RISK ASSESSMENT OF MECHANICAL FAILURE BY DETERMINING THE PROBABILTY OF FLEXURAL STRENGTH DETERIORATION IN EPOXY-GLASS LAMINATES AFTER LONG-TERM WATER IMPACT

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Abstract

Direct impact of water on laminates made of epoxy resin and glass mats of various preparations negatively affects the flexural strength of composites. Determining the minimum flexural strength allows for estimating the probability of significant deterioration in composite properties as a result of the water impact. Risk assessment of failure in given conditions of use enables constructors to take appropriate decisions on the way and time of using composites and to adopt suitable parameters at designing technical objects. The paper presents how the risk of failure changes depending on the period of water impact, pressure at production of laminates and the type of glass fibre preparation.

1. Introduction

Polymer composites are quite commonly used. They are used also in places where they are exposed to direct impact of unfavourable environmental conditions, for instance water. In view of the familiar adverse effect of long-term water impact on glass, which is frequently used as polymer composite reinforcement, the following question poses itself – how can this knowledge be applied in the design process. The very awareness that properties deteriorate is an essential piece of information in itself. However, such information fails to provide us with appropriate tools to consciously determine the so-called life-span of use already at the design stage. The design of constructions and technical objects is a complex process which requires from the designer substantial knowledge concerning the properties of materials from which particular parts are to be manufactured. Frequently in the case of polymer composites, it is essential to have a deep insight into manufacturing technologies of parts in order to be able to influence particular material properties by means of a given method. On the basis of available information regarding the place and conditions of use of a given object, at the design stage the designer takes numerous responsible decisions, which can determine users' safety during an intensive use of a given structure.

Appropriate conduct of experiments allows for emphasizing specific information so that the designer can adopt proper safety indicators and adequate assumptions during the creative process of developing a concept and further design. Additionally, it allows for determining guidelines of how a ready design should be used. The obtained data may be used also in a different case when certain parameters are imposed. These parameters have to be included in the design despite the fact that they limit creative work. Having obtained information concerning the required time and conditions of use, one can adopt design solutions adequate to assumptions on the basis of the probability of failure or the probability of properties deterioration, which can cause malfunction of technical objects.

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Reliability is a property of an object, which refers to the ability to perform specific functions under certain conditions and in a certain period of time [4, 6, 8, 10]. In the case of composite materials of a complex and complicated structure, their high quality to a large extent depends on strictly following the technological regime during production. Their properties including mechanical ones should undergo a detailed analysis. Structural defects significantly lower composite strength. The most important indicator describing the behaviour of high material properties during use is the density probability of failure. This one and other reliability indicators are usually calculated on the basis of experiments conducted in conditions of mechanical load, for instance tensile or flexural strength [12, 13] and also on the basis of dynamic trials of a high number of cycles [11]. Results of flexural strength tests are considered the most significant. Nevertheless, there is some research concerning the determination of reliability or unreliability level on the basis of the E elasticity modulus [5].

The very tests of water impact on polymer composites have been used for a considerable time and can be found in quoted references, e.g. [1, 3, 7]. In the enumerated examples and many others, it is difficult to find references to methods of marking reliability with regard to the strength of composite materials or the change of other properties. Reliability indicators used in diagnostic testing and usage of complicated technical objects can be adopted for the purpose of conducting tests on polymer composites under long-term impact of unfavourable environmental conditions. This process is presented below on the example of a long-term water impact on composites.

2. Research methodology

The main objective of the conducted experiment has been to determine an empirical distribution of the probability of laminate failure during flexural strength tests after long-term water impact. Determining such a function, at establishing minimum flexural strength value constitutes a basis for adopting the safety coefficient during the process of designing various structures.

Resin used for the test has been epoxy resin with the trade name of C.E.S. R70 including a C.E.S. H71 hardener (distributor Connector Sp. z o.o.) dedicated to it. As reinforcement, two and later four layers of glass mats produced by the domestic Krosglass S.A company have been used. Mats have been made of fibres of 12μm diameter and E type glass. Mats of the 300 g/m^2 surface density differed by the way of producing silane preparation. Powder preparation was applied on the 1002 mat, whereas emulsion preparation was applied on the 1004 mat.

