NUCET NUCLEAR ENERGY AND TECHNOLOGY

Nuclear Energy and Technology 5(2): 103–108
DOI 10.3897/nucet.5.35797

Research Article

A study into the scale effect on the strength properties of polymer composite materials*

Valentina V. Kiryushina[1], Yuliya Yu. Kovaleva[1], Petr A. Stepanov[1], Pavel V. Kovalenko[1]

1 *JSC "ORPE "Technologiya" n.a. A.G. Romashin", 15 Kievskoe shosse, Obninsk, Kaluga Reg., 249031, Russia*

Corresponding author: *Valentina V. Kiryushina* (vkiryushina@gmail.com)

Academic editor: *Yury Korovin* ♦ **Received** 15 February 2019 ♦ **Accepted** 27 April 2019 ♦ **Published** 17 May 2019

Citation: Kiryushina VV, Kovaleva YY, Stepanov PA, Kovalenko PV (2019) A study into the scale effect on the strength properties of polymer composite materials. Nuclear Energy and Technology 5(2): 103–108. https://doi.org/10.3897/nucet.5.35797

Abstract

Polymer composite materials (PCM) are used extensively and are viewed as candidates for application in various industries, including nuclear power. Despite a variety of methods and procedures employed to investigate the mechanical characteristics of PCMs, the use of the laboratory sample mechanical test results to design and model large-sized structures is not always fully correct and reasonable. In particular, one of the problems is concerned with taking into account the scale parameter effects on the PCM strength and elastic characteristics immediately in the product.

The purpose of the study is to investigate the scale effects on the mechanical characteristics of glass reinforced plastics using phenolformaldehyde and silicon-organic binders and a fabric quartz filler.

Samples of four different standard sizes under GOST 25604-82 and GOST 4648-2014 were tested for three-point bending using an LFM-100 test machine to estimate the scale effect. The thicknesses of the model samples were chosen with regard for the wall thicknesses of full-scale products under development or manufactured commercially and the test machine features, and varied in the limits of 1.6 to 7.5 mm.

The tests showed that strength decreased as the sample thickness was increased to 3 mm and more both at room and elevated (200 to 500 °C) temperatures, which can be described by an exponential function based on the Weibull statistical model. The values of the Weibull modulus that characterizes the extent of the scale effect on the strength of the tested materials were 4.6 to 6.7. The average bend strength in the sample thickness range of 3 mm and less does not vary notably or tends to increase slightly as the thickness is increased. This fact makes it possible to conclude that estimation of allowable stresses in a thin-wall product requires the use of test results for samples with a thickness that is equal to the product wall thickness since standard samples may yield overestimated allowable stress values and lead, accordingly, to incorrect calculations of the strength factor.

The results obtained shall be taken into account when defining the allowable levels of operation for full-scale products and structures of polymer composites based on the laboratory sample strength data as well as when estimating their robustness as a characteristic of the product's fail-safe operation.

Keywords

Polymer composite materials; glass reinforced plastics; scale effect; strength; Weibull statistical model; size effect

* Russian text published: Izvestiya vuzov. Yadernaya Energetika (ISSN 0204-3327), 2019, n. 1, pp. 97–105.

Introduction

Polymer composite materials (PCM) are used extensively and are viewed as candidates for application in various industries, including nuclear power. PCMs can be successfully employed and are potential substitutes for traditional metals and dielectrics used as protective compositions for heat-insulating, radiotransparent and structural load-bearing components.

It is by no means always fully correct and reasonable to use the results of laboratory sample mechanical tests to design and model large-sized structures despite the fact that different methods and procedures have been developed and are used on a broad scale to study the mechanical characteristics of PCMs. For instance, there is a problem of taking into account the scale parameter effects on the PCM strength and elastic characteristics directly in the product (structure) (Vasilyev 1988, Tarnopolsky and Skudra 1966, Bolotin and Novichkov 1980).

