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Experimental Study of High-Temperature Exposure Effect on Reinforcement-Concrete Bond in Corrosion-Damaged Reinforced Concrete

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Abstract. The object of this study is the bond between reinforcement and concrete after exposure to high temperatures and corrosion, which is critical for assessing the durability of reinforced concrete structures. The analysis of scientific sources revealed that at temperatures above 300°C, the bond deteriorates due to thermal expansion of the reinforcement, degradation of the cement matrix, and crack formation. Simultaneously, corrosion reduces adhesion and weakens mechanical interlocking, accelerating concrete deterioration. However, the combined effect of these factors remains insufficiently studied, and the existing bond models do not fully account for their simultaneous impact. In this experiment, concrete specimens with A500C reinforcement were subjected to electrochemical corrosion and heated to 400°C. Pull-out tests revealed a significant reduction in bond strength, attributed to the destruction of the adhesive layer and changes in the interaction mechanism: in unheated specimens, the bond was ensured by plastic deformations of concrete, whereas in heated specimens, it was maintained by friction against corrosion products. Comparison with previous studies on the influence of temperature, reinforcement types, and heating rates confirmed the consistency of the results and clarified the role of pre-existing corrosion. The obtained experimental data not only validates the existing studies, but also extends them by incorporating the effect of pre-corrosion, which was previously considered in a limited scope. The findings can be used to predict the consequences of thermal exposure, assess the residual strength of structures, and develop restoration methods.

Keywords: reinforcement adhesion, load-bearing capacity, cracks, slip, operating conditions, bond stress, plastic deformations, heating

Conflicts of interest. The authors declare that there is no conflict of interest.

Authors' contribution: *Tamrazyan A.G.* — supervision, conceptualization, review and editing; *Baryak D.S.* — literature review, experimental investigation, data processing, conclusions.

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Экспериментальные исследования влияния высокотемпературного воздействия на сцепление арматуры и бетона в коррозионно-поврежденном железобетоне

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Аннотация. Объект исследования — сцепление арматуры с бетоном после воздействия высоких температур и коррозии, что имеет ключевое значение для оценки долговечности железобетонных конструкций. Анализ научных источников показал, что при температурах выше 300 °С сцепление ухудшается за счет термического расширения арматуры, деградации цементного камня и образования трещин. Одновременно коррозия снижает адгезию и ослабляет механическое зацепление, ускоряя разрушение бетона. Однако комплексное влияние этих факторов изучено недостаточно, а существующие модели сцепления не учитывают их одновременное воздействие. В рамках эксперимента исследовались бетонные образцы с арматурой А500С, подвергнутые электрохимической коррозии и нагретые до 400 °С. Испытания на выдергивание арматуры выявили значительное снижение сцепления, связанное с разрушением адгезионного слоя и изменением механизма взаимодействия: в ненагретых образцах сцепление обеспечивалось пластическими деформациями, тогда как в нагретых обеспечивалось трением о продукты коррозии. Сравнение с предыдущими исследованиями, рассматривающими влияние температуры, типов арматуры и скоростей нагрева, подтвердило согласованность результатов и позволило уточнить роль предварительной коррозии. Полученные экспериментальные данные не только подтверждают существующие исследования, но и дополняют их за счет учета предварительной коррозии, что ранее рассматривалось в ограниченном объеме. Результаты могут быть использованы для прогнозирования последствий термических воздействий, оценки остаточной прочности конструкций и разработки методов восстановления.

Ключевые слова: адгезия арматуры, несущая способность, трещины, проскальзывание, условия эксплуатации, напряжения сцепления, пластические деформации, нагрев

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1. Introduction

The bond between reinforcement and concrete is a key factor that ensures the combined action of reinforced concrete as solid material [1]. Violation of this bond leads to crack formation, reduction of structural stiffness and decrease of load-bearing capacity. Various models based on experimental data and theoretical studies have been developed to calculate the reinforcement-concrete bond strength.

The main parameters affecting the bond between reinforcement and concrete:

- Strength characteristics of concrete: axial tensile strength, concrete composition, presence of micro-cracks.
- Type and geometry of reinforcement. These are mainly diameter, shape.
- Type of load: static, dynamic, cyclic.
- Reinforcement confinement: reinforcement ratio and the influence of stirrups.

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- Operating conditions: temperature and humidity conditions, corrosion and other external factors.

The following methods of calculating the bond stress are considered:

1) ***The model of M.M. Kholmyansky*** [2]. The proposed methodology of bond stress calculation is based on experimental studies:

$$\tau = B\frac{\ln(l+as)}{l+as},$$

where $B = e\cdot\tau_{\max}$ is the coefficient determined by tests; $a=\frac{e-l}{S_{\max}}$ is the coefficient dependent on bond length l and maximum slip $S_{\max}$.