Laminates have been produced by means of two methods: the contact and press moulding methods with the use of the hydraulic press and creating moulding pressure of 42MPa. Applying higher pressing at the resin hardening than at the hand lay-up allowed for obtaining laminates with a higher volumetric share of the reinforcement. In the course of press moulding, the excess amount of resin was removed. Simultaneously, the quantity of failures in the form of air bubbles decreased in the whole composite volume. Both the first and the second factor had a direct influence on the higher strength of pressed laminates. After manufacture, laminates were left in laboratory conditions for approximately one month, which allowed for further hardening of resin.

After one month since manufacture, the manufactured laminate plates were completely immersed in a container filled with water so that they would not touch each other. Such immersion allowed for a direct contact between the laminate and water in every point of its outer layers. Water was obtained from the city water supply system. In a space of every 30 days (six times) laminates were taken out of water, dried and next samples for flexural strength tests were cut out. Simultaneously, at the beginning, every time a strip (offal) of a minimum one centimeter diameter was cut off. Cutting off offals before cutting out samples allowed for adopting an assumption that water in contact with the laminate on its edge, did not exert a significant influence on test results of samples cut out slightly further in the laminate. Laminate edges were not protected against direct water impact, which to some extent reflected possible real failures during the use of the composite

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resulting from the influence of mechanical loads, e.g. in the use of yachts in the part below the level of water. After monthly cutting out of samples, the laminate strength was determined. The last samples were exposed to contact with water for six months. Tests were conducted according to the established standards, on a workstation adapted to measuring static flexural strength in the system of four-point impact of forces (Dynstat Apparatus). Since measurement results were mostly not subject to standard distribution, which was checked by means of the Shapiro-Wilk test, significance analysis was conducted on the basis of U Mann–Withney's non-parametric distribution analysis. The water impact on the flexural strength of every type of laminate was statistically significant. Subsequently, the probability of failure on the basis of reliability analysis was determined. In this case, reliability of a given technical object includes the reliability function dependent on the time of use R(t) and described as the probability dependence P [3, 9]:

$$R(t) = P\{T > t\} \tag{1}$$

The T period of failure is higher than the t period, in which the failure will not appear. Probability is a set of numbers bigger than 0, yet lower than 1. By reversing the issue, one can determine the probability of failure F(t), which is the difference between certainty as to the lack of failure and the probability of non-occurrence of failure in a given object at a given moment. Therefore:

$$F(t) = 1 - R(t). \tag{2}$$

In the case of discussed tests, in the typical reliability function, a modification was introduced and the dependence of the probability of failure dependent on the $F(\sigma)$ flexural strength value was determined. From the designer's standpoint, such an approach is more advantageous since the probability of failure at a given load of a construction element allows for conducting appropriate strength calculations of constructions [2].

3. Test results

All laminates show a significant change in flexural strength after half a year's immersion in water. The decrease in average values in all cases is approximately 50% (Fig. 1, 2). In the majority of cases, approximating functions are second degree multinomials of high or very high determination coefficient (Tab. 1). Lower R^2 values are observed in laminates produced by means of the hand lay-up method. These results are characterized by relatively high mean standard error, which directly influenced the adjustment of the regression function. By observing points of mean flexural strength, one can notice two variations in the course of deterioration. After two and four months, in a few cases (Fig. 1, 2), temporary increases in the flexural strength of a material are visible.

As expected, it has been observed that pressed laminates show higher flexural strength and such a ratio is maintained throughout the whole period of using laminates. Moreover, it has been established that the emulsion silane preparation also positively influences the flexural strength of laminates. Nevertheless, despite a greater number of layers in the laminate, lower strength is observed. After analyzing volumetric shares of reinforcement, it has been established that in laminates with a lower number of layers, there is a higher share of reinforcement than in four-layer laminates. It is independent from the type of the applied method – press moulding or hand lay-up. It can result from a lower number of contact planes between subsequent layers, where there is more resin than on the outer surfaces of the laminate, which is respectively influenced by adhesion or cohesion forces. In two-layer laminates, there is one contact surface between subsequent layers of reinforcement. On the other hand, in four-layer laminates, three contact planes can be distinguished.

