Assessment of the adhesion strength of composite curved elements

S I Koryagin, O V Sharkov and N L Velikanov
Immanuel Kant Baltic Federal University, 14, A. Nevskogo str., Kaliningrad, 236016, Russia
E-mail: skoryagin@kantiana.ru

Abstract. Modern composites have good strength properties. But insufficient adhesive strength often leads to the delamination of a coating. The Poisson’s ratio, modulus of elasticity, and thermal coefficient of linear expansion are of particular importance among the characteristics of materials that determine different properties of the coating and metal. The ratio of metal and coating thicknesses is also important. The work suggests that the temperature deformations associated with the polymerization of a coating influence the process of delamination of the reinforced polymer coating. Evaluation of the potential of the proposed calculated dependencies was carried out according to the results of experiments. A polymer coating consisting of «Sprut-Plus» adhesive composition and a filler (T-11-GVS-9 glass fabric) was applied to a surface of St.3 steel. For experimental studies, the reinforced polymer coating was kept in water and machine oil for 100 days. The thickness of the coating was taken to be 10 mm, and the thickness of the metal - from 3 to 6 mm. Calculated and experimental dependences of radial stresses on the relative thickness of the polymer coating are obtained. An increase in radial stresses at the interface between the layers of the metal and the reinforced polymer coating after holding the composite material in water has been established; it does not exceed 10%. Analysis of the results showed that the destruction of the adhesive metal-polymer joint is more likely than that of the polymer-polymer adhesive joint. In addition, the radial stresses are at their maximum at the interfaces. Prospects for further research in this direction are associated with express methods of repairing metal structures of complex configuration. It is necessary to increase the efficiency and reliability of calculations of curved elements consisting of metal with a reinforced polymer coating. This can be achieved by a combination of experimental and theoretical research.

1. Introduction
Composite materials combine the protective properties of the coating with the mechanical strength of the metal. Therefore, their application in real operating conditions of machine-building structures is promising [1–3]. In modern mechanical engineering, composite materials are increasingly used for the manufacture of structural elements with various functional purposes [4–8].

The bearing capacity of composite elements largely depends on the adhesive joint between the metal and the reinforced polymer coating [9–14], which is determined by the magnitude of the radial stresses $\sigma_r$ at their interface.

It should be noted that some of the engineering structural elements have a curved shape [15–17]. Information on stresses in polymer coatings on a curved metal surface is limited. The existing calculation methods are applicable when the metal-coating composition is deformed without bending.
2. Materials and Methods

The authors use theoretical and experimental methods to perform a comparative assessment of the radial stresses $\sigma_r$ at the interface between metal layers and reinforced polymer coatings that occur during the manufacture of composite elements with a large curvature of the working surfaces.

The effect of aggressive environmental factors (water, air, and engine oil) on the adhesive strength of composite elements is taken into account.

Theoretical study is based on the theory of the stress-strain state of thin-walled shells [18] and the general theory of elasticity [19]. At experimental studies were used the methods of turning and cutting rings [20, 21], together with a method of strain measurement [22].

The test specimens were composite elements with a curved surface with a radius $R$. St.3 steel was used as a base layer, on which a polymer coating consisting of «Sprut-Plus» adhesive composition and a filler (T-11-GVS-9 glass fabric) was applied. The application of a reinforced polymer coating on the metal surface of the element was carried out in air at a temperature of 18...20 °C.

In the process of manufacturing curved composite elements, such effects as a disruption of the uniformity in the coating layers, a delamination of the coating, and a cracking of the adhesive composition are possible. These defects may be caused by the following factors:

1. Internal residual stresses in the coating caused by differences in the physical and chemical properties of the adhesive composition and filler.
2. Formation of gaseous products during polymerization.
3. Thermal stresses due to the difference in the coefficients of linear expansion of the metal and the coating.
4. Thermal stresses due to temperature gradients in the coating during polymerization.
   In addition, the curvature of the surface also changes the temperature field.

