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FEA Study on the Microparticle Addition for Autonomic Healing of Some Polymer Composites

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Abstract

Some issues regarding the autonomic healing possibility, during the exploitation, are analyzed, for a polymeric material. The study focuses on the effects of some hollow microparticle addition into the polymer matrix. Any microparticle is filled with an adhesive; at a moment of crack increase, the local stresses enlargement determine microparticle to break. As a consequence, the adhesive tends to fill the crack and to stop its propagation. In connection with the possible negative effect of microparticle addition on the polymer structural integrity, a FEM analysis is developed, regarding the stress level at the matrix - particle interface, and also the fracture mechanics parameters at the crack tip.

Key words: *polimer matrix, additional microparticles, crack, autonomic healing, fracture toughness.*

Introduction

The polymeric materials of wind turbine blades are susceptible to develop some cracks, either on the external surfaces or in their internal structure, with various propagating direction towards the blade geometry. The presence of those cracks may affect the mechanical response of the structure, the more so as it have to support important dynamic loads and various adverse environmental actions. The possible uncontrolled crack propagation may lead to compromising the integrity of the entire structure.

In order to repair external defects, direct interventions are possible, as a result of defect observation or simple as scheduled repairs; in both cases, the cost of such interventions and repairs is high. On the other hand, the internal cracks are not visually noticeable, and their detection using non-destructive techniques is also costly and laborious. These drawbacks can be avoided, for example, using the technique that is described in the present paper.

Materials and Method

The method focuses on the use of some spherical, hollow microcapsules that are introduced into the polymer, even in the stage when the respective structure is manufactured; those thin-walled microcapsules, initially comprising an adhesive, are made from a sort of brittle material that is lacking the ability to take important amounts of plastic strain energy. At the moment when a developing crack approaches a microparticle, the stresses in its proximity come to be much higher than their usual level. As a result, microparticle breakage occurs and the adhesive penetrates into the already propagated crack (see Fig. 1); some new chemical links arise, in the material microstructure, and so the further crack propagation is avoided.

In order to observe the effects of the cited microcapsules introduction, into the polymer matrix structure, a study was made, using the finite element method; the proposed model provides, in the immediate vicinity of the microparticle, the existence of a sharp crack, possibly induced in the polymeric material using a prior fatigue test. The study was based on previous experience of the authors in this field, and also on the data that are presented in the literature.

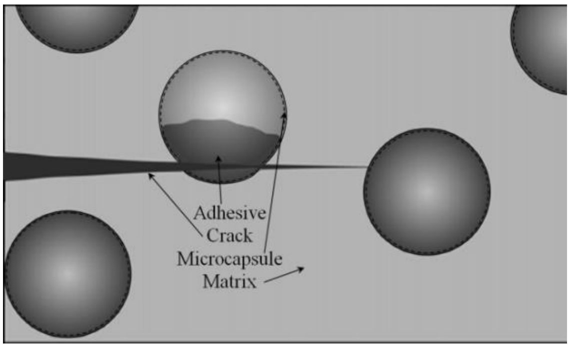


Fig. 1. The principle of autonomic healing using additional microparticles.

The proposed objectives can be achieved through consideration of several issues. Firstly, a correlation must exist, between the actual loading parameters of the studied structure, and the importance of the internal defects that are present into the material microstructure. On the other hand, at the moment when the crack reaches the microcapsule surface, the stresses in its vicinity must be at a level suitable to determine the microparticle breakage.

It is important to observe the negative effect of simple the microparticle presence, into the polymer matrix structure, where it is acting as a stress raiser. As a consequence, the analysis must be also focused on the microcapsule influence on the mechanical response and on the global fracture mechanics characteristics of the studied material.

It must be emphasized the randomness of microparticle dispersion, into the polymer matrix structure, but also the macro-homogeneity of the final material, meaning the similar physical and mechanical properties that can be measured in samples from different points of the material volume. The above described model is not actually based on the possibility of exactly positioning the microparticle at the crack tip; it is rather concerned the high probability, for the micro cracks that are developing into macro cracks, to intersect one or many of the microcapsules, as it is considered into the model. In that way, one can assume the accuracy of the numerical model, for the studied loading situation.

