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RESEARCH NOTE

Cluster Analysis of Acoustic Emission Signals for Carbon/Epoxy Composite in Four-Point Bending Test

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ABSTRACT

Due to the extensive use of composites in various industries, and the fact that defects reduce ultimate strength and efficiency during operation, detection of failures in composite parts is very important. The aim of this paper is to use Acoustic Emission (AE) non-destructive method in four-point bending test of carbon/epoxy composite to analyze and examine the failure mechanisms. This method is based on waves activated from defects in structures which are built during loading. Sensors collect acoustic signals which created by the separated layers. Each stage of failure is in specific frequency range and indicates a specific mechanism. Clustering of these signals is done with C-means and K-means algorithms then compared with the results of previous works. The failure process was shown to proceed through four stages. In both algorithms, each cluster coincides with one part of these stages.

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1. INTRODUCTION

Composites are used in many industries today to enable high-performance products at economic costs. These industries range from space to sports and include manufactured products for aircraft, transportation, energy, construction, sports, marine, and medical applications [1, 2]. Most of the requirements in industry, for instance in aerospace, cannot be satisfied with ordinary materials and need to widely change mechanical properties of materials. In these industries, light materials with high strength, erosion and impact resistance are needed.

This fact is accepted that composites like other engineering materials have defects, such as crack, delamination, fiber failure and vacancy. Thus, inspection and identification of these defects are important. Many researches have worked on flaws in structure of composites and their influence on their properties and proceeds [3-7].

Non-destructive testing (NDT) methods can identify defects without damaging the part. Since the failure mechanisms of composites are not so well known compared with metals, usually after detecting defects with NDT, it is difficult. Some of the latest NDT techniques are thermography, AE and acousto-ultrasonic [8, 9].

NDT is multi-faceted and diversified. Most of these methods allow no real-time control of structural damage evolution, in contrast to AE [10]. AE refers to the generation of transient elastic or stress waves during the rapid release of energy from localized sources within a material. The source of these emissions in metals is closely related to the dislocation movement accompanying plastic deformation and the initiation and extension of cracks in a structure under stress [11]. AE has also been done to monitor composites in bending [12, 13].

Carbon fiber-reinforced epoxy composites exhibit high specific strength, high specific stiffness and good fatigue tolerance, which have led to numerous advanced applications ranging from military and civil aircraft structures to recreational consumer products [14, 15].

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Many researches have been done on carbon/epoxy to access mechanical and physical properties and mechanisms of failure [16]. Arumugam et al. [17] predicted the residual strength of post impacted carbon/epoxy composite laminates using an online AE monitoring. Liu et al. [18] adopted the AE technique to study the failure mechanisms and damage evolution of carbon fiber/epoxy composite laminate.

Many methods are done to analyze AE signals such as wavelet and clustering [19-23]. The objective of the cluster analysis is to separate a set of data into several classes that reflect the internal structure of the data. Indeed, cluster analysis is an important tool for investigating and interpreting data [24]. The cluster identification creates a framework for analysis of a link between damage mode and AE parameters of the corresponding AE event [25]. Moevus et al. [26] distinguished the different types of matrix cracking in the composite by clustering analysis with K-means method. Godin et al. [24] worked on polyester resin and glass/polyester unidirectional specimens, subjected to tensile loading, using K-means algorithm of clustering method in AE signals.

In this work, four-point bending test on carbon/epoxy composite is done and AE parameters are monitored. These data were analyzed with clustering method. K-means and C-means algorithms are used to validate and compare the results with previous works [27-29]. The results reveal a strong relationship between failure modes and cluster-based analysis.

2. MATHERIALS AND EXPERIMENTAL PROSEDURES

2. 1. Properties of Materials An EC157 epoxy (density at 25 °C = 1.15 g/cm^3, viscosity at 25 °C = 700 $mPa.s$) was mixed with a W152 MR amminic hardener (density at 25 °C = 0.95 g/cm^3, viscosity at 25 °C = 30 $mPa.s$) at a weight ratio of 100/30.