The above factors significantly affect the mechanical properties of the composite and can cause delamination and porosity of the material. It is known that the mechanical interaction between the metal and the coating is mainly influenced by the difference in their Poisson’s ratios and, to a lesser extent, by the elastic moduli.

3. Theoretical estimation of radial stresses

The stress state of a curved composite element (Figure 1) can be considered as a set of plane stress state on the coating surface and three-dimensional stress state at the metal-coating interface. The plane stress state is estimated by the circumferential $\sigma_c$ and longitudinal (meridian) $\sigma_m$ stresses, and the three-dimensional stress – by a combination of three stresses ($\sigma_x$, $\sigma_y$ and $\sigma_z$), of which only radial $\sigma_y = \sigma_r$ stresses are necessary for subsequent calculations.

![Figure 1.](image-url)
Assuming that the main factors of delamination of the reinforced polymer coating are temperature deformations arising in the process of polymerization of the coating applied to the metal surface, the values of radial stresses can be estimated by the dependence:

\[
\sigma_r = \frac{E_1 \delta_1 E_2 \delta_2 \Delta \alpha (\alpha_1 - \alpha_2)}{R (E_1 \delta_1 + E_2 \delta_2)},
\]

(1)

where \( E_1, E_2 \) are the moduli of elasticity of the metal and coating; \( \delta_1, \delta_2 \) are the thicknesses of the metal layer and coating; \( \alpha_1, \alpha_2 \) are the thermal expansions of metal and coating, respectively; \( \Delta t \) is the temperature difference, \( \Delta t = t_2 - t_1 \); \( R \) is the radius of curvature.

Dependence (1) was obtained by solving the problem for a thin-walled curved element [18, 19] from the strain compatibility condition of the metal and coating layers.

4. Computational and experimental evaluation of radial stresses

To confirm the correctness of the calculated dependence (1), experimental studies of composite curved elements were carried out.

The study considered a case unfavorable for an adhesive joint when the resulting stresses of the base material were 0.3...0.5 of the yield point.

The approaches described in the works [20, 21] was used for determining the radial stresses. The stresses were determined by a ring method with variations – with the removal of polymer coating layers, without removing the layers, and cutting the ring in the radial direction.

Without removing the polymer coating, the radial stresses, assuming the correspondence \( p = \sigma_r \), were found using the well-known Barlow's formula [22, 23]:

\[
\sigma_r = \frac{\sigma_{c2} (\delta_1 + \delta_2)}{R},
\]

(2)

where \( \sigma_{c2} \) is the circumferential (shear) stresses on the surface of the composite element.

The value of stresses \( \sigma_{c2} \) was determined using strain measurement [24]. The strain gauges were glued to the convex surface of the composite element from the side of the coating.

The transformed Barlow's formula was used to determine the stresses in the case of successive removal of polymer coating layers from a metal surface:

\[
\sigma_r = \frac{\varepsilon_{R1} E_1 \delta_1}{R},
\]

(3)

where \( \varepsilon_{R1} \) is the deformation in the metal layer.

In this and subsequent cases, the strain gauges were glued to a metal base.

The stresses were also determined through the volume fraction of the polymer coating and the mechanical characteristics of the composite:

\[
\sigma_r = \frac{\varepsilon_{max} k_1 (1-2v_1) (v_1 - v_2) v_2 (1-v_2)}{v_2 (1-2v_1) \left(1 - \frac{k_1}{k_2}\right) + 1 + (1-2v_1) \frac{k_1}{k_2}},
\]

(4)

where \( v_1, v_2 \) are Poisson's ratio of the base and coating, respectively; \( k_1 = E_1 / (1+v_1)(1-2v_1) \); \( k_2 = E_2 / (1+v_2)(1-2v_2) \) are the constants of the base and coating material, respectively; \( \varepsilon_{max} \) is the ultimate deformation.

While simultaneously cutting the rings and removing the coating, the stresses were determined by the following dependence:

\[
\sigma_r = \frac{D}{\pi \delta R^3 \Delta R},
\]

(5)

here \( \Delta R \) is the change in the ring radius; \( D \) is the reduced rigidity of the ring in bending.
5. Comparative analysis of the results

The effect of the thickness of the bearing metal layer at a constant thickness of the reinforced polymer coating on the value of radial stresses $\sigma_r$ under various environmental factors has been investigated.