Finite Element Model

Into a polymeric material containing micro cracks, some microcapsules are dispersed having, as a material, different properties from those of the base polymer, as it is presented below:

Material Properties	Microparticle	Polymer
Mass density [$N \cdot s^2/mm/mm^3$]	0.0000000013137	0.0000000021481
Modulus of Elasticity [N/mm^2]	3650	3300
Poisson's Ratio	0.37	0.48
Shear Modulul of elasticity [N/mm^2]	785.23	163.05

The FEA study has as an objective to evaluate the stresses and strains values at the interface between the polymeric matrix and an embedded microparticle, at the moment when a crack is propagating into the base material. An ALGOR-multiphisics V22.1 program is used for modeling a central pierced crack that exist into a unidirectional loaded plate, with dimensions much larger than the crack. On the basis of the geometric and loading symmetry, the analysis can be restraint to a quarter of the plate (see fig. 2), by applying some appropriate boundary conditions, and locating the crack at the middle of specimen length.

One can observe that a model using even one eighth of the plate is also possible, and the chosen model was preferred just because the good computing capability of the system that was used, which was suitable to an accurate analysis, with more suggestive graphics results, and no restriction in translations and rotations for the central region of the plate, into the XOY plane.

The mesh network is conceived so as any microparticle node is coincidental with a node in the matrix. The microparticle-matrix contact is assumed to be a bonded one, considering the chemical links that are established at the interface, between the microcapsule and the polymeric matrix. The uniaxial loading is modeled as a stress level of 100MPa, into the Z direction, in order to facilitate the stress enlargement emphasizing into the microparticle vicinity.

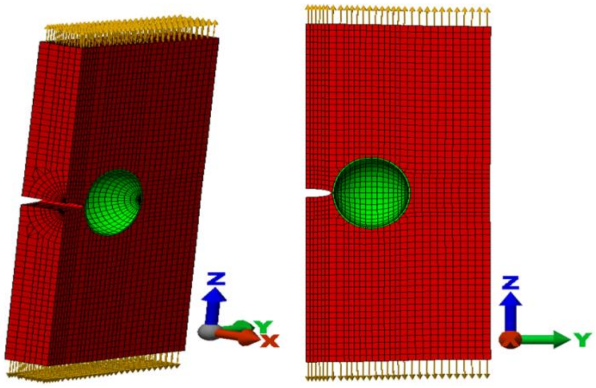


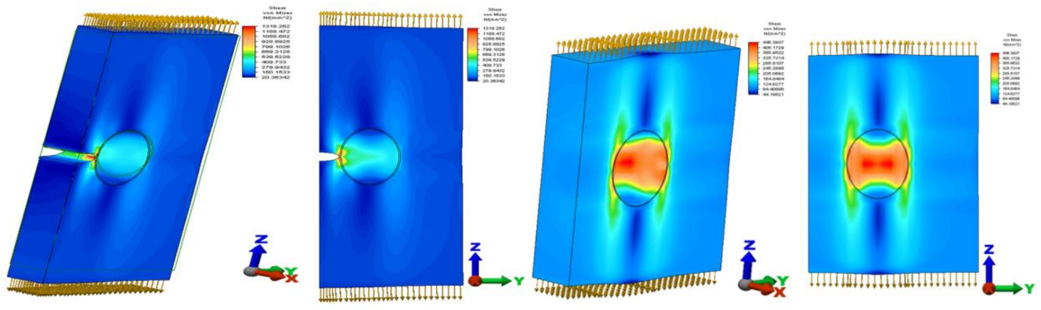
Fig. 2. Mesh network and loading application (3-D and lateral view) for the finite element analysis.

For the model of a quarter of the plate, the boundary conditions are as follows:

- translations on the X axis and rotations on Y and Z axes are prevented, considering the YOZ plane of symmetry;
- translations on the Y axis and rotations on X and Z axes are prevented, considering the XOZ plane of symmetry.

In order to emphasize some particular issues regarding the matrix-particle interface, the Von Mises stress analysis was conducted considering four different modeling configurations:

- including a crack that intersects the microparticle (Fig. 3a);
- without the presence of a crack (Fig. 3b);
- including a crack in the matrix, but no microparticle (Fig. 4a);
- the crack is present in the matrix, but it is not intersecting the microparticle (Fig. 4b).