The prepreg (GG205PIMP503) used for specimens fabrication is a 0/90 woven epoxy resin/carbon fiber (density at 25 °C =1.5 g/cm^3, weight at 25 °C =353 gr/m^2) kindly provided by Impregnatex Compositi S.r.l. (Milan, Italy).

2. 2. Four Point Bending Test for Carbon/Epoxy Composite This test method (ASTM D6272) covers the determination of flexural properties of unreinforced and reinforced plastics, including high-modulus composites and electrical insulating materials in the form of rectangular bars molded directly or cut from sheets, plates, or molded shapes [30]. These test methods apply to rigid and semi rigid materials. However, flexural strength can be determined for those materials that break or fail in the outer fibers. This test method utilizes a four point loading system applied to a simply supported beam (Figure 1) [30].

A bar of rectangular cross section rests on two supports and is loaded at two points, each at equal distance from the adjacent support point. The distance between the loading noses (the load span) is either one third or one half of the support span. A support span-to-depth ratio of 16:1 shall be used unless there is reason to suspect that a larger span-to-depth ratio may be required. The specimen is deflected until rupture occurs in the outer fibers or until the maximum fiber strain of 5% is reached, [30].

The tangent modulus of elasticity is calculated by drawing a tangent to the steepest initial straight-line portion of the load-deflection curve and using Equation (1) [30] for a load span of one third the support span and Equation (2) [30] for a load span of one half of the support span, as follows:

$$E_B = 0.21L^3 m / bd^3 \tag{1}$$

$$E_B = 0.17L^3 m / bd^3 \tag{2}$$

where E_B is modulus of elasticity in bending, L is support span, b is width of beam tested, d is depth of beam tested, and m is slope of the tangent to the initial straight-line.

3. ANALYZING METHODS

3. 1. Clustering in C-means Algorithm Fuzzy C-means (FCM) is a method of clustering which allows one piece of data to belong to two or more clusters.
Objective Function (3) [31] is minimized in C-means algorithm:

$$J_m = \sum_{i=1}^{N}\sum_{J=1}^{C} u_{ij}^m \left\| x_i - c_j \right\|^2 \quad 1 \le m \prec \infty \tag{3}$$

where $m > 1$ is any real number, u_{ij} is the degree of membership of x_i in the cluster j, x_i is the ith of d-dimensional measured data, c_j is the d-dimension center of the cluster, and ||*|| is any norm expressing the similarity between any measured data and the center. Fuzzy partitioning is carried out by (4) [31] and (5) [31] through an iterative optimization of the objective Function (3), with the update of membership u_{ij} and the cluster centers c_j:

$$u_{ij} = \frac{1}{\sum_{k=1}^{C}\left(\frac{\left\| x_i - c_j \right\|}{\left\| x_i - c_k \right\|}\right)^{\frac{1}{m-1}}} \tag{4}$$

$$c_j = \frac{\sum_{i=1}^{N} u_{ij}^{m} . x_i}{\sum_{k=1}^{N} u_{ij}^{m}} \quad (5)$$

when $\max_{ij} \left\{ \left| u_{ij}^{(k+1)} - u_{ij}^{(k)} \right| \right\} \prec \varepsilon$, this iteration will stop. where $0 < \varepsilon < 1$ is a termination and k is the iteration steps. This procedure converges to a local minimum or a saddle point of J_m. The following steps (Figure 2) describe the algorithm:

Figure 1. Bending point test

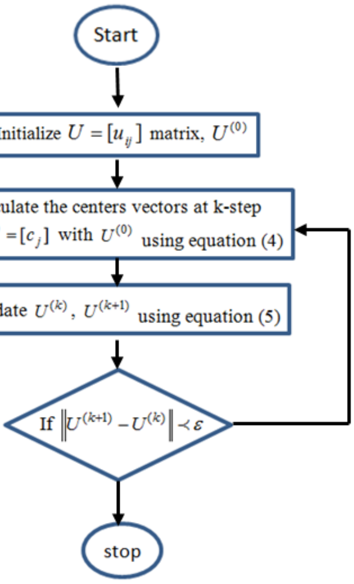

Figure 2. Flowchart of C-means algorithm

Data are bound to each cluster by means of a membership function, which represents the fuzzy behavior of this algorithm. To do that, an appropriate matrix named U is built whose factors are numbers between 0 and 1, and represent the degree of membership between data and centers of clusters [31].

