Experimental Study on Fatigue Failure Evolution
in Composite Plate Monitored by Wave Propagation Method

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Abstract

In this study, the elastic wave propagation method is used to observe the initiation and evolution of the fatigue failure form in the multilayered composite plate with an elliptical hole. The experimental tests with the use of active, pitch-catch elastic wave measurement techniques are used during the fatigue test of the composite specimens. The fatigue tests were preceded by the numerical, finite element analysis of the elastic wave propagation phenomenon in a composite plate with an elliptical hole. The sequential measurement related to the number of cycles during the fatigue tests was assumed. The time of flight (ToF) and amplitude change was monitored by piezoelectric sensors localized in the area of predictable failure form evolution. The analysis of the dynamic response of the structure under fatigue loading conditions by a relatively small number of piezoelectric transduces allows us to build cost-effective Structural Health Monitoring (SHM) system for damage detection and monitoring of the failure form evolution.

Keywords: fatigue failure, wave propagation, composite plate, elliptical hole

1. Introduction

In recent years the technological progress contributed to profound changes in the design process of the engineering structures. The development of the materials engineering and modern production processes caused that composite structures, especially laminates, which are widely used as an alternative for typical materials. The reliability of the composite elements mostly depends on the effectiveness of the monitoring methods. Observation of the structures under fatigue loading is significant from the durability point of view. The accurate estimation of the fatigue strength for structures made of composite materials is difficult. The Structural Health Monitoring (SHM) systems were developed and applied in engineering structures for permanent monitoring of the state of the constructions.

The majority of the present active SHM systems based on the guided wave propagation phenomenon describe the changes in the temporal signal features in the time domain with respect to the baseline signal [1]. Different techniques of the wave propagation measurement and data analysis were developed and verified in real structures [2-6]. Most of them deal with the plate-like structures with an embedded piezoelectric sensor network [7, 8]. Each of the damage detection systems has to be validated during the experimental tests simulating the fatigue damage evolution before application in the normal service life of the constructions.

The fatigue behavior of composite structures was described in detail by Harris [9]. Sims [10] characterized the fatigue test methods and experimental requirements emphasizing the necessity of continuous monitoring of the composites degradation. The comparison of the non-destructive testing (NDT) methods was also presented by Kuhn et al. [11]. The problem of the fatigue failure initiating from a hole is well known and commonly observed in engineered structures [12, 23]. The classic form of the fatigue crack evolution was observed also in the composite woven structures with circular [14] and elliptical hole [15]. However, the failure form evolution is much more complicated in the laminates made of unidirectional (UD) reinforcement. The evolution of the damage in the multilayered structures made of UD prepreg system based on carbon fibers was observed by Nixon-Pearson et al. [16]. The matrix splitting in the 45° plies, propagating from the hole edge was observed with accompanied local delaminations at adjacent interfaces. The coupling between different failure modes takes a different form depending on the stacking sequence configuration and shape of the hole. Prediction of the damage initiation and evolution is complicated thus the necessity of developing fast and reliable procedures for assessing the safety of composites in a wide range of high-performance applications is still observed in scientific research. One of the most effective damage detection methods used in composite structures is the active wave propagation method. Even that the analysis of the wave propagation near the holes is complicated because of the reflections from the boundaries [17] there are techniques for monitoring the state of the hole edge during the fatigue tests [19-20]. Moreover, the prognosis of fatigue life with the use of the wave propagation method is also possible and verified in experimental testes [21].

It is wort to point out that most of the currently used damage detection methods are focused on passive measurement techniques. Thus, the purpose of this paper is the experimental validation of the system based on the active wave propagation method. Prediction of the failure forms coupling in the laminate based on the unidirectional fiber reinforcement is complicated. The failure form initiation depends on the curvature of the hole in the area of stress concentration. The problem of damage evolution in multilayered structures made of unidirectional plies with different curvature of stress concentrators with permanent monitoring of the defects was not considered earlier. To observe this effect the elliptical shape of the hole was taken into account. The multipoint measuring system based on PZT elements was used during the fatigue tests of the composite plates. In most active SHM systems the number of transducers determines the cost and effectiveness of the SHM system. Thus, the localization of the small number of sensors was firstly analyzed with the use of finite element analysis simulating wave propagation in considered structure. The observation of the failure form evolution in the experimental test was carried out by sequential measurements of the wave propagation between an actuator and sensors.

