Research Article

Modelling of Mechanical Properties of Metal Plates with Polymer Coatings

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Abstract: In this work, we compare the experimental and calculated results obtained in the numerical simulation of uniaxial tension of specimens of metal plates with a thickness of 0.7 mm. For modeling, the Digimat-FE (MSC) system was used, which in numerical calculations uses the finite element solver of the Marc software package (MSC). It is shown that for samples without coatings, the found theoretical values of the critical load quite well correspond to the points on the experimental diagrams at which the dependence of the load and displacement ceases to be linear. For specimens with coatings, the critical loads are significantly lower, and for their description it is necessary to obtain a refined estimate taking into account the effect of residual stresses.

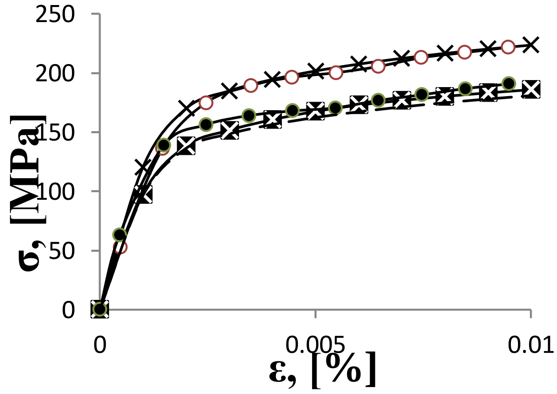
Keywords: Coatings, mechanical properties, modeling, strength, stresses.

Introduction

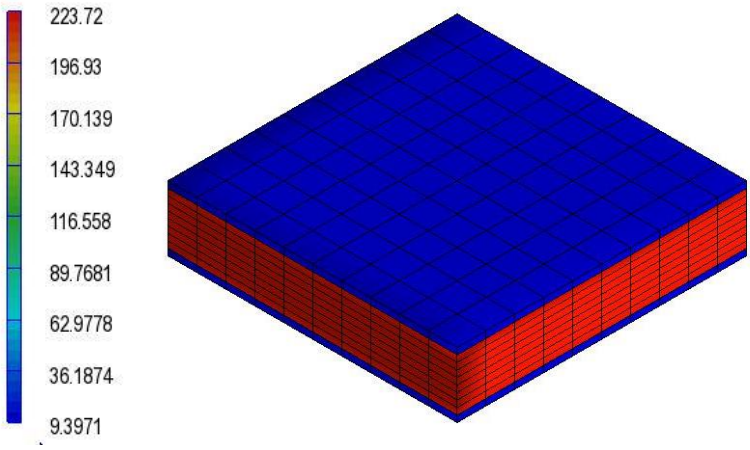
On the basis of the known mechanical properties of coatings, their strength and durability can be assessed taking into account the action of external loads and taking into account the presence of residual stresses arising from the use of heat treatment during the coating process [1-9]. It is also possible to evaluate the effect of coatings on the mechanical behavior of protected thin-walled structures[10-14]. When carrying out strength calculations of large-sized structures, the effect of coatings can often be neglected if the wall thickness of the products significantly exceeds the thickness of the coatings and the rigidity of the coatings is much lower than the rigidity of the structure material[15-20]. However, it is obvious that if the thickness of the coating is comparable to the thickness of the structural element and if the coatings have sufficient rigidity, then their effect cannot be neglected under certain loading conditions[21-29]. On the other hand, coatings properties can be adjusted my the external mechanical action [30-41].

Calculation of the mechanical properties of coated metal plates

The effect of the coating in tensile tests is reduced to a decrease in the level of determined average stresses. The decrease occurs due to an increase in the calculated cross-sectional area of the coated sample. From the point of view of the bearing capacity of the samples, the effect of coatings is insignificant.This is confirmed by calculations. Fig. 1a shows a comparison of the experimental and calculated results obtained in the numerical simulation of uniaxial tension of specimens 0.7 mm thick (Fig.1b). For modeling, the Digimat-FE (MSC) system was used, which in numerical calculations uses the finite element solver of the Marc software package (MSC). As the initial data, the calculation included an experimental stress-strain diagram for a steel substrate and elastic characteristics of the coating: Poisson's ratio of 0.4 and Young's modulus equal to 1 GPa, 3 GPa, or 6 GPa. In the calculations, a uniaxial stress state was specified with a stepwise increase in tensile deformations. At each step of the calculation, the system calculated the average stresses arising in the fragment and, thus, a stress-strain diagram was constructed, which was compared with the experimental data. The calculation was carried out up to 1% deformations at which the polymer coating material is deformed in the linear elastic zone and does not collapse. It was assumed that the deformations of the coating and substrate are compatible. The size of the simulated fragment of the plate was 1×1 cm. Figure 1a shows that the influence of the intrinsic elastic properties of the coatings is insignificant even for the thin samples considered in the calculations, the thickness of which exceeds the thickness of the coatings by only 7 times.



a



b

Fig. 1. Comparison of simulation results and experimental diagrams for the case of uniaxial tension of 0.7 mm thick specimens (a) and an example of finite element modeling of a representative fragment of a coated specimen (b). The color scale shows the level of maximum normal stresses found in the calculation at a given modulus of elasticity of the coating 3 GPa.