2) ***CEB-FIP Model Code 90***[1]. This model describes the relationship between bond stress τ and slip s over several diagram regions:

$$\tau=\begin{cases}\tau_{\max}\left(\frac{s}{s_1}\right)^{\alpha}, & 0\le s<s_1;\\ \tau_{\max}, & s_1\le s<s_2;\\ \tau_{\max}+\left(\tau_f-\tau_{\max}\right)\frac{s-s_2}{s_3-s_2}, & s_2\le s<s_3;\\ \tau_f, & s>s_3,\end{cases}$$

where $\tau_{\max}$ is the maximum bond stress; τ_f is the residual bond stress; s_1, s_2, s_3 are the slips at the key points on the diagram.

3) ***Modification of CEB-FIP*** [3]. The model accounts for the nonlinear behavior of the downward branch of the diagram:

$$\tau=\begin{cases}\tau_{\max}\left(\frac{s}{s_{\max}}\right)^{\alpha}, & s\le s_{\max};\\ \tau_{\max}\left(\frac{s}{s_{\max}}\right)^{-\alpha'}, & s>s_{\max}.\end{cases}$$

4) ***ACI Committee 318***[2]. The American Concrete Institute proposes a model relating bond stress f_b to normal stress σ_n:

$$f_b=\frac{2\mu}{\pi}\sigma_n+f_{\text{adh}},$$

where $\sigma_n=\sigma_c+\sigma_{st}+\sigma_{\text{conf}}$ is the normal stress including concrete confinement σ_c, stirrup reaction σ_{st} and transverse stress σ_{conf}; f_{adh} is the bond stress due to adhesion.

5) ***Y. Tian et al.*** [4]. This bond model includes three stages:

$$\tau=\begin{cases}\kappa_1 S, & 0\le s\le s_{\text{cr}};\\ \tau_{\text{cr}}+\kappa_2(s-s_{\text{cr}}), & s_{\text{cr}}<s\le s_u;\\ \tau_u+\kappa_3(s-s_{\text{u}}), & s_u<s\le s_r;\\ \tau_r, & s>s_r,\end{cases}$$

where τ_u, τ_r, s_u and s_r describe the characteristics of bond stress and slipping at different stages.

[1] *CEB-FIP Model Code 90.* Available from: http://www.tocasa.es/zona2/CEB_FIP_model_code_1990_ing.pdf (accessed: 22.07.2024).

[2] ACI Committee 318, Building Code Requirements for Structural Concrete (ACI 318-02) and Commentary (318R-02). *American Concrete Institute*. Farmington Hills, MI; 2002.

Corrosion of reinforcement is one of the most significant factors affecting the bond between reinforcement and concrete. It causes destruction of the adhesive bond, changes in the geometry of the reinforcement and weakening of the mechanical interlocking.

Empirical models are proposed by various researchers for quantitative analysis of the relationship between the bond and the degree of corrosion:

1) ***J.G. Cabrera*** [5]. The model describes the decrease in bond stress as a function of the degree of corrosion (n):

$$R_t = 1 - 5.6n,$$

where R_t is the relative bond strength (in fractions of the original), n is the degree of corrosion;

2) ***K.D. Stanish, R.D. Hooton, S.J. Pantazopoulou*** [6]:

$$R_t = 1 - 3.5n;$$

3) ***Y. Yuan, S. Yu, F. Jia*** [7]. The model takes into account the effect of concrete cover layer c and reinforcement diameter d:

$$R_t = 1 - \left(10.544 - \frac{1.586c}{d}\right)n;$$

4) ***Y. Auyeung, P. Balaguru, L. Chung*** [8]:

Exponential relationship model:

$$R_t = e^{-32.51n};$$

5) ***L. Chung, S.H. Cho, J.H.J. Kim, S.T. Yi*** [9]:

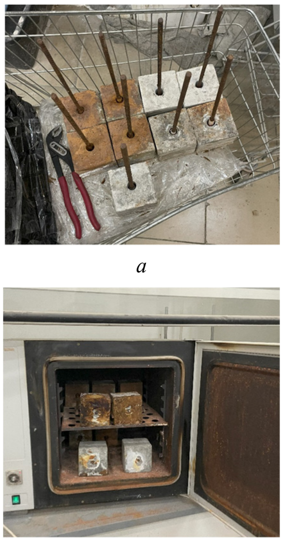
$$R_t = 0.0159n^{-1.06},\ R_t \le 1.0.$$

The analysis of the existing models of reinforcement-concrete bond shows that most of them are based on geometric, mechanical and chemical characteristics of materials, as well as external factors such as corrosion of reinforcement. These relationships allow to give a reasonable approximation of the bond strength under normal service conditions and in the presence of corrosion damage. However, temperature effects, especially under conditions of short-term or long-term exposure, remain a poorly studied aspect, despite their significant influence on the strength characteristics of reinforced concrete structures [10; 11].