2. Material and methods

Composite plates with an elliptical shaped hole in the middle were considered. The important dimensions of the specimen with the schematically marked grips for the fatigue tests and load direction were demonstrated in Figure 1a. Figure 1b demonstrates the localization of the piezoelectric actuator and sensors.
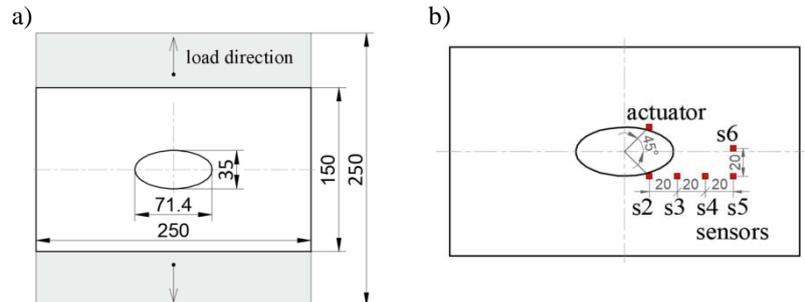
Figure 1. a) The composite plate with an elliptical hole with marked grips
and load direction, b) configuration of the actuator and sensors.

The laminates were made of 8 layers - epoxy/glass prepreg (TVR 380 M12/26%/R-glass) having the following properties: $E_1 = 47.12$ [GPa], $E_2 = 14.61$ [GPa], $v_{12} = 0.09$, $v_{21} = 0.28$, $G_{12} = 16.03$ [GPa]. The material properties were determined in the uniaxial tension tests with the use of ASTM D 638 standard. The standard specimens (Type I) were mechanically cut off from the plates. The transverse strain was measured by electric resistance wire strain gauges. Laminates were cured in the autoclave at 135 °C for 120 min and 0,8 bar of the partial vacuum. During the autoclave process, the specimens were additionally loaded by external pressure equal to 4,5 bar. The accurately controlled production process of the laminated plates with the use of autoclave allows obtaining high quality structural components with a high volume fraction of fibers. The symmetrical composite stacking sequence was considered $-[\pm 45, \pm 45]_s$. The total thickness of the plates was equal to 2 mm. The fatigue test was conducted using hydraulic tension machine MTS 793A. The tensile loading condition was carried out. The mean loading force value equal to 38 [kN] was achieved during the quasi static tension of the plates. Then the fatigue tests were conducted with an amplitude equal to ±4 [kN] and frequency 30 [Hz]. The fatigue loading conditions were the same for both tested specimens. Figure 2 demonstrates the exemplary failure form evolution during the fatigue tests of the considered plates. The current number of cycles is presented in each picture. The direction of the matrix splitting propagating from the hole was roughly tangential to the hole boundary.

a)   b)
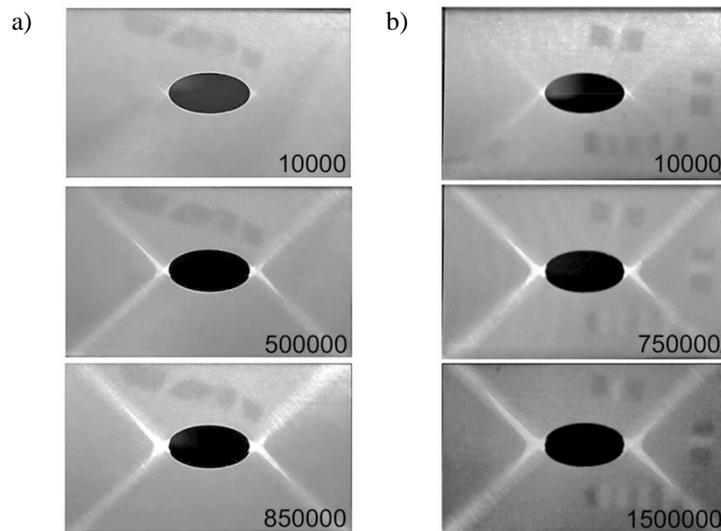
Figure 2. The failure form of the composite plates with a total number of cycles in the fatigue test equal to a) 850000 and b) 1500000.