The scale effect of strength means a failure of classical similarity laws observed in mechanical tests of geometrically similar samples. This is an apparent failure since it goes to prove that the sample strength is affected by parameters having a dimension of length but not included in classical equations of elasticity and plasticity theory. This may be a characteristic dimension of fiber, grain, microscopic crack, etc. The coarser the composite structure is and the more commensurable the structural scales of length are with the sample scales, the more profoundly the scale effect manifests itself, all other things being equal.

The scale effect of the composite strength is a natural consequence of the structure heterogeneity. At the same time, the structure heterogeneity is stochastic. With the current technology level, defects (microcracks, delamination, local debonding, surface blisters, buckling, excessive porosity, and others) may take place in the composite material fabrication process. The presence of defects leads to the statistical variability of physical and mechanical properties and to scale effect.

Therefore, estimation of scale effects on strength is important in design of composite structures, and formulation of the respective approach to this represents an essential stage in the development of composite material technology.

The most effective way to take into account the scale effect of strength for similar isotropic materials is to use the Weibull statistical model (Bolotin 1965, Barinov and Shevchenko 1996, Levshanov et al. 2006) based on the assumption that the product volume is a combination of small individual volumes and the failure of one of these will lead to the catastrophic failure of the product as the whole.

The probability of a failure of a product of the volume V in a heterogeneous stressed state, with regard for the volume size and the extent of the stress distribution irregularity within the volume, can be estimated using the distribution function

$$P(\sigma) = 1 - \exp\left[-\frac{1}{V_0} \int_V \left(\frac{\sigma - \sigma_{min}}{\sigma_0} \right)^m dV \right], \quad (1)$$

where m, σ_0, σ_{min} are the Weibull distribution parameters; and V_0 is the volume of a standard sample. The parameter m, known as the Weibull modulus, is the dispersion measure of the material strength values and characterizes the level of the strength scale dependence.

Despite the fact that the Weibull model is used successfully for brittle isotropic materials to determine the interconnections of the breaking stress for different material volumes, its application is not so evident for anisotropic materials, such as glass reinforced plastics, even in a simple case with uniaxial tension in the direction of reinforcement (Serensen and Strelyaev 1962,Serensen and Zaytsev 1965, Yermolenko 1986, Argon 1978, Bullock 1974, Hitchon and Phillips 1978, Fujii and Zako 1982, Cui et al. 1994, Bazant et al. 1996).

The purpose of the study is to investigate the scale effects on the strength of fiberglass materials and the suitability of the Weibull statistical model to this end.

Test items and experimental procedures

The test items are PCMs based on phenolformaldehyde resins (FNkv.) impregnated further with a solution of methylphenylspirosiloxane – MFSS-8 (FNkv.+MFSS-8) (Rusin et al. 2014). The products used in the study have been fabricated based on a satin-woven quartz fabric by pressure impregnation method (Gurtovnik 2003).

To assess the scale effect of strength, test beams of the FNkv. and FNkv.+MFSS-8 materials were fabricated with four standard sizes: 1.6×10×32 mm; 3.0×10×60 mm; 4.0×10×80 mm; and 7.5×10×150 mm. The thicknesses of the model samples were chosen with regard for the wall thicknesses of full-scale products under development or manufactured commercially and the test equipment features. The samples were manufactured using one batch of fabric and impregnated with a single batch of binder to minimize the process side effects on the material properties.

A procedure developed at JSC "ORPE "Tekhnologiya" named after A.G. Romashin, based on GOST 25604-82 and GOST 4648-2014, was used for the tests. This procedure establishes the method for bend testing of composite materials reinforced with glass or organic fibers in a temperature range of minus 60 °C to plus 1500 °C. In principle, the method suggests that the freely supported test sample with a rectangular cross-section is subjected to bending at a constant rate in the middle between the supports until it breaks or until the sample reaches the preset relative strain or deflection value. And the ultimate bend strength is understood to mean the maximum value of the bending fracture stress.