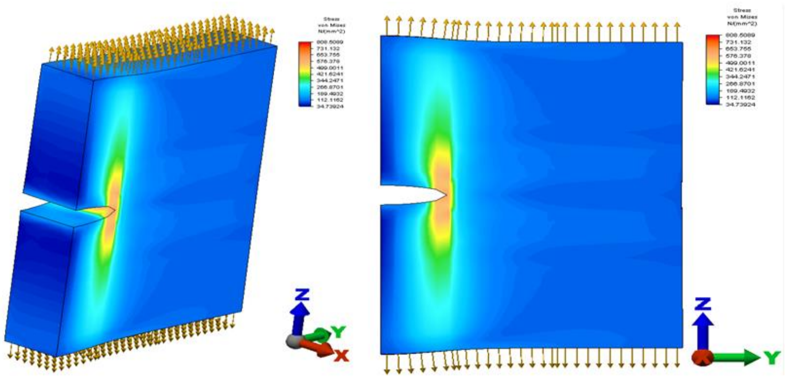
(a) (b)

Fig. 3. Analysis results (3-D and lateral view), considering (a) a crack intersecting the microparticle, and (b) without the presence of a crack.

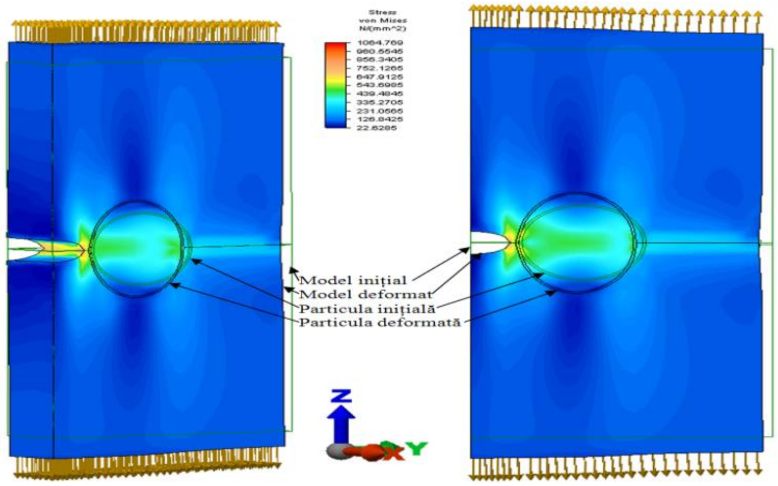
When the model situation is analyzed, before and after the loading application (see Figure 4b), some comments are necessary, regarding the loading effects on the model, as follows:

- its dimension along the loading direction increases – the model elongates;
- simultaneously, the dimensions on the transversal directions decrease;
- the two planes (XOZ and YOZ) where the boundary conditions were imposed are not moving from their initial position.

On the basis of these remarks, one can assume the accuracy of the numerical modeling and analysis; as a consequence, the results that are obtained can be considered as reliable. The established dimensions for the model (of a quarter of the plate), the microparticle, and the crack are all presented in Figure 5.



(a)



(b)

Fig. 4. Analysis results (3-D and lateral view), considering (a) a crack in the matrix, but no microparticle, and (b) the crack in the matrix is not intersecting the microparticle.