The progressive evolution of the damage during the fatigue loading conditions finally resulted in the evolution of the global failure form. The effect of the failure form initiation and evolution was observed by the wave propagation system containing the PZT transducers in the active wave propagation method. The active pitch-catch measurement technique was used with the use of surface-mounted piezoelectric transducers (Noliac CMAP06). One of the PZT elements was an actuator that excites the five cycles of the Hanning windowed tone burst excitation signal with the 100 [kHz] frequency (Figure 1). The multipoint measuring system allows to assess the state of the whole structure including the fact that damage evolution may not be symmetrical according to the applied loading conditions and may be concentrated or more dissipated depend on the curvature of the hole. The sequential measurements of the wave propagation with the interval equal 5000 or 10000 cycles were carried out without interruptions in the fatigue loading. To estimate the state of the structure, the time of flight (ToF) of the elastic wave was calculated. ToF parameter was defined as the time between the wave generated by an actuator and wave detected by the sensors. The fatigue defects of the plate cause the disturbance of the elastic wave and influence on the ToF parameter. The time lag between ToF measured at the beginning of the test (ToF$_0$) and measured during the fatigue test (ToF$_N$) was used for monitoring the state of the structure. During the fatigue tests of the plates with the elliptical holes the amplitude of the wave was also monitored. Both parameters were compared with the plates without damage at the beginning of the fatigue tests.

3. The elastic wave propagation results

The numerical model of the elastic wave propagation phenomenon in the analyzed composite plate was prepared with the use of the finite element method applied in Ansys package. The higher-order shell elements having six degrees of freedom per node were used in the analysis. The numerical simulation was carried out for an intact structure to observe the wave propagation in the case of a structure with an elliptical hole. The actuator was modeled as a point force in the same form as used in the experimental test. The output signal was registered as out of plane displacement component. The wave propagation phenomenon in the particular time steps was demonstrated in Figure 3. The three measuring points were defined (N1, N2, and N3) to observe the elastic wave behavior after propagation near the hole. The time of analysis has been carefully selected to ensure the propagation in the analyzed region and to avoid the influence of the reflections from boundaries on the wave propagation results.
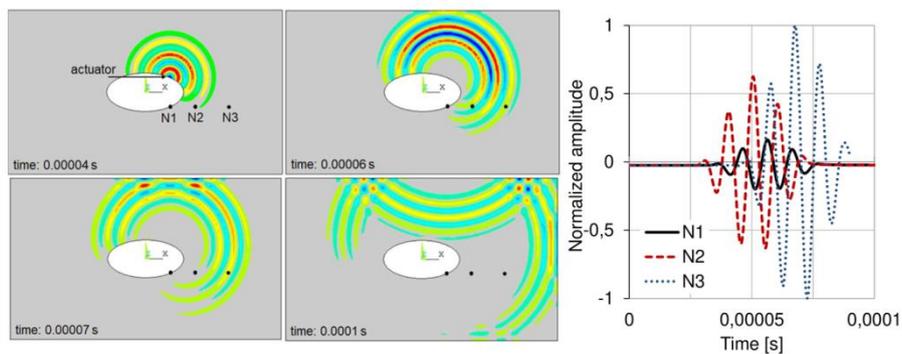
Figure 3. The numerical results of the wave propagation in the composite plate.

The influence of the hole curvature to the elastic wave amplitude can be easily noticed. Even though the measuring points N1 and N2 were closer to the actuator, the curvature of the hole caused a substantial amplitude reduction than for N3 measuring points. The separation of the elastic wave of the hole edge can also be observed which may influence on the effectiveness of the wave propagation method when the sensors are localized near the curvature of the hole.

Based on the numerical results, fatigue tests of the two plates with the horizontal elliptical hole were considered with the use of five piezoelectric sensors localized in the area of hole edge and expected failure form evolution. The fatigue test of the first plate was stopped after 850000 cycles. In the second case, the 1.5 million cycles of the fatigue load were observed. None of the analyzed plates achieved final damage. Figure 4 demonstrates the amplitude measurement (A_N) related to the amplitude of the normalized elastic wave at the beginning of the tests (A_0). The amplitude measured by sensor s2 indicates the problems with the detection of the elastic wave on the opposite side of the elliptical hole what was also visible in the numerical results. The specific shape of the hole caused the difficulties associated with the separation of the elastic wave fronts from

