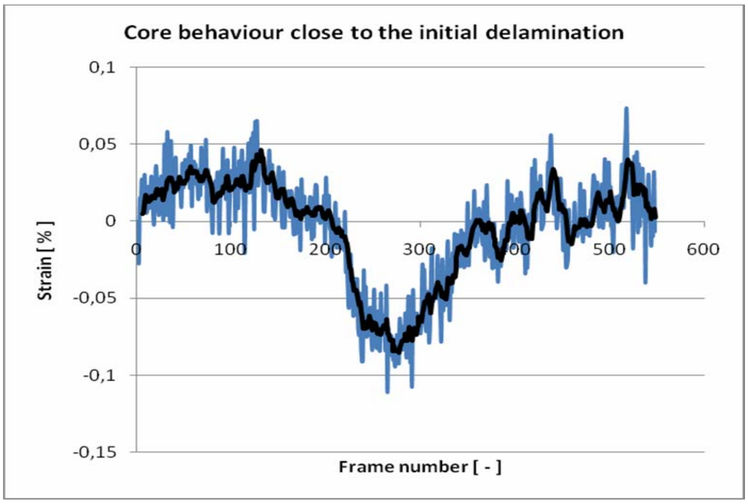
After the initiation of damage in the interface the material around the tip of the crack (core) relaxes and strains diminish; meanwhile strains in interface increase significantly. The final (complete) damage of the interface zone is attained when the material of the core relaxes completely and strains remain mostly constant, as seen in figure 9 (domain IV). All presented results were reported by Miron in [6].

Three distinct strain responses can be identified by analyzing the strain evolution that occurs in the core of the sandwich material, close to the interface region.

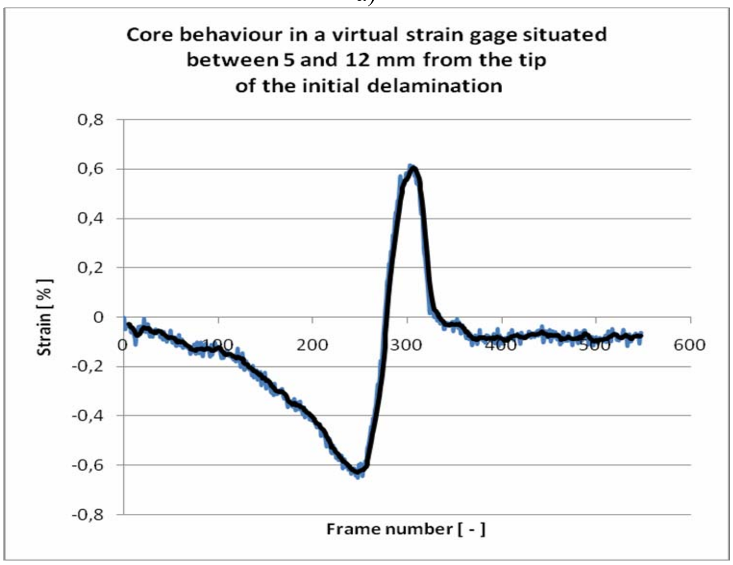
Figure 5 a) shows the evolution of the strain recorded in the core, at the position of the initial crack tip. Local traction strains are recorded for the first part of the experiment, followed by a relaxation zone. The strains that are recorded in the core, at the initial crack tip position are relatively small causing a high amount of noise in the results obtained using DIC method. The resolution of the ARAMIS 2M system is in the vicinity of strain 0.05 % level obtained for this monitored position (measuring range is from 0.01 % and the strain accuracy is up to 0.01 %).

The main solution to avoid noise obtained during analysis is to use a smaller sized calibre but this will also reduce the size of the analyzed area; such a decision is not desirable because of the rigid body motion the tested specimen suffers during the experiment which will affect the results. In the same time, a smaller area of analysis allows the study of a smaller interface length, and in the case of unstable crack propagation growth the crack tip will leave the area of analysis.