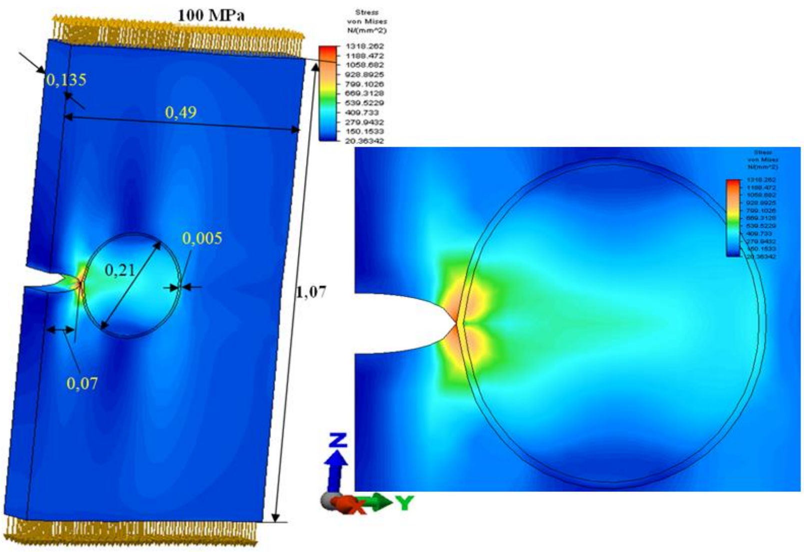
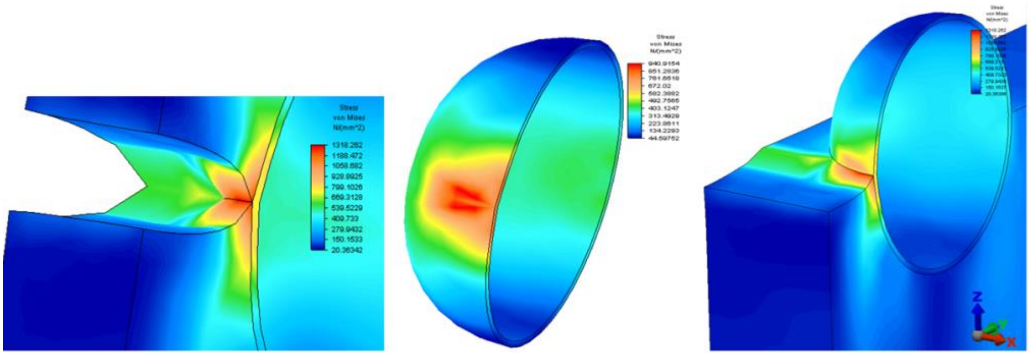


Fig. 5. The von Mises stresses maps (3-D and close lateral view), in the vicinity of a microcapsule.

Analysis Results Concerning the von Mises Stresses Variation

The von Mises stresses maps (see Figure 5) are referring to the moment when the crack front is intersecting a microcapsule; some remarks are important to be noted, regarding the stresses level, in the microparticle vicinity, as follows:

- when a stress level of 100MPa is assumed to be reached, due to the external loading of the structure, the stress at the crack tip is presumed to be 1318MPa; probably the effective stress in the material of wind turbine blades is not as high as 100MPa, but an increase of 13 times the nominal level, for the stress at the crack tip will almost certainly lead to the breaking of microcapsule; moreover, the requirement of its brittle fracture will be met;
- the microparticle takes mostly the stresses that are produced into the polymeric material, at the crack tip (see Figure 5b);
- the maximum stresses follow the microcapsule boundary (see Figure 6b);
- the stress concentration is given mainly by the crack presence; when the microcapsule is not included into the plate (see Figure 4a), the stress level at the crack tip is of 808MPa; the microparticle presence is acting obviously as a disturbing factor, such that the maximum stress level into the polymeric matrix is estimated at 1318MPa.



a) polymeric matrix b) microcapsule c) matrix-microcapsule interface

Fig. 6. Stress concentration at the crack tip.

Regarding the microcapsule (see Figure 6b), the presumed maximum stress level in its material is 9.4 times the nominal loading stress; this should be taken into account when choosing the material on which the microcapsules are to be made.

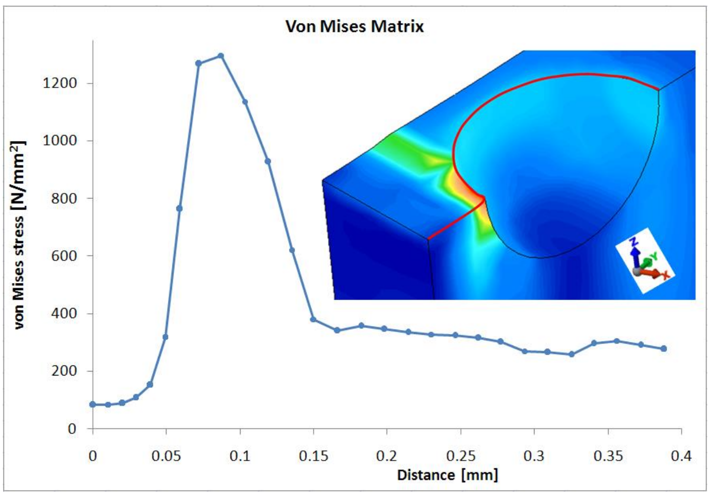


Fig. 7. Von Mises stress level into the polymeric matrix, in the microcapsule vicinity – on the red line.

