Influence of the Porous Structure of a Cement Substrate on the Stress State of Coatings

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Abstract. The article presents the results of a study of the effect of pores, unfilled with a paint composition, on cracking of paint coatings. A model for calculating stresses is presented. The effect of the discrete nature of the contact of the coating with the substrate on the distribution of internal stresses in the coating is established. The effect of the pore size on the substrate and the coating thickness on the values of internal stresses is shown. It was found that in the absence of cracking in the coating, the dependence of the stress on the pore diameter in the contact zone is practically not manifested. It is shown that at a coating thickness of more than 0.09 cm, the relative deformations of the coating exceed the value of the ultimate elongation, cracking is predicted. The stress values in the coating above the pore not filled with the paint composition are constant. For the area of dense abutment of the coating, the dependence of the stress value on the pore diameter is observed.

1. Introduction

Coatings for finishing the facades of buildings, performing aesthetic protective functions, must have a high quality appearance \cite{1, 2}. The presence of defects on the surface of coatings contributes not only to a decrease in decorative properties, but also to their premature destruction. Cracking is one of the common causes of coating failure \cite{3-7}. According to the theory of brittle fracture, cracking of coatings will occur if the internal tensile stresses reach the value of the cohesive strength of the coating material, i.e.

\[
\sigma > R_{\text{coh}}
\]  

(1)

The coating-substrate system is a laminate material. As in any laminate system, the contact layer plays a decisive role, binding the paint composition to the base. The influence of the substrate on the structure of paint and varnish coatings is considered in works \cite{8-11}. The influence of the nature of the substrate on the properties of coatings increases with the use of porous substrates. According to \cite{12-15}, in coatings formed on a porous substrate, a shift of the zone of maximum internal stresses into the depth of the substrate is observed.

In relation to the contact area of the coating with the substrate, internal stresses can act in different directions. Distinguish between tangentially directed and normally directed stresses. With a rough substrate (the surface of plaster, concrete, asbestos cement) surface protrusions to some extent "absorb" internal stresses. With an increase in the thickness of the coating, if the thickness of the coating exceeds...
the height of the protrusions, the protrusions themselves are not able to compensate for the effect of internal stresses. It in some cases also leads to cracking of the coatings [16-19].

Taking into account the discrete nature of the contact, it becomes necessary to take into account the presence of pores that are not filled with the paint composition.

2. Materials and methods

The calculation of internal stresses in the coatings was carried out in accordance with the following procedure [20]. Fig. 1 shows the design model of the coating (layer 2). For a strip of coating of unit width, tightly adjacent to the base, the differential equilibrium equation has the form

\[ \frac{d^2u}{dx^2} - n^2U = -n^2 \varepsilon x \]  

(2)

where \( n = \sqrt{G/H_E} \)

\( U(x) \) - unknown uniaxially displacements of the coating;

\( E \) is the modulus of elasticity of the coating;

\( G \) - shear modulus of the coating.

For the coverage area above the pore, where there is no interaction with the base, the differential equilibrium equation takes the form

\[ U'(x) = 0 \]  

(3)

Thus, the problem is reduced to solving two differential equations: equation (2) for the section over the pore \((0 < x < 1/2)\), equation (3) for the section of dense abutment of the coating

\[ \frac{1}{2} < x < L/2 \]

The solution to these equations is:
\[ U_1(x) = C_1(x) + D_1 \] at \( 0 < x < l/2 \)  
\[ U_2 = C_2 \text{ch}(nx) + D_2 \text{sh}(nx) + x \varepsilon \] at \( \frac{l}{2} < x < \frac{L}{2} \)  

Integration constants \( C_1, D_1, C_2, D_2 \) are determined from the boundary conditions:
- symmetry condition for displacements relative to the pore center
  
at \( x = 0 \) \( U_1 = 0 \);  
continuity condition for displacement and deformation at the pore boundary
  
at \( x = \frac{l}{2} \) \( U_1 = U_2, \quad U_1' = U_2' \)  
and no stress in the crack
  
at \( x = \frac{L}{2} \) \( U_2 - 2U_1 = 0 \)

