Research Article

Theoretical Estimations of Influence of Polymer Coatings on the Elastic Modulus and Ultimate Strength of Steel Samples

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Abstract : In this work, the model of a three-layer inhomogeneous strip and Voigt averaging are used to simulate the effective tensile modulus of the plates. To model the effective bending modulus of samples, the theory of bending of non-uniform beams is used. Good agreement was obtained between the calculated and experimental values of the elastic moduli determined in the tests for central tension and three-point bending. In this case, the calculation error does not exceed 5% for plates with a thickness of 1,5 mm and 10% for plates with a thickness of 0,7 mm. To assess the ultimate strength of the samples, an approximate estimate according to Voigt was used, which gives an error, in relation to experimental data, of the order of 10-15%, depending on the thickness of the steel substrate.

Keywords: Elastic modulus, three-layer heterogeneous strip model, bending theory, polymer coatings.

1. Introduction

The values of the mechanical characteristics of polymer films can differ significantly from the properties of coatings applied directly to metal surfaces [1-9]. This is due to the adhesion of the coating to the substrate, the presence of defects in the coating on the substrate [10-17]. It should also be noted that the properties of polymer coatings depend on many factors [18-30]. The main ones include: time from the moment of coating application, humidity, temperature, deformation rate, etc. With increasing humidity, temperature and deformation rate, the elastic modulus of the coating decreases. At the same time, knowledge of the elastic properties of coatings makes it possible to simulate their behavior under various operating conditions using widespread commercial finite element packages, such as NASTRAN, ANSYS, LS DYNA and others [31-39].

2. Theoretical analysis of the mechanical characteristics of multilayer plates

A coated plate will be considered as a strip or beam of non-uniform thickness, consisting of three layers - a central steel layer and two outer layers of epoxy resin (Fig. 1).

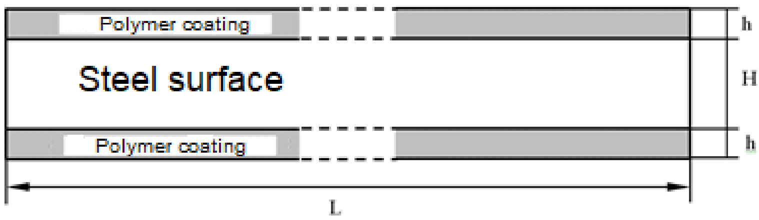

Fig. 1. Model of steel samples with polymer coating. The length of the working part of the samples (or the distance between the supports during bending) L = 80 mm. Coating layer thickness h = 0,1 mm, steel thickness H = 0,7 mm or H = 1,5 mm.

The main relation for determining the relationship between the effective modulus of elasticity of a three-layer sample and Young's modulus of each of the layers can be obtained from considering the Voigt model. It is assumed that the deformations over the sample thickness are constant. In this case, the following relation holds for predicting the elastic modulus of specimens with coatings under tension:

$$E_p = 2E_n \frac{S_n}{S} + E_{cm} \frac{S_{cm}}{S} = 2E_n \frac{h}{H+2h} + E_{cm} \frac{H}{H+2h} \quad (1)$$

where $S=(H+2h)b, E_p$ – total cross-sectional area of the sample and the effective modulus of elasticity determined from the tensile test results of the coated sample; $S_n=hb, E_n$ – cross-sectional area corresponding to the coating layer and Young's modulus of the coating; $S_{cm}=Hb, E_{cm}$ – cross-sectional area and Young's modulus of the steel layer; H – cross-sectional area and Young's modulus of the steel layer, h – coating layer thickness, *H+2h* – thickness of coated sample; b – sample width.

An approximate estimate of the tensile strength of samples can also be obtained using the Voigt model:

$$\sigma_B=2\sigma_{Bn}\frac{h}{H+2h}+\sigma_{Bcm}\frac{H}{H+2h} \tag{2}$$

Here σ_{Bn},σ_{Bcm} - ultimate strength of coating materials and steel. In the calculations, we will assume that $\sigma_{Bn}=40\,M\Pi a, \sigma_{Bcm}=350\,M\Pi a$.

To simulate the deformed state of coated plates during three-point bending tests, we will use the relations of the theory of bending of inhomogeneous beams. The bending moment M, acting in the central part of the specimen can be represented as the sum:

$$M=M_n+M_{cm}$$

where M_n – part of the moment attributable to the coating layers, M_{cm} – part of the moment corresponding to the resistance of the steel strip.

Expressing the moments in terms of Young's moduli and moments of inertia of the layers and taking into account the presence of two layers of the coating, we obtain:

$$\frac{E_u J}{R}=2\frac{E_n J_n}{R}+\frac{E_{cm}J_{cm}}{R},$$

where E_u – the effective modulus of elasticity, which can be determined for a coated specimen in bending tests, J, J_n, J_{cm} – are the moments of inertia of the total cross section of the specimen, coating layer and steel, respectively; *R* – radius of curvature of a bent sample.