3. 2. Clustering in K-means Algorithm The procedure of K-means unsupervised algorithm follows a simple way to classify a given data set through a certain number of clusters fixed a priori. Defining K centroids (one for each cluster), is the main idea. These centroids should be placed in a cute way. The better choice is to place them as much as possible far away from each other. The next step is to take each point belonging to a given data set and connect it to the nearest centroid. The first step is completed when no point is pending and an early groupage is done. At this point it is needed to re-calculate K new centroids as centers of the clusters resulting from the previous step. After owing these K new centroids, a new connecting has to be done between the same data set points and the nearest new centroid. A loop has been created. As a result of this loop, it is noticed that the K centroids change their location step by step until no more changes are seen. Finally, this algorithm aims at minimizing a squared error function as an objective function (6) [33]:

$$J = \sum_{j=1}^{k} \sum_{i=1}^{n} u_{ij}^{m} \left\| x_i^{(j)} - c_j \right\|^2 \quad (6)$$

where $\left\| x_i^{(j)} - c_j \right\|^2$ is a chosen distance measure between a data point $x_i^{(j)}$ and the cluster center c_j, is an indicator of the distance of the *n* data points from their respective cluster centers. The following steps (Figure 3) describe the algorithm:

Although it can be proved that the procedure will always terminate, the K-means algorithm does not necessarily find the most optimal configuration, corresponding to the global objective function minimum. The algorithm is also significantly sensitive to the initial randomly selected cluster centers. The K-means algorithm can be run multiple times to reduce this effect [32].

4. RESULTS AND DISCUSSION

In these tests each AE signal has five parameters (Counts, Amplitude, Rise Time, Duration and Energy). Thus, the signal makes five dimension spaces. Principal Components Analysis (PCA) reduces the dimensions of the observation space in which given objects are studied. The reduction is obtained by creating new linear combinations of variables characterizing the objects studied. These combinations, termed principal components, must satisfy certain mathematical and statistical conditions [33]. Variance percentage of eigenvalues of PCAs is shown in Figure 4.