The tests to determine the ultimate static bend strength were conducted for the fabric filler warp and at temperatures of $T = 20$, 200, 400, and 500 °C. The sampling scope was five FNkv. samples and five FNkv.+MFSS-8 samples for each size and each temperature.

Results and discussion

The results of the tests to determine the ultimate bend strength for the FNkv. and FNkv.+MFSS-8 materials are presented in Tables 1 and 2 respectively. Diagrams of the maximum bending fracture stress dependence on the sample thickness at different test temperatures are presented in Figs. 1, 2. The studies took into account only the test results for the samples failing in the tension area; no samples with other failure patterns (delamination, contact collapse, etc.) were considered.

An analysis of the presented data shows that, in a temperature range of 3.0 to 7.5 mm, both materials exhibit a tendency towards a decrease in the sample average ultimate bend strength for all test temperatures. On the average, the strength of the samples with $h = 7.5$ mm is 30 % as small as the strength of the samples with $h = 3.0$ mm.

Table 1. Ultimate bend strength (MPa) for the FNkv. samples of different sizes at different test temperatures.

Sample thickness, mm	Test temperature T, °C			
	20	200	400	500
1.6	430 ± 10	421 ± 17	285 ± 18	192 ± 28
3.0	486 ± 51	421 ± 61	236 ± 21	180 ± 4
4.0	405 ± 21	325 ± 28	213 +8	147 ± 10
7.5	360 ± 21	275 ± 25	171 ± 11	128 ± 9

Table 2. Ultimate bend strength (MPa) for the FNkv.+MFSS-8 samples of different sizes at different test temperatures.

Sample thickness, mm	Test temperature T, °C			
	20	200	400	500
1.6	436 ± 33	373 ± 39	251 ± 6	193 ± 4
3.0	453 ± 62	394 ± 47	259 ± 10	201 ± 4
4.0	348 ± 33	325 ± 23	237 ± 14	162 ± 11
7.5	325 ± 7	284 ± 13	192 ± 8	137 ± 10

As the sample thickness increases from 1.6 to 3.0 mm, the average strength either varies insignificantly or tends to grow slightly (the maximum growth of 13 % is recorded at $T = 20$ °C for the FNkv. material). The absence of a major change in strength or its decrease in the test materials with $h = 3$ mm and less is in a good agreement with similar results obtained by other researchers for polyether fiberglass reinforced with variously woven fabrics and given in (Tarnopolsky and Skudra 1966). A zero or reverse scale effect of strength in "thin" plastics was observed with a wall thickness of 2 mm and less due to which this study is expected to be continued in a thickness range of 2.0 to 3.0 mm and using sufficiently representative samples. At this stage, however, the result obtained for "thin" plastic makes it possible to conclude that the normal distribution law function shall be used to describe the strength of the material in a "thin-wall" product and to estimate the probability of its fail-safe operation, and test results for samples with a thickness corresponding to the product wall thickness shall be used to estimate the allowable stresses.

To assess the suitability of the Weibull model for describing the scale dependence of strength, a problem was initially solved concerning the correctness of using the Weibull distribution function (1) to describe the test results for the material's standard samples.

Fig. 3 presents a bar diagram of the ultimate bend strength for the FNkv.+ MFSS-8 samples with a size of 4×10×80 mm at $T = 20$ °C and its approximation by the normal distribution function and a two-parameter Weibull distribution function ($\sigma_{min} = 0$). The sampling scope was increased to $N = 50$ samples to minimize the estimation error of the Weibull parameters (Barinov and Shevchenko 1996, Kiryushina et al. 2006).