Thus, to predict the modulus of elasticity of coated plates, determined in bending tests, we will use the following expression:

$$E_u=2E_n\frac{J_n}{J}+E_{cm}\frac{J_{cm}}{J} \tag{3}$$

The moments of inertia of the total cross-section and layers of steel and coating are determined by the formulas:

$$J=\frac{b(H+2h)^3}{12};$$

$$J_{cm}=\frac{bH^3}{12}; \tag{4}$$

$$J_n=\frac{bh^3}{12}+\left(\frac{h+H}{2}\right)^2 hb.$$

Here it is taken into account that the coating layers are shifted relative to the neutral line of the sample by an amount (H+h)/2. Substituting (4) into (3), we obtain the following nonlinear dependence of the bending elastic modulus of the sample on the thickness of the coating and steel layers:

$$E_u=2E_n\frac{4h^3+6h^2H+3hH^2}{(H+2h)^3}+E_{cm}\frac{H^3}{(H+2h)^3} \tag{5}$$

Figure 2 shows the dependence of the values of the elastic moduli in tension and bending of samples with coatings, calculated by formulas (1) and (5). As the initial data, the standard values of Young's moduli of the materials used were used: for steel 08PC Young's modulus is E_{cm}=190 GPa, for polymer coating – E_n=3 GPa. The dependence is plotted on the relative thickness of the steel layer in the sample *H/(H+2h)*. Under tension, there is a linear dependence of the elastic modulus E_p on this parameter (see expression (1)). Bending module E_u nonlinearly depends on the relative thickness of the steel layer, and its calculated values are always lower E_p. Figure 2 also shows the lower bound of the Voigt-Reis fork - Reis averaging. It can be seen that the calculated values of the bending modulus do not go beyond this fork.

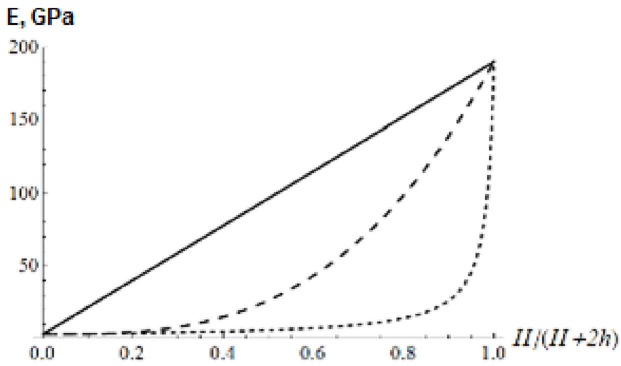

Fig. 2. Calculated dependence of the modulus of elasticity of coated plates on the relative thickness of steel. Solid line - tensile modulus E_p (1), dashed - flexural modulus E_u (5), dashed - Reis averaging.

Figure 3 shows a comparison of the calculated values of the elastic moduli and the experimental data obtained as a result of testing specimens with a thickness of 1,5 mm and 0,7 mm for central tension and three-point bending. The scatter of the obtained experimental values is shown..

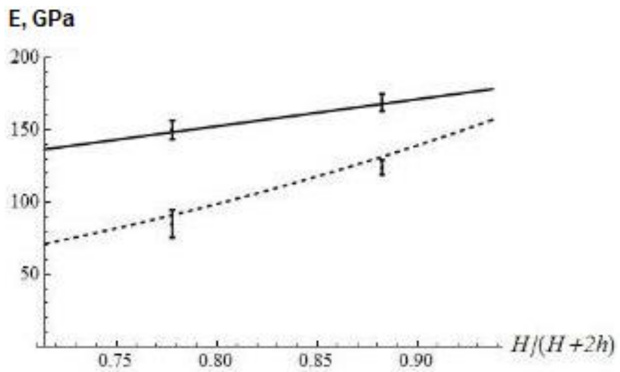

Fig. 3. Comparison of the calculated and experimental values of the elastic moduli of plates with coatings. The solid line is the tensile modulus (1), the dashed line is the flexural modulus (5). The vertical stripes correspond to the scatter of the obtained experimental data.

A comparison of the experimental values of the ultimate strength of the samples and the approximate dependence (2) is shown in the figure 4.

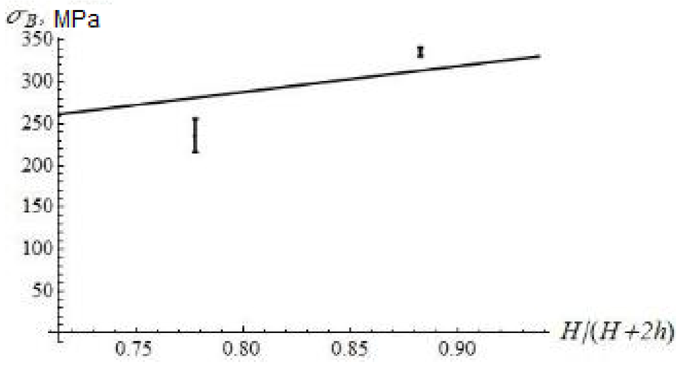

Fig. 4. Comparison of the experimental values of the tensile strength of the samples (vertical lines corresponding to the scatter of values) and the approximate dependence (2).

The experimental results are in good agreement with the calculated values, except for the results of bending tests for thin specimens with a thickness of 0,7 mm. This is apparently due to the insufficient accuracy of the test equipment used for too thin and pliable samples.

3. Conclusion

Models were developed to determine the flexural stiffness depending on the initial radius of curvature generated by residual stresses developing in the coating, mechanical and geometric characteristics of multilayer systems. To construct these models, the elementary provisions of the theory of beams are used. The derivatives of the functions of these models allow calculating the Young's modulus of the coverage. Young's modulus of a multilayer system is calculated from the slope of the load-displacement curve within the linear deformation (obtained in bending tests), while the ratio of the gap to the thickness of the sample is infinite. Several residual stress models are included in the model for determining Young's modulus of a coating undergoing residual stresses.

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