Calculations of radial stresses were carried out according to dependencies (1)–(5), in which the following magnitudes were taken: $\Delta t=100 ^\circ C$; $E_1=2\cdot 10^5$ MPa, $E_2=1.9 \cdot 10^4$ MPa; $\alpha_1=12\cdot 10^6$ 1/deg, $\alpha_2=9\cdot 10^5$ 1/deg; $R=300$ mm; $v_1=0.30$, $v_2=0.15$.

When carrying out calculations and experimental studies, the thickness of the reinforced polymer coating $\delta_2$ was taken equal to 10 mm, and the metal thickness $\delta_1$ was taken in the range from 3 to 16 mm.

In addition, the composite elements made in air at a temperature of 18...20 °C were kept in water and machine oil for 100 days.

Tables 1–2 show the behavior of radial stresses obtained by theoretical and calculation-experimental methods, depending on the thickness of the polymer coating.

**Table 1.** Calculated and experimental radial stresses.

| $\delta_2$, mm | Value of $\sigma_r$, MPa | By dependencies | Ring turning method | Ring cutting method |
|---------------|--------------------------|----------------|-------------------|-------------------|
|               |                         | (1)            | (2)               | (4)               |
| 3             | 80.0                     | 74.4           | 71.3              | 68.1              | 76.3              |
| 5             | 88.8                     | 82.4           | 76.9              | 75.5              | 83.9              |
| 8             | 94.8                     | 88.2           | 84.8              | 80.6              | 89.8              |
| 10            | 96.9                     | 90.1           | 86.7              | 81.4              | 92.0              |
| 12            | 98.4                     | 91.5           | 88.4              | 83.7              | 92.9              |
| 14            | 99.6                     | 92.6           | 89.2              | 84.7              | 93.7              |
| 16            | 100.3                    | 93.2           | 89.9              | 85.3              | 94.4              |

A slight increase (by 5…9%) in radial stresses at the interface between the layers of the metal and the reinforced polymer coating after keeping the composite material in water for 100 days can apparently be explained by the interaction of the coating with water (Table 2).

**Table 2.** Radial stresses after exposure to water and oil.

| $\delta_2$, mm | Value of $\sigma_r$, MPa | Ring turning method | Ring cutting method |
|---------------|--------------------------|-------------------|-------------------|
|               | In oil                   | In water          | In oil            | In water          |
| 3             | 68.4                     | 71.8              | 76.5              | 80.3              |
| 5             | 75.3                     | 79.1              | 84.0              | 88.2              |
| 8             | 80.7                     | 84.7              | 89.9              | 93.6              |
| 10            | 81.2                     | 85.3              | 92.2              | 96.6              |
| 12            | 83.9                     | 88.0              | 93.2              | 97.7              |
| 14            | 84.5                     | 88.8              | 93.9              | 98.2              |
| 16            | 85.4                     | 89.7              | 94.5              | 99.7              |
The mechanism of the effect of water on the adhesive strength of bond between a metal and a reinforced polymer coating is far from clear. Observations have shown that polymer-coated metal adhesive joints are often destroyed in an interfacial manner, i.e. the interface is particularly sensitive to a decrease in adhesion strength under the influence of water. In this case, water is accumulated near the interface, and its further penetration into the adhesive joint of the metal and the coating and between the layers of the polymer coating is difficult. The observations made it possible to establish that the destruction of the adhesive metal-polymer joint is more likely than the polymer-polymer adhesive joint destruction. The density of the reinforced polymer coating decreases slightly (by about 1%) due to the destruction of macromolecules of the adhesive composition at the interface under the influence of water.

After exposure for 100 days in engine oil, the values of radial stresses were almost equal to those in air at a temperature of 18...20 °C (Table 2).