The analysis performed does not discard the use of Gaussian and Weibull distributions to describe the

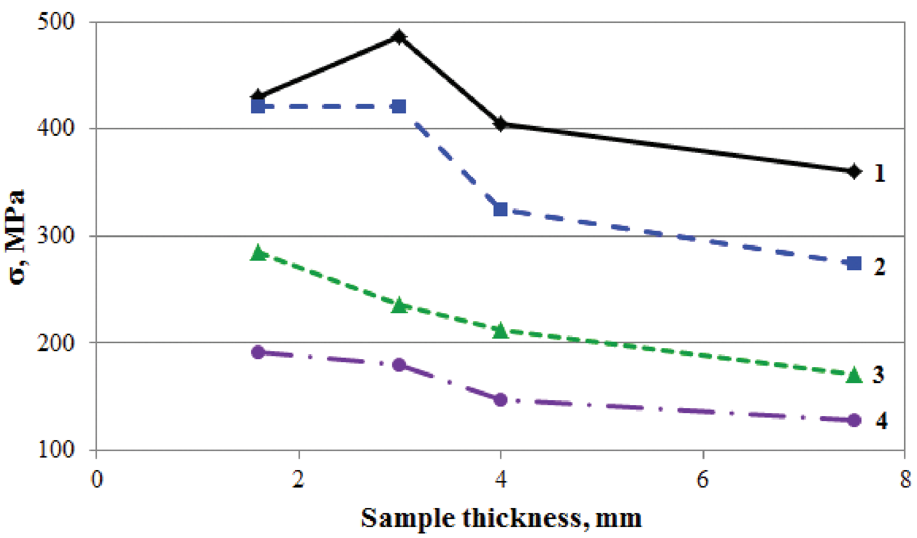

Figure 1. Maximum bending fracture stress of the FNkv. samples as a function of the sample thickness at different test temperatures: 1 – 20 °C; 2 – 200 °C; 3 – 400 °C; 4 – 500 °C.

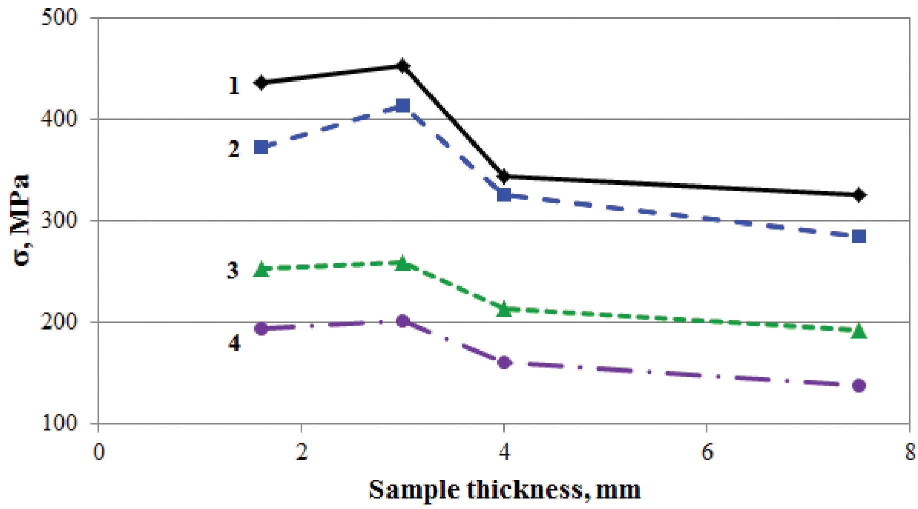

Figure 2. Maximum bending fracture stress of the FNkv.+MFSS-8 samples as a function of the sample thickness at different test temperatures: 1 – 20 °C; 2 – 200 °C; 3 – 400 °C; 4 – 500 °C.