Figure 7 presents the variation of von Mises stresses into the polymeric matrix, on the initial contour of crack flanks and in the microcapsule vicinity (the red line, in the figure). The point at zero distance is also marked – on the crack flank, on the border of the model. One can observe the stress enlargement, when the distance to the crack tip (and also to the microcapsule) decreases. The maximum stress level is presumed to be 1297MPa (for 100MPa – the nominal loading stress), and it is reached on the left zone, in relation to the vertical median plane YOZ.
The microcapsule is positioned (see again Figure 5a) between the coordinates of 0.07mm and 0.28mm. The stress level decreases, when the distance from the crack tip increases, and as a consequence the microcapsule breakage will start at its point of contact with the crack tip, where the stress reaches the maximum level; in this respect, the adhesive from the microcapsule fills firstly the crack tip area.

When analyzing the von Mises stress variation on the external microcapsule contour (the red line in Figure 8), one can observe that the maximum stress level (857MPa) is reached on the left zone, in relation to the vertical median plane YOZ. It is a different value, comparing with the maximum stress level into the microcapsule material (940MPa), that is not reached on the red line, but in a point placed below it.

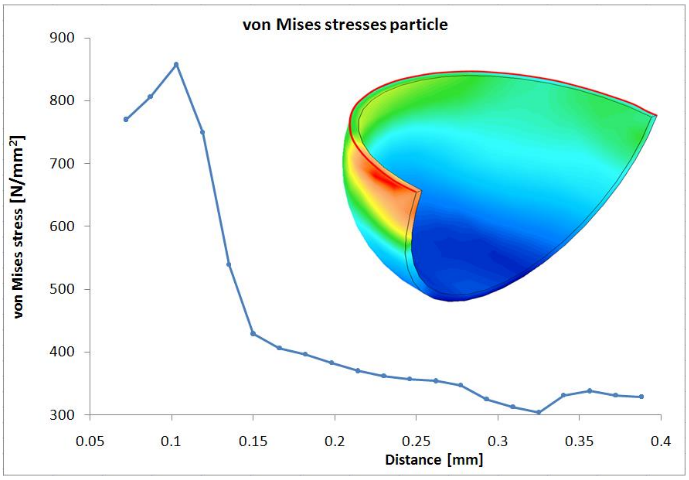
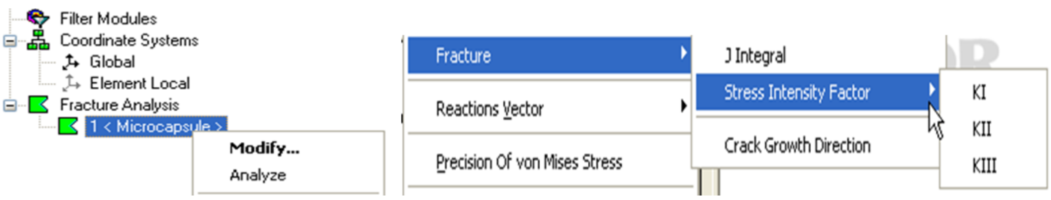


Fig. 8. Von Mises stress variation on the microparticle crack contour – the red line.

It is also observed that the maximum stress level is not the same for the matrix (1297MPa) (Figure 7, on the indicated contour), and for the microcapsule (857MPa) (Figure 8, also on the marked contour).