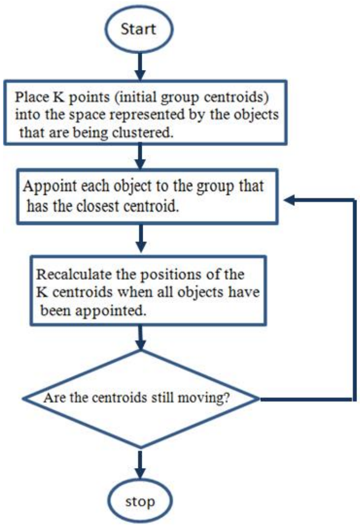

Figure 3. Flow chart of K-means algorithm

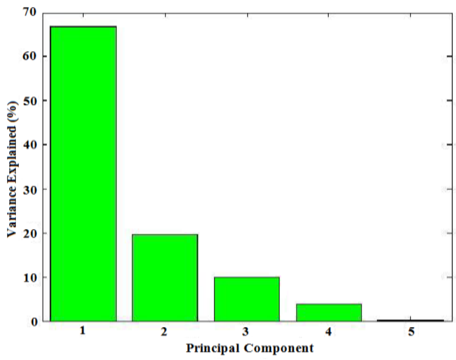

Figure 4. Percentage of the variance of eigen values of PCA

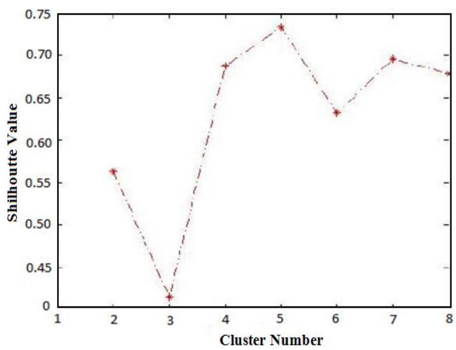

Figure 5. Clustering validation using silhouette

The axes 1 and 2, respectively, with 66.82% and 19.47% and the total variance percentage of 86.29% are selected as the main axes. After the dimensional reduction, the number of clusters must be specified. So, silhouette function is used. Each cluster is represented by a so-called silhouette, which is based on the comparison of its tightness and separation. This silhouette shows which objects lie well within their cluster, and which ones are merely somewhere in between clusters. The entire clustering is displayed by combining the silhouettes into a single plot. The average silhouette width provides an evaluation of clustering validity, and might be used to select an 'appropriate' number of clusters [34]. Figure 5 indicates this validation.

As shown in Figure 5, clustering with maximum validity occurs in 5 clusters. Clustering with C-means algorithm is shown in Figure 5.

Clustering with K-means algorithm is shown in Figure 7. Based on C-means and K-means algorithm, Table 1 shows range of amplitudes which each cluster are included.

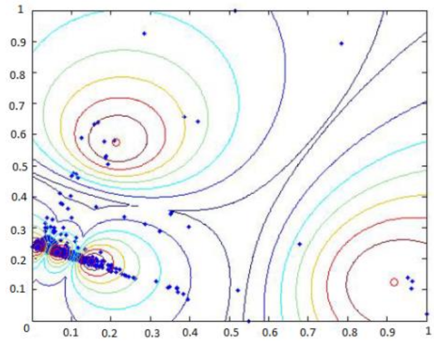

Figure 6. Data clustering with C-means algorithm

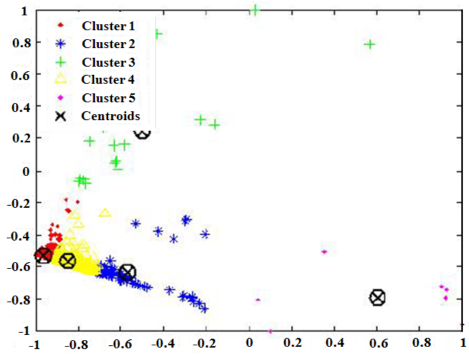

Figure 7. Data clustering with K-means algorithm

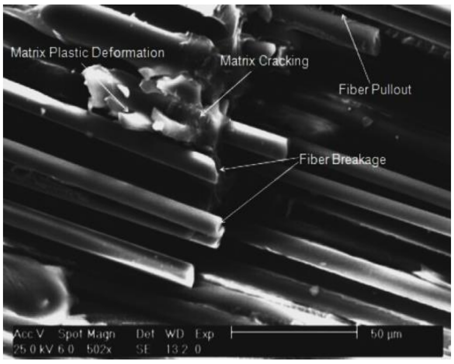

Figure 8. Example of microstructure of the composite after fracture by SEM [18]

TABLE 1. Range of amplitudes with K-means algorithm

Clusters	Range of amplitudes with K-means algorithm	Range of amplitudes with C-means algorithm
First cluster	35-40 dB	75-100 dB
Second cluster	48-70 dB	35-40 dB
Third cluster	35-85 dB	45-70 dB
Fourth cluster	40-49 dB	39-45 dB
Fifth cluster	75-100 dB	35-82 dB

TABLE 2. Fracture mechanisms of carbon-epoxy composites [27]