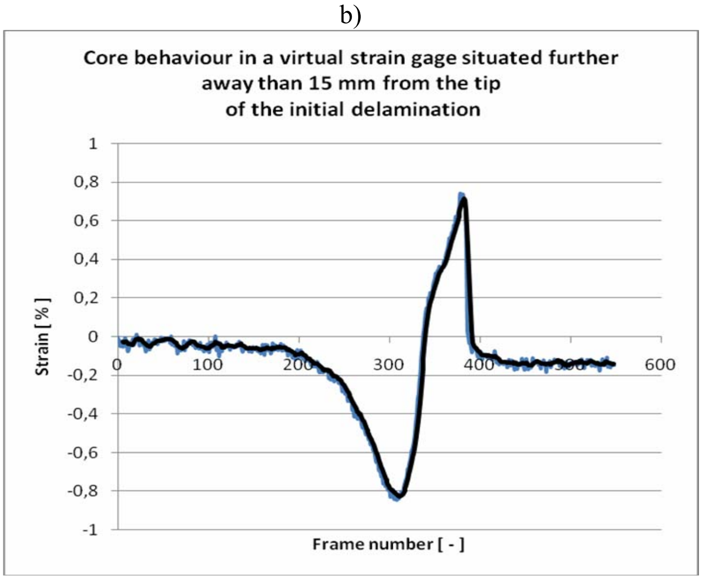
A second type of core behaviour is noted as being typical for measuring points positioned between 5 and 12 mm from the crack tip, represented graphically in figure 5 b). First, the core close to the interface layer suffers a local compression which lasts until the crack tip advances to its vicinity. The local compression stage is followed by a local tensile strain that will last until the interface damage initialization. The moment of interface damage initialization is marked by the maximum value of the strain recorded in the core. During damage development the core gradually relaxes marking the end of the damage process. The complete failure of the interface corresponds to the end of the relaxation in the core.



a)



b)



c)

Fig. 5. Strain evolution in the core at different distances from the initial delamination: a) strains at the initial delamination; b) strains in between 5 to 12 mm from the crack tip; c) strains at distances greater than 15 mm from the crack tip.

The third type of strain localization is similar to that described above, the only difference consists in the presence, at the beginning of the test, of a zone in which no loading of the core is recorded (Fig. 5 c)). This is because the measuring point is located far enough from the initial crack tip. As the crack steadily propagates towards the measuring position, the material behaves similar to the previous description. This type of behaviour was found for all the measuring points placed at a distance greater than 15 mm from the initial crack tip.

In order to take a decision which of the determined properties will be taken into consideration for establishing the average interface parameters, the experimental results were statistically analyzed. Figure 6 shows the frequency of occurrence of a certain strain at the interlaminar damage initiation moment, and figure 7 shows the frequency of occurrence of crack opening at the time of damage completion.

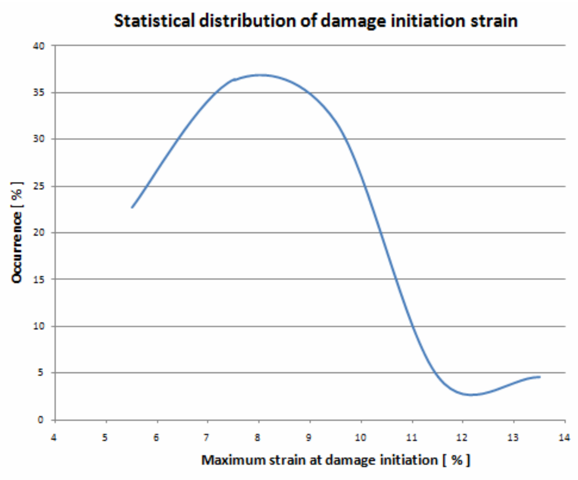


Fig. 6. Occurrence of maximum strain at damage initiation

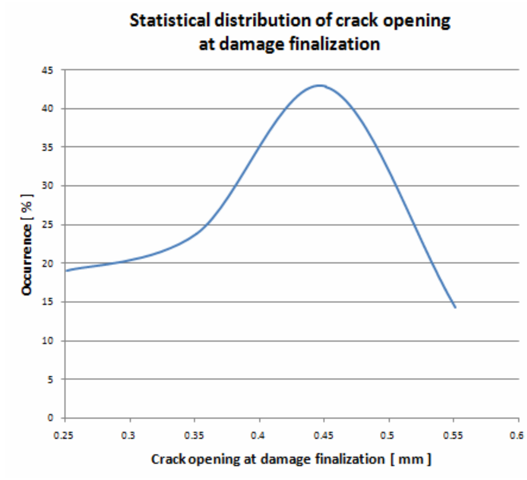


Fig. 7. Occurrence of crack opening at damage finalization

For the damage initiation parameters only the maximum strains ranging between 5 and 10.5% were averaged, and for the damage completion crack openings ranging between 0.3 and 0.5 mm were taken into account. The results are presented in table 2.