Substituting the values of the constants in (6),(7) you can obtain the final solution of the original differential equations:

\[ U_1(x) = \varepsilon x \left[ 1 - \frac{1}{\text{ch}(\beta - \alpha)} + \alpha \text{sh}(\beta - \alpha) \right] \] at \( 0 < x < \frac{l}{2} \)  
\[ U_2(x) = \varepsilon \left[ 1 + \frac{\text{ch}(nx - \alpha) + \alpha \text{sh}(nx - \alpha)}{\text{ch}(\beta - \alpha) + \alpha \text{sh}(\beta - \alpha)} \right] \] at \( \frac{l}{2} < x < \frac{L}{2} \) \( \alpha = \frac{n l}{2}, \beta = \frac{n L}{2} \)

Relative deformations and corresponding the stresses \( \sigma = \varepsilon U^r \) of the finishing layer over pore are constant:

\[ U_1(x) = \varepsilon \left[ 1 + \frac{1}{\text{ch}(\beta - \alpha)} + \alpha \text{sh}(\beta - \alpha) \right] \]  
Outside the pore, the relative deformations change according to the law

\[ U_2(x) = \varepsilon \left[ 1 + \frac{\text{ch}(nx - \alpha) + \alpha \text{sh}(nx - \alpha)}{\text{ch}(\beta - \alpha) + \alpha \text{sh}(\beta - \alpha)} \right] \]

Cracks in the finishing layer will appear if the largest deformations exceed the ultimate deformations of the layer \( \varepsilon_{lim} \)

\[ \varepsilon \left[ 1 + \frac{1}{\text{ch}(\beta - \alpha)} + \alpha \text{sh}(\beta - \alpha) \right] \geq \varepsilon_{lim} \]

From this condition, taking into account the notation (9), it is possible to obtain the calculated distances between shrinkage cracks in the finishing layer

\[ L = 1 + 2/n \ln \left\{ \frac{\varepsilon}{(\varepsilon - \varepsilon_{lim})(1 + \alpha)\chi} + \sqrt{\frac{1}{(1 - \alpha^2)(\varepsilon - \varepsilon_{lim})}} \right\} + \frac{1 - \alpha^2}{\varepsilon^2} \]
Polyvinyl acetate paint was used as paint formulations. Shrinkage strains were measured using an IZA-2 optical comparator.

Tensile strength (cohesive strength) was determined in accordance with GOST 18299-72 * “Paints and varnishes. Method for determining ultimate tensile strength, elongation at break and elastic modulus” on a tensile testing machine IR 5057-50. The method is based on stretching a test specimen 0.7 × 10 × 50 mm in size to rupture at a deformation rate of 1 mm / min. The samples were fixed in the clamps of a tensile testing machine so that its longitudinal axis was located in the direction of tension, and the applied forces acted uniformly over the entire cross section of the sample. The tests were carried out at air temperature = 20 ± 2 °C and relative air humidity = 65%. The calculation of the ultimate tensile strength was carried out according to the test results of at least five samples of each composition. Tensile strength, MPa (N / mm²) for each sample was calculated by the formula:

\[ R_{cog} = \frac{F_{pl}}{S_{oi}} \]  

where \( F_{pl} \) is the tensile load at the moment of rupture, N; \( S_{oi} \) - initial cross-sectional area of the sample, m².

The elongation at break of each sample (\( \varepsilon \)) in percent was calculated by the formula:

\[ \varepsilon_i = \frac{\Delta l_i}{l_0} \]  

where \( \Delta l_i \) is the increment in the length of the working part of each sample, mm; \( l_0 \) - the initial length of the working part of each sample, mm.