70 dB <	50-70 dB	40-50 dB	< 50 dB	Amplitude / Event duration
			Carbon fiber fracture	$\prec 100\mu s$
	Initiation and slow growth of delamination			Average $\approx 120\mu s$
		Friction of delaminated faces		$\prec 150\mu s$
Rapid advances of delamination				$\succ 200\mu s$

Kanji Ono [27] worked on AE behavior of flawed unidirectional carbon fiber-epoxy composites. His paper reported an experimental investigation on mechanical and AE behavior of specially designed and manufactured carbon fiber epoxy composites. Unidirectional composite laminates with various flaw configurations were tested in tension and their mechanical and AE responses were determined. Table 2 shows the reported results by Kanji Ono [27].

Norio Sato et al. [28] investigated the fracture mechanism of unidirectional carbon/epoxy composite by scanning electron microscope (SEM). Following four stages indicated the failure process: (1) fiber breakage began to occur at a load of about 60% of the failure load; (2) as the applied load was increased, plastic deformation occurred first from the broken fiber tip along the fiber sides, followed by final matrix cracking in the plastic region; (3) just before failure, partial delamination occurred, originating from fiber breakage and matrix cracking; (4) finally, a catastrophic crack propagation occurred from the delamination, leading to composite failure.

Comparing the results of C-means clustering with [27-29], it is concluded that the fifth cluster is noise because it is not in any ranges of Table 2 and has low weight of data. Other four clusters have coincidence with rapid advances of delamination, carbon fiber fracture, initiation and slow growth of delamination and friction of delaminated faces, respectively. Comparing the results of K-means clustering with [27-29], it is concluded that the third cluster is noise. Other four clusters have coincidence with carbon fiber fracture, initiation and slow growth of delamination, friction of delaminated faces and rapid advances of delamination, respectively.

5. CONCLUSION

- AE non-destructive method in four-point bending test of carbon/epoxy composite is used to analyze and examine the failure mechanisms.
- Clustering of these signals is done with C-means and K-means algorithm.
- K-means is an exclusive clustering algorithm; C-means is an overlapping clustering algorithm. In other words, C-means clustering is a soft version of K-means, where each data point has a fuzzy degree of belonging to each cluster.
- C-means clustering indicates that the fifth cluster is noise. Other four clusters have coincidence with rapid advances of delamination, carbon fibre fracture, initiation and slow growth of delamination and friction of delaminated faces, respectively.
- K-means clustering shows that the third cluster is noise. Other four clusters have coincidence with carbon fibre fracture, initiation and slow growth of delamination, friction of delaminated faces and rapid advances of delamination, respectively.

6. REFERENCES

1. Ning, H., "Composites and their applications", ***InTech***, (2012).
2. Behzad, M., Tajvidi, M., Ehrahimi, G. and Falk, R.H., "Dynamic mechanical analysis of compatibilizer effect on the mechanical properties of wood flour/high-density polyethylene composites", ***Series: Journal Articles***, (2004).
3. Shabana, Y., Karihaloo, B.L., Zhu, H. and Kulasegaram, S., "Influence of processing defects on the measured properties of $Cu - Al_2O_3$ composites: A forensic investigation", ***Composites Part A: Applied Science and Manufacturing***, Vol. 46, (2013), 140-146.

