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Numerical analysis of damage in silica filled epoxy products using XFEM and its verifications

Analiza procesu pękania w produktach z izolacją żywiczną przy wykorzystaniu metody XFEM

Abstract

The paper summarizes the study of cracking phenomena in silica filled epoxy material. Numerical analyses of cracking phenomena were performed using Extended Finite Element Method (XFEM) for a full scale element as well as in a microscale, for the Representative Volume Element (RVE). Experimental verification consists of both C2 tests for real products and *in-situ* tensile tests and microstructural observations with the Scanning Electron Microscope (SEM). At the end, a summary with conclusions related to the prepared numerical analyses and experiments is included.

Keywords: XFEM, cracking, epoxy insulation, in-situ tests, C2 test

Streszczenie

W artykule przedstawiono wyniki analiz pękania izolacji żywicznej wypełnionej kwarcem. Analizy numeryczne przeprowadzone były dla obiektu w pełnej skali, jak i dla próbki reprezentatywnej (RVE) w mikroskali. Weryfikacja eksperymentalna zawierała obserwacje produktów po testach C2, testy *in-situ* oraz obserwacje pod mikroskopem zniszczonej struktury. Podsumowanie wraz z wnioskami z badań zawarto na końcu artykułu.

Słowa kluczowe: XFEM, pękanie, izolacja żywiczna, testy *in-situ*, test C2

1. Introduction

Nowadays, we can observe a trend of growing requirements for different kinds of products. This especially relates to power products which should be more and more robust. Some of the representative ones are medium and high voltage electrical components, where epoxy resin-based systems with silica filler are widely used as insulation. Such products are required to operate in harsh environments. This may activate the process of formation and propagation of cracks within the resin material, which can be one of the failure modes. The cracking phenomenon affects also manufacturing [1]. Epoxy based parts are very often produced by casting, during which (post)curing cracking may appear if the process is not optimized. Therefore, understanding the cracking phenomena is very desirable, as it could give additional possibilities to modify the composite, allow for a better optimization of production process parameters and would make epoxy based products more robust under harsh conditions.

2. Silica filled epoxy

In the last 30–40 years, epoxy resins have found widespread applications in the manufacturing of medium and high voltage electrical components. However, their low thermal conductivity as well as relatively low toughness (resistance to brittle cracking) may limit their applications. This may be improved somehow by filling polymer matrix with other materials like silica. Silica filled epoxies are commonly used in power products, mainly as insulating materials to encapsulate electrical components, owing to their very good dielectric properties. Application of silica improves thermal conductivity of composite, which is very important in power applications, but it decreases material toughness.

By adding a filler, such as silica, to a polymer matrix, physical, mechanical and thermal properties of composite change. In a simplified way, composite properties can be determined by the rule of mixtures based on volume fractions of components in the composite. However, in that case the filler size, its shape and the strength of filler/matrix interface may have influence on mechanical properties.

3. Fracture mechanics

3.1. Basics

Fracture mechanics is still a new, developing approach to materials strength [2]. Contrary to classic material strength approaches, where it is assumed that material is ideal and does not have any imperfections, in fracture mechanics it is assumed that there are some discontinuities therein. As a consequence, material strength depends on three parameters (applied load, crack size, fracture resistance) instead of two (applied force, material resistance) used in classical mechanics [3]. Three cracking modes can be distinguished: opening, in-plane shear, out-of-plane shear. It should be noted that usually there is a need to deal with mixed types of cracking modes [4]. Each of the above-mentioned methods corresponds with stress field, which is:

$$\sigma_{uj}^{T} = \frac{K_T}{\sqrt{2\pi r}} f_{ij}^{T}(\theta) \tag{1}$$

where

- σ – stress,
- i, j – x, y or z coordinates,
- K – stress intensity factor,
- T – cracking mode (1, 2 or 3),
- r, θ – polar coordinates placed in the crack tip,
- f – functions dependent on θ.

In an isotropic, elastic type of material, f functions take the form of the following equations:

$$\sigma_{xx} = \frac{K_T}{\sqrt{2\pi r}} \cos\left(\frac{\theta}{2}\right)\left[1 - \sin\left(\frac{\theta}{2}\right)\sin\left(\frac{3\theta}{2}\right)\right] \tag{2}$$

$$\sigma_{yy} = \frac{K_T}{\sqrt{2\pi r}} \cos\left(\frac{\theta}{2}\right)\left[1 + \sin\left(\frac{\theta}{2}\right)\sin\left(\frac{3\theta}{2}\right)\right] \tag{3}$$

$$\tau_{xy} = \frac{K_T}{\sqrt{2\pi r}} \cos\left(\frac{\theta}{2}\right)\sin\left(\frac{\theta}{2}\right)\cos\left(\frac{3\theta}{2}\right) \tag{4}$$

and stress distribution around the crack peak can be described as shown in Fig. 1.