Table 2. Properties of the interface

Strain at damage initiation	[%]	7.4568	7.46
Crack opening at damage finalization	[mm]	0.419143	0.42

If several measuring points are able to register the progress of stable crack growth – as in test no. 1 – we can represent the successive strains variation in the material of the core, very close to the interface. Figure 8 shows that maximum strain in the core is obtained at about 15 mm from the tip of the initial delamination, in measuring point 4. Then, it slightly decreases within a distance of about 10 mm, meanwhile the delamination propagating slowly. When unstable crack propagation occurs the shape of the strains variation in the core is the same but, as there are less measuring points, we cannot record a complete distribution in front of the stably propagating crack.

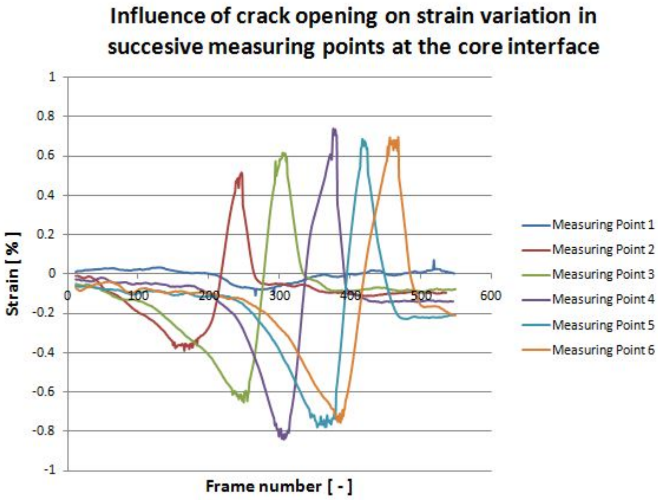


Fig. 8. Strain variation in successive measuring point at interface failure

Conclusions

Interface failure in a sandwich component is analyzed in detail by using the digital image correlation method. Virtual strain gages are emulated at the interface and beneath it, in the material of the core. The moment of damage initiation and its evolution are monitored by measuring the local opening strain with the ARAMIS system both at the interface and beneath it, in the material of the core. Several monitored points assess crack propagation and the response of the interface. Variation of strains in the core at the initiation of the damage and when damage is finalized can be measured. Crack opening can be also measured when there is not left any interface adhesive, that is failure is completed.

Strain localization in front of the initial delamination shows different patterns, as illustrated in figure 5, depending on the relative distance from the tip. When comparing figures 5 c) to 5 b) the compression strains in the core disappear, as we are further away from the delamination tip. However, the maximum positive strains are about the same, as 0.6-0.7 %, showing an imminent delamination failure. In fact figure 8 confirms this observation, and as delamination propagates in a stable manner the strain reaches a maximum value in the core of about 0.7 % in three successive points in the moment of damage initiation.

There are four distinctive domains of opening strain variations at the interface that clearly put into evidence the moments of initialization and finalization of damage.

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Localizarea deformatiilor specifice in timpul propagarii unei fisuri de interfata dintre materiale diferite

Rezumat

Cedarea interfetei dintr-un compozit sandwich este analizata in detaliu folosind metoda corelarii digitale a imaginii. Traductoare tensometrice virtuale au fost emulate la interfata si in apropierea acesteia, in materialul miezului. Momentul deteriorarii initiale si propagarea delaminarii sunt analizate cu ajutorul sistemului ARAMIS in puctele de monitorizare alese. Se poate masura valoarea deformatiilor specifice la initierea deteriorarii si cand aceasta este finalizata. Deschiderea fisurii de interfata la propagare poate fi deasemenea stabilita. In functie de distanta relativa fata de varfului delaminarilor, localizarea deformatiilor specifice arata moduri diferite de variatie si este urmarita cu atentie.