4. Joffre, T., Miettinen, A., Wernersson, E.L., Isaksson, P. and Gamstedt, E.K., "Effects of defects on the tensile strength of short-fiber composite materials", ***Mechanics of Materials***, Vol. 75, (2014), 125-134.
5. Gowayed, Y., Ojard, G., Prevost, E., Santhosh, U. and Jefferson, G., "Defects in ceramic matrix composites and their impact on elastic properties", ***Composites Part B: Engineering***, Vol. 55, (2013), 167-175.
6. Stout, M., Koss, D., Liu, C. and Idasetima, J., "Damage development in carbon/epoxy laminates under quasi-static and dynamic loading", ***Composites Science and Technology***, Vol. 59, No. 16, (1999), 2339-2350.
7. Samaratunga, D., Jha, R. and Gopalakrishnan, S., "Wave propagation analysis in laminated composite plates with transverse cracks using the wavelet spectral finite element method", ***Finite Elements in Analysis and Design***, Vol. 89, (2014), 19-32.
8. Kline, R.A., "Nondestructive characterization of composite media, CRC Press, (1992).
9. Wang, Y. and Wu, Q., "Experimental detection of composite delamination damage based on ultrasonic infrared thermography", ***International Journal of Engineering-Transactions B: Applications***, Vol. 27, No. 11, (2014), 1723-2495.
10. Perrin, M., Gaillet, L., Tessier, C. and Idrissi, H., "Assessment of stress corrosion cracking in prestressing strands using ae technique", ***Journal of Acoustic Emission***, Vol. 26, (2008), 32-39.
11. Prateepasen, A., "Pitting corrosion monitoring using acoustic emission, INTECH Open Access Publisher, (2012).
12. Padmanabhan, K., "Failure behaviour of carbon fibre/epoxy composites in pin-ended buckling and bending tests", ***Composites***, Vol. 26, No. 3, (1995), 201-206.
13. Ni, Q.-Q. and Jinen, E., "Fracture behavior and acoustic emission in bending tests on single-fiber composites", ***Engineering fracture mechanics***, Vol. 56, No. 6, (1997), 779-796.
14. Kumar, B.G., Singh, R.P. and Nakamura, T., "Degradation of carbon fiber-reinforced epoxy composites by ultraviolet radiation and condensation", ***Journal of Composite Materials***, Vol. 36, No. 24, (2002), 2713-2733.
15. Heydari, M. and Choupani, N., "A new comparative method to evaluate the fracture properties of laminated composite", ***International Journal of Engineering-Transactions C: Aspects***, Vol. 27, No. 6, (2013), 991-1004.
16. De Groot, P.J., Wijnen, P.A. and Janssen, R.B., "Real-time frequency determination of acoustic emission for different fracture mechanisms in carbon/epoxy composites", ***Composites Science and Technology***, Vol. 55, No. 4, (1995), 405-412.
17. Arumugam, V., Shankar, R.N., Sridhar, B. and Stanley, A.J., "Ultimate strength prediction of carbon/epoxy tensile specimens from acoustic emission data", ***Journal of Materials Science & Technology***, Vol. 26, No. 8, (2010), 725-729.
18. Liu, P., Chu, J., Liu, Y. and Zheng, J., "A study on the failure mechanisms of carbon fiber/epoxy composite laminates using acoustic emission", ***Materials & Design***, Vol. 37, (2012), 228-235.
19. Qi, G., Barhorst, A., Hashemi, J. and Kamala, G., "Discrete wavelet decomposition of acoustic emission signals from carbon-fiber-reinforced composites", ***Composites Science and Technology***, Vol. 57, No. 4, (1997), 389-403.
20. Marec, A., Thomas, J.-H. and El Guerjouma, R., "Damage characterization of polymer-based composite materials: Multivariable analysis and wavelet transform for clustering acoustic emission data", ***Mechanical Systems and Signal Processing***, Vol. 22, No. 6, (2008), 1441-1464.
21. Bussiba, A., Kupiec, M., Ifergane, S., Piat, R. and Böhlke, T., "Damage evolution and fracture events sequence in various composites by acoustic emission technique", ***Composites Science and Technology***, Vol. 68, No. 5, (2008), 1144-1155.
22. Khamedi, R., Fallahi, A. and Oskouei, A.R., "Effect of martensite phase volume fraction on acoustic emission signals using wavelet packet analysis during tensile loading of dual phase steels", ***Materials & Design***, Vol. 31, No. 6, (2010), 2752-2759.
23. Pappas, Y., Markopoulos, Y. and Kostopoulos, V., "Failure mechanisms analysis of 2d carbon/carbon using acoustic emission monitoring", ***NDT & E International***, Vol. 31, No. 3, (1998), 157-163.
24. Godin, N., Huguet, S., Gaertner, R. and Salmon, L., "Clustering of acoustic emission signals collected during tensile tests on unidirectional glass/polyester composite using supervised and unsupervised classifiers", ***NDT & E International***, Vol. 37, No. 4, (2004), 253-264.
25. Li, L., Lomov, S.V., Yan, X. and Carvelli, V., "Cluster analysis of acoustic emission signals for 2d and 3d woven glass/epoxy composites", ***Composite Structures***, Vol. 116, (2014), 286-299.
26. Moevus, M., Godin, N., R'Mili, M., Rouby, D., Reynaud, P., Fantozzi, G. and Farizy, G., "Analysis of damage mechanisms and associated acoustic emission in two sic f/[si–b–c] composites exhibiting different tensile behaviours. Part ii: Unsupervised acoustic emission data clustering", ***Composites Science and Technology***, Vol. 68, No. 6, (2008), 1258-1265.
27. Ono, K., "Acoustic emission behavior of flawed unidirectional carbon fiber-epoxy composites", ***Journal of Reinforced Plastics and Composites***, Vol. 7, No. 1, (1988), 90-105.
28. Sato, N., Kurauchi, T. and Kamigaito, O., "Fracture mechanism of unidirectional carbon-fibre reinforced epoxy resin composite", ***Journal of Materials Science***, Vol. 21, No. 3, (1986), 1005-1010.
29. Karbhari, V.M., "Non-destructive evaluation (nde) of polymer matrix composites, Elsevier, (2013).
30. International, A., "Standard test methods for flexural properties of unreinforced and reinforced plastics and electrical insulating materials by four-point bending, ASTM International, (2010).
31. Bezdek, J.C., Ehrlich, R. and Full, W., "Fcm: The fuzzy c-means clustering algorithm", ***Computers & Geosciences***, Vol. 10, No. 2, (1984), 191-203.
32. Jain, A.K., "Data clustering: 50 years beyond k-means", ***Pattern Recognition Letters***, Vol. 31, No. 8, (2010), 651-666.
33. Mackiewicz, A. and Ratajczak, W., "Principal components analysis (pca)", ***Computers and Geosciences***, Vol. 19, (1993), 303-342.
34. Rousseeuw, P.J., "Silhouettes: A graphical aid to the interpretation and validation of cluster analysis", ***Journal of Computational and Applied Mathematics***, Vol. 20, (1987), 53-65.