Some Results Regarding the Fracture Mechanics Parameters

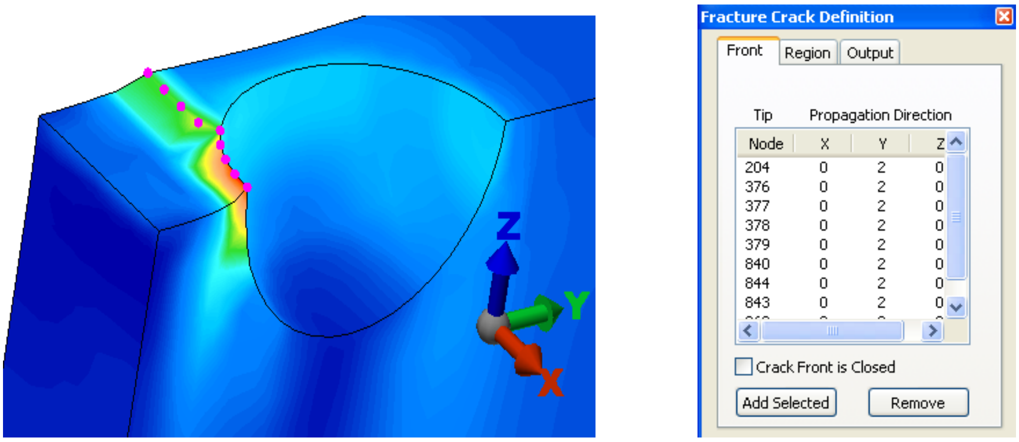
Some fracture mechanics material characteristics are to be established, in connection with a crack presence into the polymeric matrix. The analysis is also based on the above described numerical model that was initially used, into the FEA study for evaluating the stresses, strains and displacements that are produced by the external loading.



a) the module interface b) results that are obtained

Fig. 9. Fracture mechanics module, as a part of Algor software.

The fracture mechanics parameters – J integral, fracture toughness K_{Ic} and crack growth direction – are established using an especially developed module of Algor software (Figure 9). The input data are the coordinates of the points from the crack tip that are used into the analysis (see Figure 10).



a) the crack tip nodes b) the nodes and the likely crack growth direction

Fig. 10. The nodes position on the crack tip and the crack growth direction.

The following paragraph is focusing on fracture toughness variation, in terms of J integral, and respectively of K_{Ic} parameter, along the crack front (that is marked with a red colour in figures). It must be noted that the J integral is used for estimating the fracture toughness, for the materials which are characterized by large amounts of plastic strain, when load is beyond their yield stress. The polymeric matrix is such a material in this model, and all the points on the red line in the figures are located into the matrix material. It can be observed (Fig. 11) that the maximum value of J integral is 0,0933 N·mm/mm^2 that is reached close to the vertical median plane.

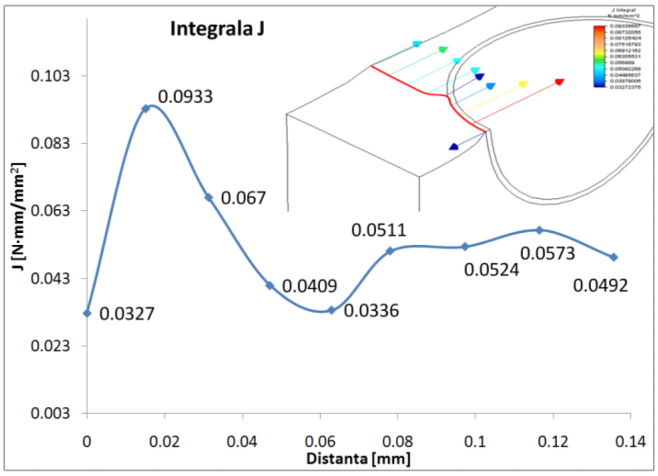


Fig. 11. The J integral variation on the likely cracking contour.

The K_{Ic} parameter is the critical value of stress intensity factor for the mode I of loading, which is the case for here described loading situation. This parameter variation is analyzed in the vicinity of the microcapsule, which material is presumed to fracture in a brittle manner. The maximum K_{Ic} fracture toughness value, into the microcapsule zone (see fig. 12), was estimated at the level of 11.68 N·mm$^{3/2}$ and it is also reached into the region close to the vertical median plane, as it is the case for J integral. One can conclude that the maximum fracture toughness values are reached in the same point, for both the matrix and the microcapsule, in a node that is located in the vicinity of the median plane.

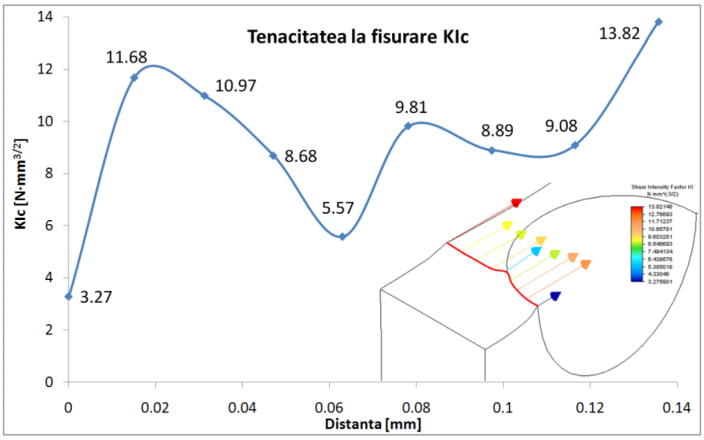


Fig. 12. Fracture toughness K_{Ic} variation on the likely cracking contour.