One can notice that if $r \to 0$, then $\sigma \to \infty$. This means that each crack has a singularity at the peak.

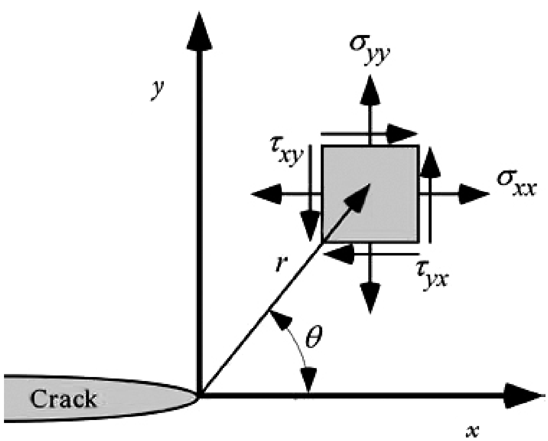


Fig. 1. Stress distribution around the crack peak

There are a lot of approaches for numerical modelling of fracture mechanics. The classic ones are based on time-independent crack behaviour (Linear-Elastic or Elastic-Plastic Fracture Mechanics) and material isotropy. But new computational methods, like time-dependent fracture behaviour or the one based on material microstructure are still being developed by CAE software companies.

3.2. Approaches for numerical analysis of damage process

In the literature, a number of numerical approaches that can be used for analysis of cracking in composites can be found. The most popular methods are the Element-Based Cohesive Behaviour (EBCB), Surface-Based Cohesive Behaviour (SBCB), Virtual Crack-Closure Technique (VCCT) and Extended Finite Element Method (XFEM). Each of these methods has advantages and disadvantages, but two of them may be particularly helpful during the analysis of damage in epoxy resin-based materials. One of them is VCCT, which is one of the newest approaches, based directly on brittle fracture mechanics equations [5]. It is a very powerful technique for modelling brittle fracture and delamination. However, the eXtended-Finite Element Method developed by Belytschko et al. [6] is these days the most promising technique for modelling damage in composite materials. This method is based on the partition of unity instead of crack propagating along the nodes. The traditional Finite Element Method (FEM) coupled with meshing tools does not yet manage to simulate efficiently the propagation of 3D cracks for geometries relevant to engineers in industry [7]. In the XFEM approach, in order to represent a crack on its proper length, nodes whose support contains a crack tip are enriched with discontinuous functions. Such functions are provided by the asymptotic modes of displacement (elastic if calculation is elastic) at the crack tip. Thus, the XFEM is mainly targeted towards problems with strong or weak discontinuities. Application of this technique and the obtained results are presented in the paper.

4. Analysis of damage in dry transformer coil

Dry transformers are very often exposed to harsh operation conditions. In order to evaluate their robustness and minimize the risk of failure, specific standards and tests are defined. An example is C2 test [8], during which a coil or transformer is cooled down to – 25 C and heated up by double nominal current. For our study, the coil was cooled down to – 50 C in order to evaluate what is its maximal strength.

4.1. 3D simulations

Analysis of dry transformer coil during the C2 test is complex and requires knowledge of temperature distribution in the coil. Therefore, a numerical approach which takes into account all relevant phenomena such as anisotropic and temperature dependent material properties, Joule heat generation, heat transfer by conduction, convection and radiation was