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RESEARCH NOTE

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چکیده

با توجه به حجم کاربرد بسیار وسیع کامپوزیت‌ها در صنایع مختلف و این حقیقت که وجود خرابی در کامپوزیت‌ها موجب افت استحکام نهایی و کاهش کارایی آن حین عملکرد می‌گردد، شناسایی خرابی‌ها در قطعات کامپوزیتی از اهمیت بسیار بالایی برخوردار است. در این پروژه با استفاده از روش غیرمخرب آکوستیک امیشن، علایم امواج منتشر شده ناشی از تست خمش چهار نقطه‌ای کامپوزیت‌های کربن/اپوکسی مورد تحلیل و بررسی قرار می‌گیرد. این روش بر اساس امواج ساطع شده در اثر فعال شدن عیب در سازه در حین بارگذاری استوار است. سیگنال‌های به دست آمده در اثر جدایش لایه-ای توسط حس‌گرهای آکوستیکی جمع آوری وتحلیل شده است. هر مرحله از واماندگی در محدوده فرکانسی خاصی قرار گرفته و مکانیزم خاصی را توجیه می‌کند. در کار حاضر دسته‌بندی داده‌ها با بهره‌گیری از دو روش C-means و K-means انجام، و نتایج آن با کارهای قبلی مقایسه شده است. روند واماندگی شامل چهار مرحله است. در هر دو الگوریتم، هر دسته با یک قسمت از این مراحل انطباق دارد

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