The likely crack growth direction is presented, using some arrows (whose size is not important), in Figure 13; on the majority of crack front length, its growth direction is included into the horizontal median plane XOY, and so the crack tip advances toward the microcapsule and can determine its breakage.

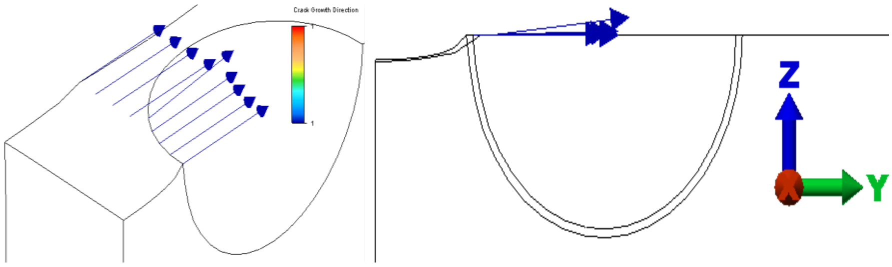


Fig. 13. The likely crack growth direction.

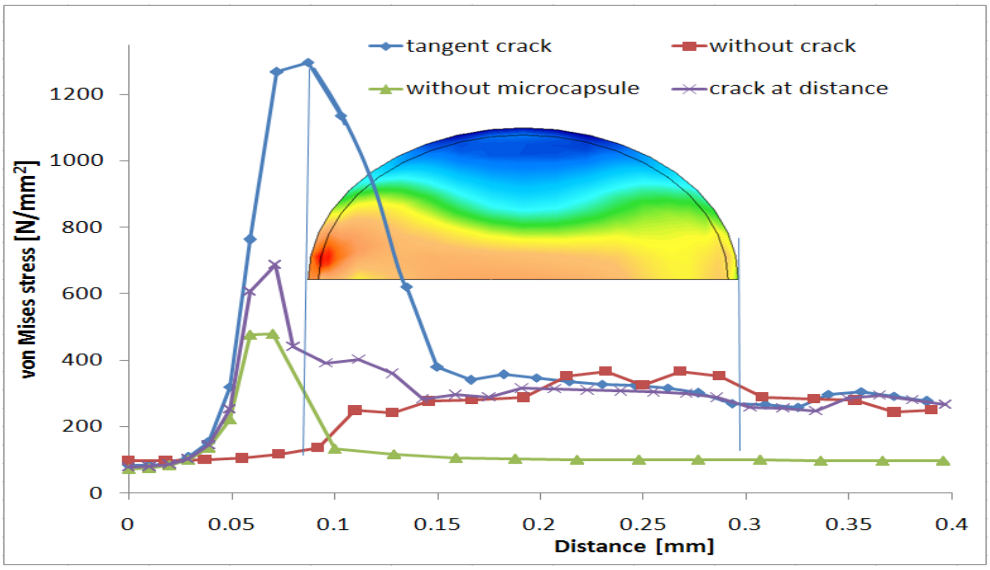


Fig. 14. Comparison of results regarding the von Mises stress level, for the four different numerical models: crack intersecting the microcapsule; no crack; no microcapsule; crack at a distance from the microcapsule.

Besides the already described case, with the crack front intersecting the microcapsule, some other numerical models were developed and used in finite elements analyzes, in order for their results to be compared with the above cited ones. These new models assume, respectively, the absence of a crack, the absence of microcapsule, and the existence of a crack, but at a distance from the microcapsule. The graphs from Figure 14 present the von Mises stress variation (on the same contour as in Figure 7) for the four models that were used; on the other hand, the Table 1 from below summarizes the maximum stress values for the studied cases.