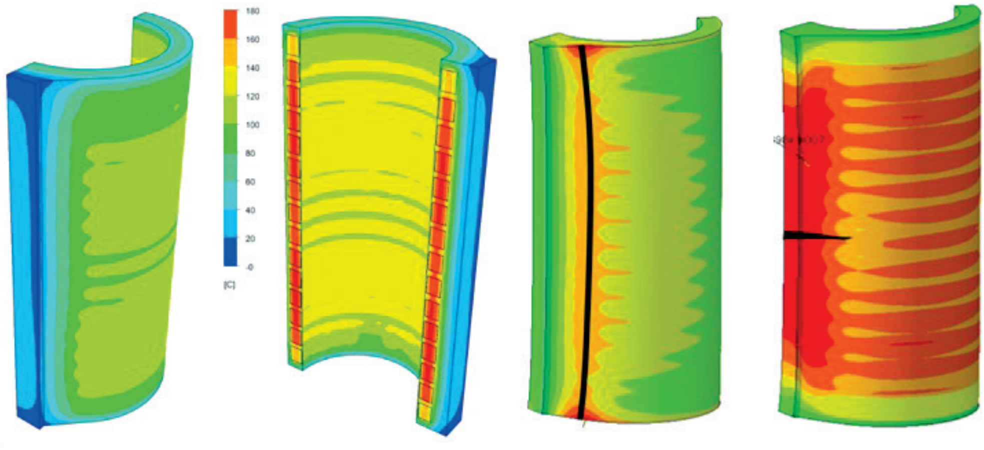
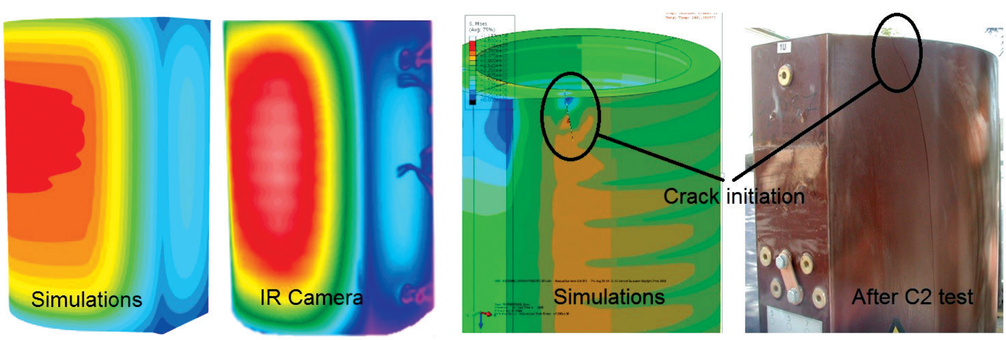


Fig. 2. Calculated temperature distribution (left) and probably crack scheme based on stress distribution (right)

developed and used [9]. Based on the calculated temperature distribution and heat transfer coefficients, it is possible to go to the next step – the cracking analysis. This one has been carried out in commercial software ABAQUS. As a result, the distribution of stress, strain and displacement is obtained. This allows us to estimate the cracking scheme and the risk of its occurrence as depicted in Fig. 2.

4.2. Verification of the simulations

The verification of the results obtained during simulations contains both comparison of temperature distribution (Fig. 3a) as well as crack initiation and propagation after a visual inspection of the coil during and after the C2 test (Fig. 3b).



a) b)

Fig. 3. Comparison of: a) temperature distribution and b) crack initiation and propagation line

5. Microscale analysis of cracking

In the previous chapter, a good agreement between the results from the simulation and the test can be observed. However, if one would like to modify the composite and make epoxy based products more robust, there is a need to investigate microstructural damage.

5.1. Crack simulations of 2D RVE

For numerical analyses of cracking in a microscale, a 2D Representative Volume Element (RVE) was generated on the basis of a real microstructure analysed by a scanning electron microscope (SEM). In such a SEM-image of the real microstructure, the grey scale values of different pixels were evaluated by an in-house developed software tool. In the first analyses, in order to reduce the required computation time, the numerical model has been simplified as presented in Fig. 4. RVE has dimensions of 100 x 100 μm.

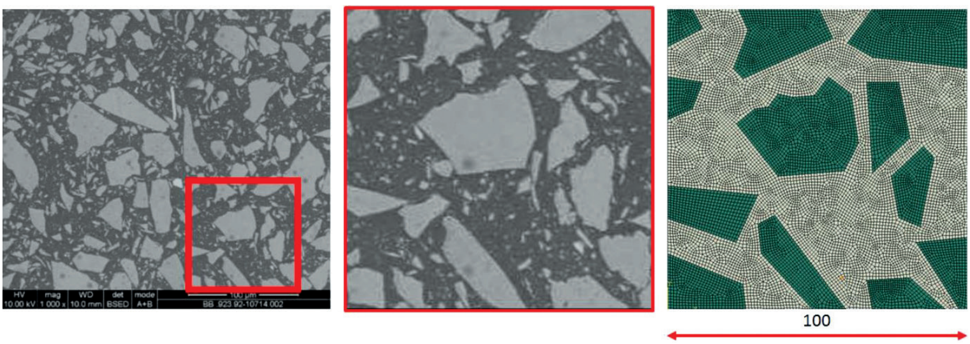


Fig. 4. Exemplary SEM image of the micro-silica filled epoxy composite (left and middle) and 2D FE model (right)