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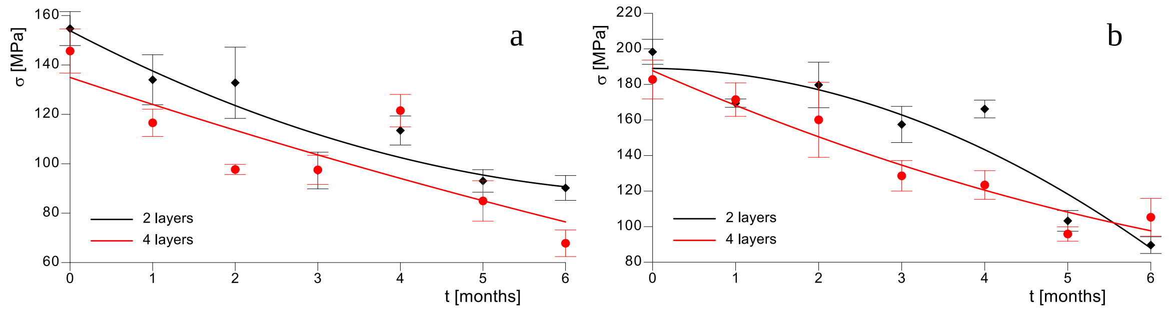

Figure 1. Influence of time of the water impact on laminates produced by hand lay-up method using glass mats with preparation of silane, a - powder, b – emulsion

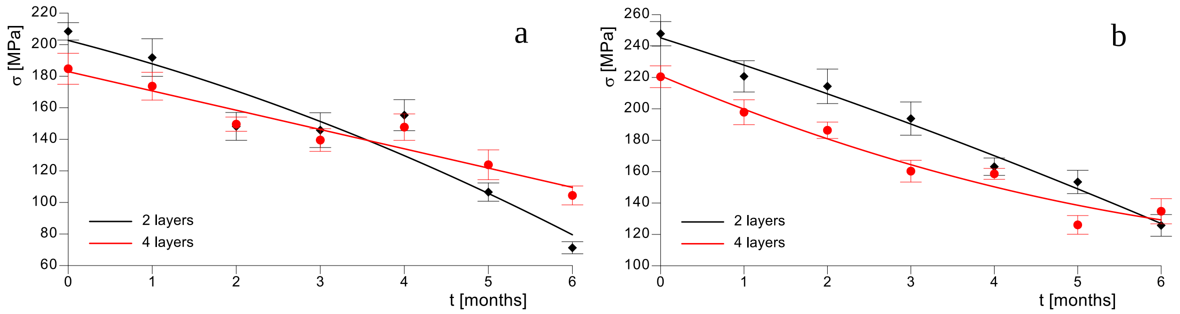

Figure 2. Influence of time of the water impact on laminates produced by press method using glass mats with preparation of silane, a - powder, b - emulsion

Table 1. Regression functions of $\sigma(t)$ flexural strength of composites depending on the time of their exposure in water (R^2 – determination coefficient)

Method	Mat	Number od layers	σ(t)	R^2
press moulding	1002	2	$\sigma = 202.6892944 - 13.725608\, t - 1.133853677\, t^2$	0.901
	1002	4	$\sigma = 182.9125064 - 12.22871501\, t$	0.922
	1004	2	$\sigma = 245.2227575 - 16.88743707\, t - 0.4714777551\, t^2$	0.985
	1004	4	$\sigma = 221.0389633 - 22.44017732\, t + 1.190169645\, t^2$	0.956
hand lay-up	1002	2	$\sigma = 153.859687 - 17.44613672\, t + 1.152577614\, t^2$	0.880
	1002	4	$\sigma = 134.941112 - 11.14887819\, t + 0.233359753\, t^2$	0.674
	1004	2	$\sigma = 189.0203589 - 0.5851178745\, t - 2.712515817\, t^2$	0.883
	1004	4	$\sigma = 187.7348813 - 20.40120782\, t + 0.898217582\, t^2$	0.944

Figures 3 and 4 present sample results of probability of failure calculations during the flexural strength tests of two-layer laminates produced by means of the hand lay-up (Fig. 3) and press moulding method (Fig. 4) by using glass mats of silane powder preparation. The number of months when laminates were immersed in water has been marked with numbers from 0 to 6.