Table 1. Maximum von Mises stress level for the four models

	Model	Maximum stress [N/mm^2]	Position
1	Crack tangent	1318	Left in the matrix
2	Without crack	446	Left in the matrix
3	Without microcapsule	808	At the crack tip
4	Crack at a distance	1064	Left in the matrix

One can observe on the figure that the maximum stress values are reached when the crack intersects the microcapsule, into its immediate vicinity; this result can be explained even by the crack presence, together with the particle existence in the proximity of the crack tip.

The simple microcapsule presence leads to a stress increase into the polymeric material, as can be seen on the red color graph (for the model „without crack”) from Figure 14. This fact is also observed on the other graphs: when the crack is located at a distance from microparticle, the stress increases as well, but to a lesser extent, compared to the case of intersection between the crack and the microcapsule. For the model with no microcapsule, but with an existing crack, the stress value at the crack tip is high, but it decreases a lot beyond that point.

Conclusions

The polymeric materials have the capability to recover most of their accidentally lost bearing capacity, by using some microcapsules, containing an adhesive, and being dispersed into the polymer structure. When a propagating crack is present in the vicinity of such an inclusion, it is possible for it to determine the microcapsule to break and the adhesive to fill the respective crack; as a consequence, the links between the crack flanks can be restored and so the crack growth can be prevented. For this to happen, the local stress rising, as a result of crack growth and when the crack is intersecting the microparticle, must be high enough to produce the breakage of the microcapsule.

On the other hand, it must observed that the simple presence of the inclusion can be assumed as a micro defect into the polymer structure, and its influence on the mechanical response, during the exploitation, of the global material must be analyzed, considering or not the presence of a propagating crack into the structure.

In this respect, the paper presents a FEA study on the local stress state that is developed into a polymeric structure, when some hollow spherical microcapsules are dispersed into it. Four types of modeling were used and their results were compared for establishing the influence of the microcapsule presence on the local stress state in the material.

It was firstly observed that the propagating crack and the simple presence of the dispersed microcapsules are both determining the stress increase, in the microparticle vicinity. The greatest role seams yet to belong to the crack presence – the modeling results show that the crack involves a local stress rise (808MPa) that is twice as large as the increase caused by the microparticle presence (446MPa). It must be noted that the cited maximum stress values were indicated in two separate locations: the first at the crack tip, the second at about the middle of the microcapsule.

When the above described modeled processes are simultaneously occurring, the local von Mises maximum stress reaches a level of about 13 times higher than the nominal stress (1318MPa vs. 100MPa) that is estimated to be achieved into the non-influenced polymer structure, at a distance from the crack and the microcapsule. The effective local stress could be lower than the above cited level, but one can assume that the microcapsule material must break at a stress level 13 times higher than the normal stress that is estimated to be obtained into the studied structure, for some usual operating conditions.

The FEA results also showed that even when the crack remains far from the microcapsule, the local stress is still at a high level (808MPa vs. the nominal stress of 100MPa), so that the polymeric material must be strong enough to prevent a possible crack to increase.

It is also important to note that the simple microcapsules dispersion, into the polymer structure, leads to a significant stress increase (of 4.46 times), by comparing with the initial structure loading situation, even when the crack is not present. As a consequence, the nominal stress level into the studied structure must be low enough, in order for the stress increase (determined by the microcapsules presence) to not affect the structural integrity of the composite material.

Acknowledgements

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Studiu FEA asupra posibilităţii de a se evita propagarea fisurilor prin ranforsare cu microparticule a unei matrici polimerice

Rezumat

Lucrarea urmăreşte evaluarea posibilităţii de autoreparare, în timpul funcţionării, a materialului polimeric pentru pale de turbină. Studiul bazat pe analiza cu elemente finite vizează influenţa adiţionării de microcapsule sferice, goale, în matricea polimerică. Microcapsulele sunt umplute iniţial cu un adeziv, propagarea fisurii ducând la creşterea tensiunilor şi spargerea microcapsulelor; adezivul din interior *umple fisura şi îi opreşte propagarea. Trebuie stabilit dacă prezenţa particulelor sferice poate fi tolerată fără a compromite integritatea structurală a materialului în funcţionare. Studiul FEA vizează starea de tensiuni din imediata vecinătate a particulei de incluziune şi determinarea principalilor parametri de mecanica ruperii la vârful fisurii.*