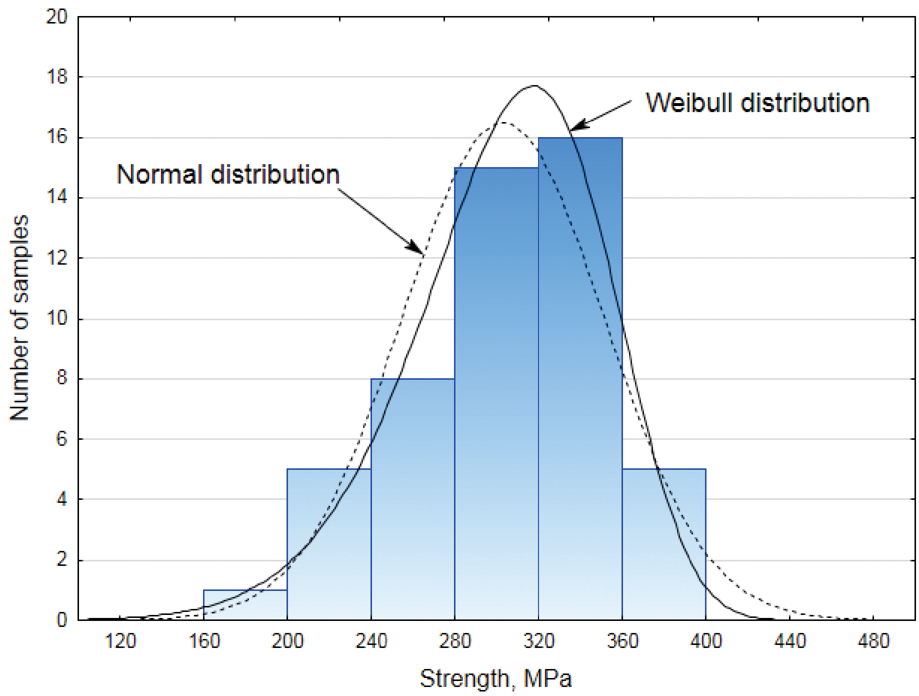

Figure 3. Distribution of the bend strength values during bending of standard FNkv.+ MFSS-8 samples at $T = 20°C$.

strength test results for the material samples. However, since the empiric distribution is slightly asymmetric, Weibull distribution is more suitable for the experimental data approximation. The level of significance based on the Mann fitting criterion (Kapur and Lamberson 1980) was $p > 0.90$. The estimated Weibull parameters obtained by the maximum likelihood method (Kiryushina et al. 2006, Ivchenko and Medvedev 1992) are equal to $m = 7.7$; $\sigma_0 = 317$ MPa. The Weibull modulus value is close to the values of this parameter for a number of Russian glass reinforced plastics (Serensen and Strelyaev 1962, Serensen and Zaytsev 1965).

It is important, when using the Weibull model, to take into account the scale effect of strength for engineering analysis. Assuming that the sample failure probability is $P = 50$ %, we get the following scale dependence from expression (1):

$$\sigma^{av}_0/\sigma^{av}_1 = (V_{eff1}/V_{eff0})^{1/m}, \quad (2)$$

where σ^{av}_0, σ^{av}_1 are the average ultimate strengths; and V_{eff1}, V_{eff0} are effective (stressed) volumes (Jajatilaka and Trustrum 1977). This relation can be used to estimate the ultimate strength of the material volumes at different loading patterns, as well as to predict the average ultimate strength of the material in a product from the breaking stress of laboratory samples.

Instead of effective volumes, effective surface areas can be used in expression (2), which depends on which types of defects, volumetric or superficial, control the surface.

Figs. 4, 5 present relative decreases in the average ultimate strength of the FNkv. and FNkv.+MFSS-8 materials depending on the relative sample volume increase jointly with the scale dependences built on their basis (2). The scale dependences have been built based on the values σ for three groups of samples with h = 3.0, 4.0, and 7.5 mm, for which a strength decrease was detected as h was increased.

As follows from the presented data, there is a varying error observed in the experimental data approximation by an exponential curve for different test temperatures. The greatest divergence is recorded at T = 200 °C for the FNkv. material (12.6 %), and at T = 20 °C for the FNkv.+MFSS-8 material (15.7 %). For the other test temperatures, the differences in the predicted and experimental ultimate strength estimates for both PCMs were not more than 10 %. This prediction error could be caused by the insufficient number of the tested samples and, consequently, by high values of the mean estimation errors, due to which it has been recommended that the investigations should be continued. However, it is already the initially obtained results that do not run counter to the fact that the experimentally observed scale effect of strength for the tested PCMs can be described by dependence (2) that stems from the Weibull model.