Due to the applied symmetry conditions (in X and Y directions) and displacement condition (0.005mm) applied to one of the edges, the sample was extended during the analysis. Maximal Principal Stress (MaxPS) was chosen for Fracture Initiation Criterion and the value that caused the failure was set to 60 MPa. Adhesion between the matrix and the filler was taken into account during the simulation.

In order to analyze the microstructural cracking of epoxy-based composite, basic mechanical properties have to be determined: Young's modulus and critical strain energy release rate. In case of Young's Modulus, traditional tension test can be used. In case of Critical Strain Energy Release rate, the number of approaches is limited. In this case, special samples were prepared and tested using the Optical Crack Tracing (OCT) technique by Fraunhofer Institute in Germany.

5.2. Results and its verification

As a result, stress-strain curves, stress distribution and crack initiation locations have been obtained. Selected results are shown below. Stress-strain curve is presented in Fig. 5.

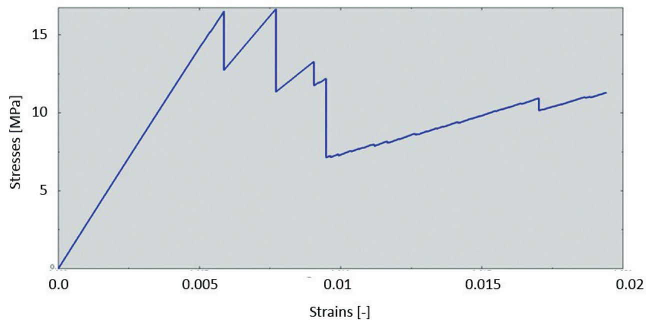


Fig. 5. Stress-strain curve

Peaks visible in Fig. 5. above indicate delamination between the matrix and silica filler, during which a portion of energy was released. Stress distribution for the presented case and crack initiation locations marked with red circles are presented in Fig. 6.

These simulations results would indicate that the initiation of epoxy resin material damage probably takes place at the interface as a result of the loss of interface strength and delamination.

The problem of cracking in polymers and composites is relatively new. Accordingly, the number of standards for the determination of fracture toughness for these materials is limited, although many research institutes have addressed this issue in recent years.

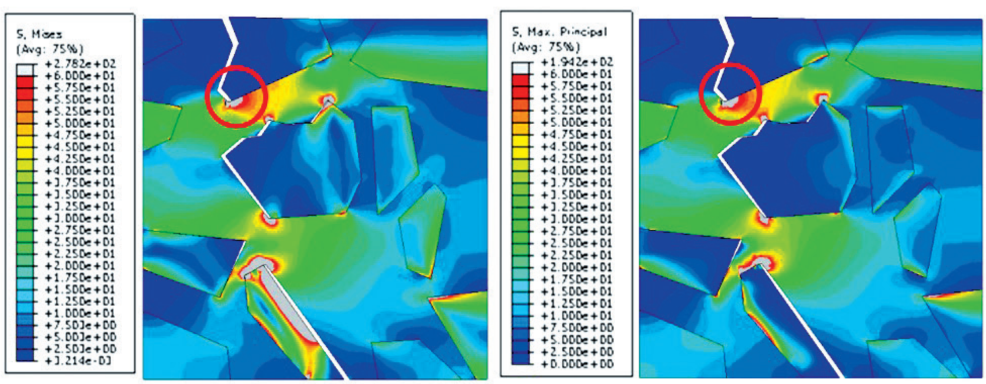


Fig. 6. Stress [MPa] distribution and selected crack initiations (red circles) at the end of analysis

The aim of the experiment was to determine the tensile strength of the composite and to observe the microstructure in order to analyze the process of crack initiation and propagation. At the beginning, by means of a Scanning Electron Microscope (SEM) the microstructure of the composite was obtained. Next, the tensile strength of the samples has been determined by means of a Microtest 5000 tensile machine. Observations performed by means of SEM revealed a complex microstructure of the silica-filled composite (Fig. 7). Observing the process of initiation and propagation of cracks with a scanning electron microscope is very demanding as it is a very rapid process. The resulting images show a breakthrough that in the tested composite crack propagates in the matrix and often runs at the interface between the matrix and the inclusions, which could confirm results from the simulations.