The results of testing plates for buckling in compression are shown in Fig. 1. Each diagram in these figures is obtained by averaging experimental data over five samples of the same type. The lower end of the samples was fixed motionless in the grip of the testing machine, and a compressive vertical load was applied to the upper end, also through rigid fixation in the grip. Therefore, in fact, in the experiment, the boundary conditions corresponding to the rigid pinching of the ends of the plates were realized. Fig. 1 shows the found dependences of the displacements of the upper ends of the samples (displacement of the cross arm of the testing machine) on the level of the applied compressive load. It can be seen that, under conditions of supercritical deformation, the diagrams of samples without coatings are significantly higher than those for samples with coatings. The difference in the behavior of the samples turns out to be minimal for the case of their greatest thickness and maximum for thin samples (Fig. 1a, b), which is natural.

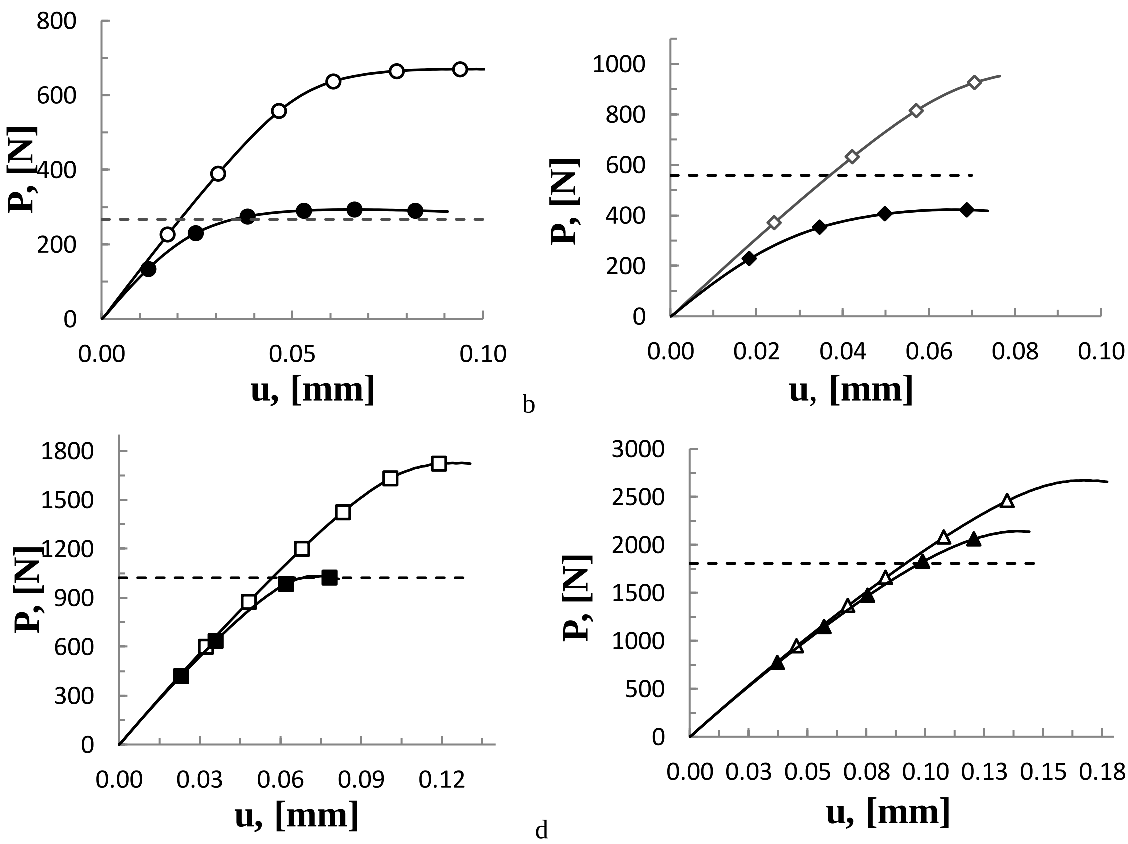


Fig. 2. Results of tests for buckling in compression. The designations are similar to those shown in Fig. 1. The dotted line shows the theoretical value of the critical load buckling.

The theoretical values of the critical load buckling in the graphs $P_{кр}$ in Fig. 2 are marked with horizontal dashed lines. These values were found on the basis of the well-known formula from the theory of bar stability for the case of vertical load action and rigid pinching of the bar ends:

$$P_{кр} = \frac{4\pi^2 EJ}{l^2},$$

where $l =$ 86 mm - rod length, E – Young's modulus, J – moment of inertia of the cross-section of the bar.

When modeling uncoated plates, we take $E = E_{cm}$ – Young's modulus of steel, $J = J_{cm} = bh^3/12$ – moment of inertia of samples with thickness h and width$b$. When modeling coated plates, the flexural stiffness of the corresponding bar should be calculated taking into account the additional contribution from the coating layers: $EJ = 2E_n J_n + E_{cm} J_{cm}$, where$E_n$ - modulus of elasticity of the coating, J_n – moment of inertia of coating layers, offset relative to the neutral line of the bar. However, the use of such a refined estimate leads to an insignificant change in the calculated critical load (within 2%), which cannot explain the obtained experimental data. Therefore, in the graphs in Fig. 2 shows the only critical load value calculated without considering the effect of coatings.

Note that for samples without coatings, the found theoretical values of the critical load are in good agreement with the points on the experimental diagrams at which the dependence of the load and displacement ceases to be linear (see Fig. 2). For specimens with coatings, the critical loads turn out to be significantly lower, and to describe them, most likely, it is necessary to obtain an updated estimate taking into account the effect of residual stresses.

Conclusions

Thin-walled structural elements of aviation, space, automobile technology, which receive loads, are usually made with a thickness of more than 1 mm. In this case, in static strength calculations, the effect of thin polymer coatings can be neglected. However, when assessing the supercritical behavior of structures with loss of stability, when performing nonlinear calculations, etc. neglecting the effect of coatings can lead to errors in the resulting predictions.

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