the edge of the hole. Moreover, this effect was strengthened by the initiation of fatigue damage. As it may be observed in Figure 4 the measurement of the amplitude reduction caused by the evolution of the damage during the fatigue tests was observed by all other sensors. In most cases, the first stage of the fatigue test was connected with the dynamic decrease of the amplitude. In the second part of the test, the stabilization of the amplitude reduction was visible. Such a behavior corresponds to the typical stiffness degradation of the composite structures.
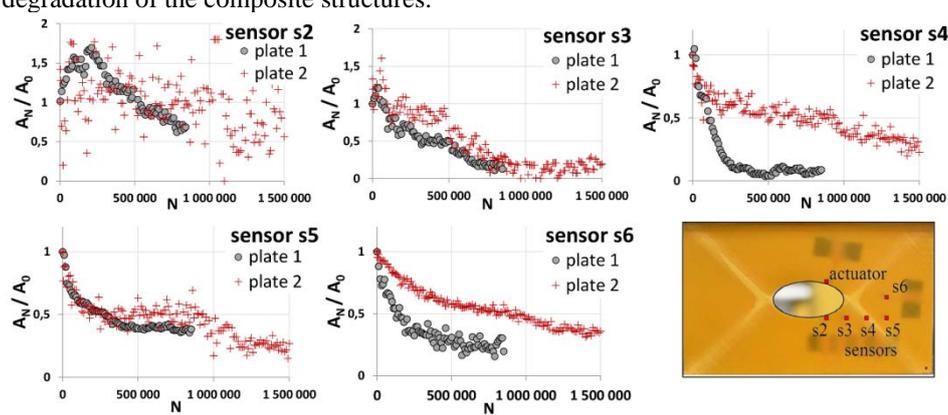
Figure 4. The results of the amplitude measurement for sensors s2-s6.

The visible differences between considered plates were observed by sensor s4. It should be noticed that this sensor was placed directly on the edge of the fatigue damage. The stochastic character of the real damage evolution resulted in significant amplitude reduction.

Figure 5 presents the time of flight measurement related to the ToF parameter at the beginning of the tests. The effect of the ToF increase during fatigue tests can be noticed. The good agreement of the ToF measurement in both analyzed plates was achieved. The exception is the measurement done by sensor s4.
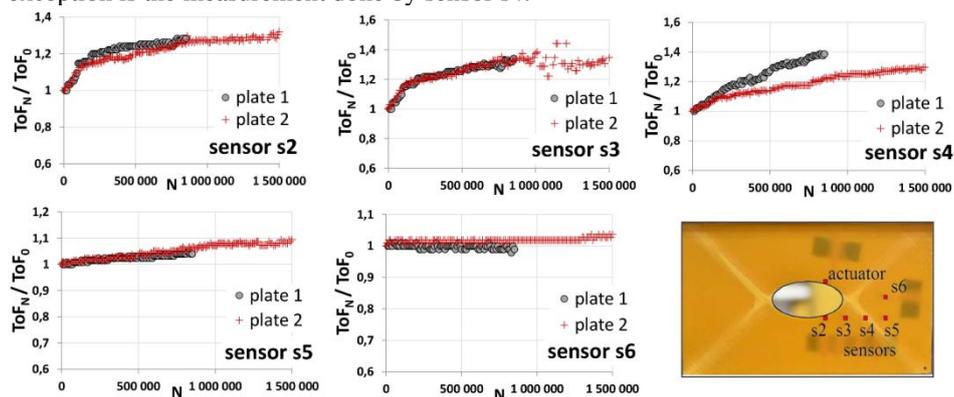
Figure 5. The results of the time of flight measurement for sensors s2-s6.

What is interesting the increase of the ToF parameters for sensors s5 and s6 was lower than for sensors s2 or s3. It may be caused by the mutual position of the actuator and particular sensors, the level of the damage evolution, or the deformation of the plate during the fatigue test. Nevertheless, the presented results proved that the wave propagation method can be an efficient tool for damage detection and monitoring of the failure form evolution in the composite structures.

4. Conclusions

In the paper, the system containing the active wave propagation analysis was applied to monitor the damage growth in the composite plates with an elliptical hole during the fatigue tests. The wave propagation method is often applied in thin structures but the limitations associated with the reflections of the propagating wave from the boundary of the structures or stiffeners complicate the interpretation of the detected signals. However, careful selection of the analysis time, localization of the sensors, and application of the straightforward signal parameters allow building relatively low-cost damage detection system which makes possible also the monitoring of the failure form evolution. The failure modes and forms of the laminates based on unidirectional reinforced plies depend on the stacking sequence and curvature of the stress concentrators. The visible influence of the elliptical hole shape on the elastic wave propagation behavior was observed. The different stages of stiffness degradation were observed during the fatigue tests. The concentration of the damage near the edge hole but at some distance from the cutout edge indicates the relation between unidirectional plies orientation and curvature of the hole in the stress concentration area. This effect may be crucial from the durability point of view and will be deeply analyzed in future research. Damage evolution connected with the matrix splitting and delaminations growing were effectively monitored by the proposed system with the use of relatively easy to observed parameters.

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