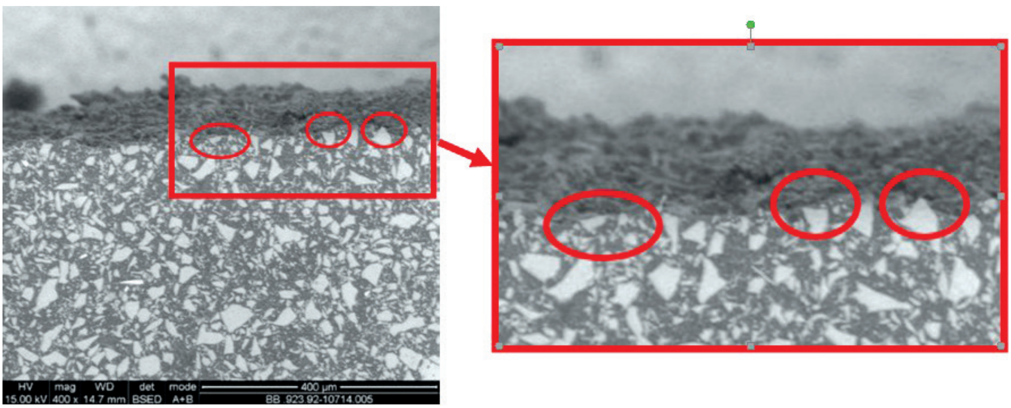


Fig. 7. Fracture surface and microstructure of the composite with marked areas of delamination

6. Summary

Silica filled epoxies are commonly used in power products mainly as insulating materials to encapsulate components on high electrical potential, owing to their very good dielectric properties. Power products are required to operate in harsh environments, for example outdoor applications in regions exposed to intensive sunlight, low temperatures, or excessive thermal extremes. These requirements may activate the process of formation and propagation of the cracks within the resin material. The cracking phenomenon affects not only electrical apparatuses in service conditions, but also causes manufacturing problems.

For the study of cracking phenomena in silica filled epoxy material, the Extended Finite Element Method (XFEM) was selected and mentioned in the first part of the article, together with basics of fracture mechanics. Analyses of cracking phenomena were performed for a full scale element (dry transformer coil) as well as in a microscale (RVE). Experimental verification consists of in-situ tensile tests and microstructural observations with the Scanning Electron Microscope (SEM).

Performed simulations and tests indicate the fact that the initiation of epoxy resin material damage probably takes place at the interface as a result of cracking and loss of a silica/matrix bond. This results in weakening of the epoxy resin microstructure in this area, which leads to further structural degradation consisting in the propagation of matrix cracks and, as a result, complete damage of the composite structure. The presented research of silica/epoxy composite damage confirmed that analysis of the epoxy resin microstructural damage is not trivial and further study is required for its better understanding.

References

[1] Nowak T., Kmita G., Sekula R., *Numerical and experimental analysis of thermal-induced residual stresses in epoxy resin based products*, Proc. 8th International Congress on Thermal Stresses, University of Illinois at Urbana-Champaign, USA 2009.

[2] Anderson T.L, *Fracture Mechanics,* Third Edition, CRC Press 2005.

[3] Wei R.P., *Fracture Mechanics. Integration of mechanics, materials science, and chemistry*, Cambridge University Press, 2010.

[4] Ochelski S., *Metody doświadczalne mechaniki kompozytów konstrukcyjnych,* Wydawnictwo Naukowo-Techniczne, Warszawa 2004.

[5] Krueger R., *Virtual crack closure technique: History, approach, and applications*, Applied Mechanics Reviews, Vol. 57(2), 2014, 109–143.

[6] Belytschko T. Moës N., Dolbow J., *A finite element method for crack growth without remeshing,* International Journal for Numerical Methods in Engineering 46 (1), 1999 131–150.

[7] Datta D., *Introduction to eXtended Finite Element (XFEM)*, Erasmus MSc in Computational Mechanics, Ecole Centrale de Nantes 2013.

[8] IEC 60076-11, Power transformers – Part 11: Dry-type transformers.

[9] Matysiak Ł., Platek R., Banas M., Sekula R., *eRAMZES – Novel Approach for Simulation of Reactive Molding Process*, 26th European Conference on Modelling and Simulation, Koblenz 2012, 128–135.