If one adopts an assumption that a 50% decrease in the average flexural strength in relation to average strength of laminates not exposed to water impact (marked on Figures by a vertical lines with the description of 50%) means excluding the laminate from use, it emerges that such a decrease in the presented examples with the probability equaling 0.2 occurs in relation to laminates produced by means of the hand lay-up method already after 3 months of the laminate's immersion in water (Fig. 4). Conversely, pressed laminates can be subject to failure with the probability of 0.1 already after 3 months. After 5 months – with the probability of 40%, while after half a year, the failure will certainly occur after applying appropriate mechanical load. If, however, in the case of constructions with a higher safety standard, one adopts that a 30% decrease in strength (marked on Figures by vertical dotted lines with the description of 70% average maximum value) is considered a critical condition, then a constant contact between sample laminates and water is possible only throughout the period of one month. Prolonging this period results in the increase in probability, which is 30% in the case two-layer non-pressed laminates with powder preparation. However, in the case of such pressed laminates, the probability increases to 40%. It is already a high risk of failure.

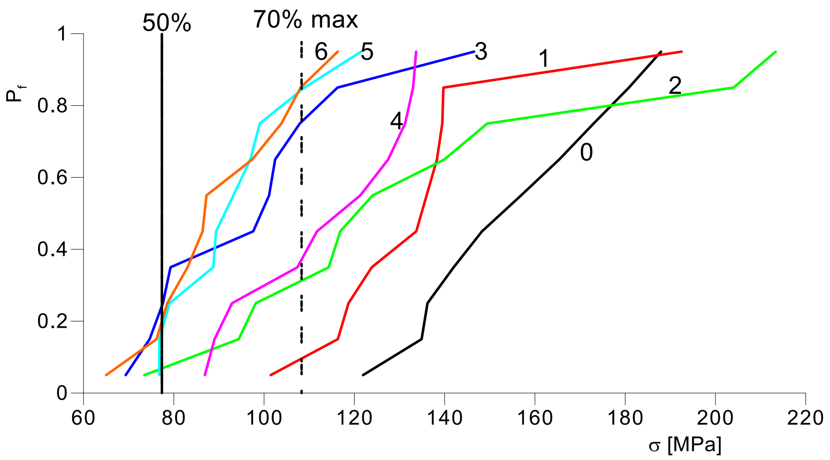

Figure 3. The probability of the failure of laminates produced by the hand lay-up method based on two layers of glass mat with preparation of silane powder (the description in the text)

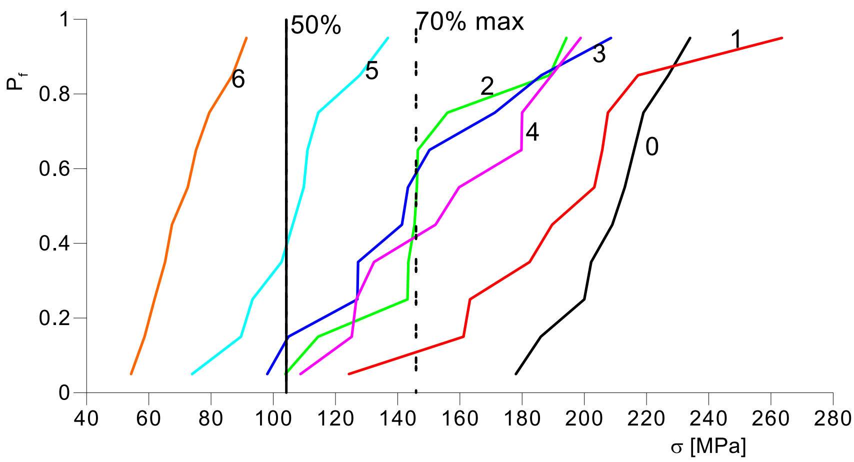

Figure 4. The probability of the failure of laminates produced by the press method based on two layers of glass mats with preparation of silane powder (the description in the text)

3. Conclusions

Water significantly contributes to the deterioration in the flexural strength of laminates made of glass mats and epoxy resin by means of the hand lay-up method and press moulding. After half a year of laminates' contact with water, a decrease in the flexural strength has been about 50%. Silane emulsion preparation increases the flexural strength of composites. Moreover, better flexural strength is achieved by the press moulding method. Pressed composites have fewer defects in their structure and a higher volumetric share of reinforcement.

Use of composites exposed to permanent contact with water, in the case of two-layer composites with powder preparation produced by the press moulding method, can cause failure with probability of 0.4 after just two months of permanent contact with water. Such probability occurs at the assumption that

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the critical condition of a composite is equivalent to 30% decrease in the flexural strength in comparison with a composite not exposed to the impact of unfavourable environmental conditions.

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