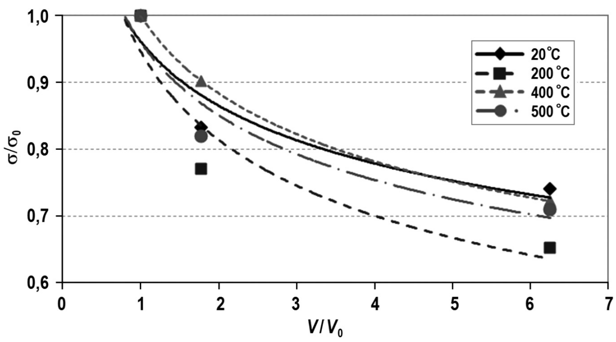

Figure 4. Relative decrease in the average ultimate strength of the FNkv. material as a function of the relative volume increase.

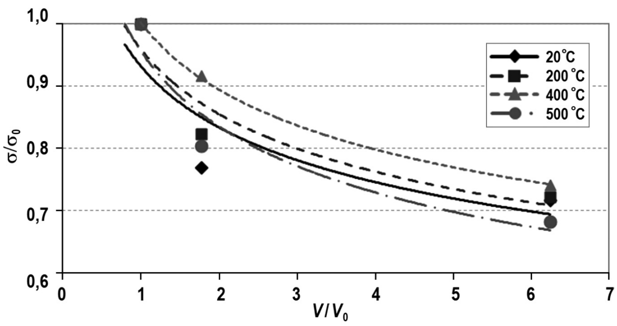

Figure 5. Relative decrease in the average ultimate strength of the FNkv.+MFSS-8 material as a function of the relative volume increase.

The Weibull modulus values, estimated from the degrees of the approximating scale curves, are m = 4.6 – 6.7 for the FNkv. material and m = 5.1 – 6.2 for the FNkv.+MFSS-8 material. These values are close to the values of the parameter m obtained as the result of the strength tests for standard samples of commercially manufactured materials, which confirms once again that the use of the Weibull model is correct.

Conclusion

The paper presents the results of the initial stage of the study to estimate the scale effect of the PCM strength based on phenolformaldehyde and silicon-organic binders. The following conclusions can be made based on the investigation results.

1. In the sample thickness range of 3 mm and less, the average ultimate bend strength either varies insignificantly or tends to grow slightly, which makes it possible to conclude that the normal distribution law function shall be used to describe the strength of the material in a "thin-wall" product and to estimate the probability of its fail-safe operation, and test results for samples with the thickness corresponding to the product wall thickness shall be used to estimate the allowable stresses.
2. The sample size influences greatly the maximum bend stress during a failure with the sample thickness being 3 mm and more. On the average, an ultimate strength decrease of 30 % is observed.
3. The processing of mechanical test results for test beams with different cross-sections has shown that the dependence of strength on scale can be described by exponential equation (2) that stems from the Weibull statistical model used effectively to estimate the scale effect of the isotropic material strength. The values of the Weibull modulus that characterizes the degree of the scale dependence of strength are m = 4.6 – 6.7 for the FNkv. material and m = 5.1 – 6.2 for the FNkv.+MFSS-8 material and are close to the values of this parameter for a number of Russian glass reinforced plastics.
4. The Weibull statistical model can be used to estimate the scale effects on the strength of samples and structures of PCMs. Investigations in this field however require to be continued with a larger number of samples so that to minimize statistical errors and with testing samples of other configurations and using other loading patterns.

The results obtained in the study shall be taken into account when determining the allowable levels of operation for full-scale products and structures of polymer materials based on the laboratory sample strength data, as well as when estimating their reliability (probability of fail-safe operation).

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