The modulus of elasticity was calculated from the “stress - deformation” diagram by the tangent of the angle of inclination to the abscissa axis of the tangent (Z) drawn to the initial rectilinear section of the diagram. The elastic modulus for each sample was calculated by the formula:

\[ E_i = \frac{R_i}{\varepsilon_i} \]  

where \( R_i \) is the ultimate tensile strength at the moment of separation of the tangent from the stress-strain diagram, MPa; \( \varepsilon_i \) - elongation at break, %.

3. Research results

In accordance with the above equations (7), (8), (10), (11) the stress values in the coatings were calculated depending on the pore size, coating thickness using the example of PVAC paint. The results of calculations and studies are summarized in Table 1.

| Coating thickness, H, [cm] | Pore diameter, [cm] | Stress value, [MPa] | In the coating over pore | In the coating on contact with the substrate |
|---------------------------|-------------------|-------------------|-------------------------|----------------------------------------|
| 0,09                      | 0,3               | 0,585             | 0,585                   | 0,519                                  |
| 0,09                      | 0,2               | 0,585             | 0,519                   | 0,519                                  |
| 0,01                      | 0,05              | 0,585             | 0,519                   | 0,519                                  |
| 0,06                      | 0,3               | 0,54              | 0,501                   | 0,501                                  |

1. Cracks are not predicted.
2. Cracking is predicted

| x  | σ  | σ̂   |
|----|----|------|
| 0.18 | 0.2 | 0.657 | 0.069/2.094 |
| 0.1  | 0.2 | 0.657 | 0.061/2.084 |
| 0.05 | 0.2 | 0.657 | 0.059/2.08 |
| 0.0  | -   | -    | 0.0582/2.079 |
| 0.225| 0.2 | 0.657 | 0.041/2.056 |
| 0.1  | 0.2 | 0.657 | 0.033/2.046 |
| 0.05 | 0.2 | 0.657 | 0.031/2.043 |
| 0.0  | -   | -    | 0.039/2.042 |

Notes: The stress values are given for x - 7 contact length l = 16 cm. Above the line are the stress values x - I cm, below the line - the distance between shrinkage cracks, cm.

Analysis of the experimental data (Table 1) shows that no cracking of the coating is observed at a coating thickness of up to 0.09 cm. This is also confirmed by the calculated data in accordance with equation (2.14). The values of the stresses of the coating above the pore are constant and at a coating thickness H = they are = 0.54 MPa, and at a coating thickness H = 0.09 cm = 0.585 MPa, while in the coating upon contact with the substrate, respectively 0.519 MPa and 0.501 MPa at x - 7 cm with a contact length of 16 cm. In the absence of cracking in the coating, the dependence of the stress on the pore diameter in the contact zone is practically not manifested.

When the coating thickness is more than 0.09 cm, the relative deformations of the coating exceed the value of marginal extensibility and, in accordance with equation (11), cracking is predicted, which is confirmed by experimental data. In this case, the stresses in the coating over the pore not filled with the paint composition are = 0.657 MPa, and for the area of dense adhesion of the coating, the dependence of the stress value on the pore diameter is observed (Table 1). So, with a coating thickness of H = 0.225 cm, the value of internal normal stresses with a pore diameter l = 0.2 cm at the contact boundary is = 0.041 MPa, and with a pore diameter l = 0.05 cm -0.0315 MPa. With a decrease in the coating thickness, the dependence of the stress on the pore diameter manifests itself to a greater extent. So, with a coating thickness of H = 0.18 cm, the stresses are respectively = 0.069 MPa and = 0.0591 MPa.

4. Conclusion

Thus, the presence of pores in the contact zone of the coating with the cement substrate contributes to the appearance of a more inhomogeneous stress-strain state in comparison with a smooth, inporous substrate. In order to increase the crack resistance, and, consequently, the operational resistance of coatings, it is necessary to strive by technological methods to create cement substrates characterized by uniformly distributed small pores.

5. References

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