Studies have shown that the value of the radial stress at the interfaces reaches its maximum and decreases as it approaches the surface, i.e. with an increase in the thickness of the composite element, the magnitude of this stress increases.

6. Conclusion
A good qualitative and quantitative agreement was obtained between theoretical and experimental values of radial stresses at the interface between the metal and polymer coating layers. The greatest discrepancies between the maximum and minimum stress values do not exceed 17...20%.

It is shown that the main reason for the appearance of radial stresses in composite elements is the difference in Poisson's ratios and linear expansion of materials. In addition, as a result of plastic flow of the metal, the difference between the Poisson's ratios of the base and the coating increases, since the material of the base (metal) has a higher Poisson's ratio, i.e. the magnitude of stresses increases significantly with the development of plastic flow.

The correctness of using dependencies (1)–(5) for engineering estimation of radial stresses at the interface between metal and polymer coating layers has been experimentally confirmed.

References
[1] Zhang K, Zhang W and Ding X 2019 Procedia CIRP 85 114–120
[2] Kheruvimov A, Nikonov A and Aliukov S 2018 SAE Technical Papers 2019-April (April)
[3] Gay D, Hoa S V and Tsai S W 2002 Composite materials: Design and applications (Boca Raton: CRC Press) p 552
[4] Somireddy M, Singh C V and Czekanski A 2020 Engineering Failure Analysis 107 104232
[5] Sharma S, Sudhakara P, Nijjar S, Saini S and Singh G 2018 Materials Today: Proceedings 5(14) 28195–28202
[6] Sun H, Tao Y and Zhang J 2020 J. of Alloys and Compounds 847 156527
[7] Koryagin S I, Sharkov O V and Velikanov N L 2018 Materials Science Forum 938 46–53
[8] Xu S, Chena L, Gong M, Hu X, Zhang X and Zhou Z 2017 Composites Part B: Engineering 111 143-147
[9] Nurprasetio I P, Budiman B A and Aziz M 2018 Int. J. of Adhesion and Adhesives 85 193–201
[10] Sun S, Yang R, Han J, Guo H and Xing L 2016 Surface and Coatings Technology 297 19–26
[11] On S Y, Kim M S and Kim S S 2017 Composite Structures 159 636–645
[12] Ekrem M and Avci A 2018 Composites Part B: Engineering 138 256–264
[13] Bartkowiak M, Czech Z, Mozelewskas K and Nowak M 2020 Polymer Testing 90 106603
[14] Zhai L L, Ling G P and Wang Y W 2008 Int. J. of Adhesion and Adhesives 28(1–2) 23–28
[15] Zappino E, Zobeiry N, Petrolo M, Vaziri R, Carrera E and Poursartip A 2020 Composite Structures 241 112057
[16] Li B, Li H, Hu X, Feng G, Yao X and Wang P 2020 J. of the European Ceramic Society 40(8)
[17] De Miguel A G, De Pietro G, Carrera E, Giunta G and Pagania A 2018 *Computer Methods in Applied Mechanics and Engineering* **337** 481–500

[18] Ventsel E and Krauthammer T 2001 *Thin Plates and Shells: Theory: Analysis, and Applications* (Boca Raton: CRC Press) p 688

[19] Lurie A I 2010 *Theory of Elasticity* (Berlin: Springer Science & Business Media) 1050 p

[20] Totten G E, Howes M and Inoue T 2002 *Handbook of Residual Stress and Deformation of Steel* (Ohio: ASM International) p 499

[21] Niku-Lari A 2002 *Advances in surface treatments: Technology-Applications-Effects. Vol. 4. Residual Stress* (Amsterdam: Elsevier) p 586

[22] Sinclair G B and Helms J E 2015 *Int. J. of Pressure Vessels and Piping* **128** 1–7

[23] Salehi M M, Khalkhali T and Davoodi A A 2016 *Polymer Science Series A* **58** 567–577

[24] Keil S 2017 *Technology and Practical Use of Strain Gages: With Particular Consideration of Stress Analysis Using Strain Gages* (Berlin: Ernst & Sons) p 512