Although a number of studies have examined the reinforcement-concrete bond behavior after exposure to high temperatures [12; 13], these studies mainly focus on individual aspects, such as the effect of anchorage length [12] or fiber reinforcement of concrete [13], but do not provide a comprehensive picture of the effect of different temperature regimes on the bond. Similarly, studies [14; 15] consider the dynamic behavior of the bond during heating, but their methodologies do not allow to fully describe the behavior of the reinforcement under real service conditions

In addition, a number of publications are devoted to the investigation of the reinforcement bond under specific conditions, such as the use of steels with high corrosion resistance [16] or the influence of high-strength reinforcement [17], which is certainly important, but does not solve the problem of comprehensive analysis of the temperature effects. Thus, despite the available studies, currently, there is insufficient experimental data to evaluate the reinforcement-concrete bond subjected to short-term or long-term heating in detail, which emphasizes the relevance of this study.

Despite the existence of general approaches to the evaluation of temperature effects on materials, there are no accurate empirical relationships that allow to take into account the effect of heating on the bond. Moreover, the failure mechanisms under such conditions, including adhesion failure and loss of mechanical interlocking, have not been sufficiently substantiated experimentally. This complicates both the development of new design solutions and correct prediction of service life of reinforced concrete structures subjected to thermal effects.



a *b*

Figure 1. Test specimens:
a — not exposed to heating;
b — exposed to heating
Source: photo by D.S. Baryak

Figure 2. Experimental setup with a test specimen
Source: photo by D.S. Baryak

a *b*

Figure 3. Specimens after testing:
a — reinforcement;
b — concrete prisms
Source: photo by D.S. Baryak

2. Methods

In this study, the influence of heating to temperatures of about 400°C on the reinforcement-concrete bond was experimentally evaluated. The purpose of the experiment was to study the failure mechanism of the test specimens and to determine the characteristic relationships between temperature and bond stress. The experimental procedure included reinforcement pull-out tests from concrete specimens subjected to different levels of heating. The pull-out tests were performed on the Instron 3382 electromechanical universal testing machine (manufacturer: Instron, city: Norwood, country: USA) with a maximum load capacity of 100 kN, equipped with the Bluehill control system and providing high accuracy of measurements due to electronic control of load and deformation. Heating was performed using the SNOL 7.2/1100 laboratory muffle furnace (manufacturer: AB UMEGA GROUP, city: Utena, country: Lithuania) with a maximum heating temperature of 1100°C, operating temperature range of +50° to 1100°C and temperature accuracy of ±1°C. The data obtained allowed not only to determine the degree of influence of temperature on adhesion, but also to identify the key degradation mechanisms, which can serve as a basis for further improvement of the existing models.

The experiment was conducted at the premises of Moscow State University of Civil Engineering (National Research University). A500C grade steel bars of 400 mm length and 8 mm diameter and B25 grade concrete cubes were used for specimen fabrication. The working length of rebar in contact with concrete was 40 mm (equivalent to five rebar diameters). The rest of the rebar was isolated from the concrete using plastic tubing. The general view of the specimens before testing, the experimental setup and the specimens after testing are shown in Figures 1–3. Electrochemical attack method was used to create corrosion damage. The specimens were placed in plastic containers filled with 5% NaCl solution. Using a DC stabilizer, a positive charge was applied to the rebar and a negative charge was applied to the solution. Electrochemical corrosion was conducted at a constant current strength of 0.5 A for 60 days. As a result, bars with a corrosion percentage of 12% in terms of rebar diameter and 23% in terms of cross-sectional area were obtained.

Sample preparation

Two groups of specimens were prepared for the experiment:

1. Control group: unheated specimens.
2. Damaged rebar group: heated specimens.

3. Results and Discussion

During processing of the experimental data, the averaged values were obtained, which were used for plotting the graphs of the relationship between the displacement of the free end of the reinforcing bar and the magnitude of the applied load. The results are summarized in Table, and also in Figure 4.

As a result of experimental data processing, it was found that for the specimens before heating, the average value of the reinforcement-concrete bond strength is 24.47 MPa, while after heating to a temperature of 400°C this value decreases to 17.38 MPa. Thus, heating of the specimens leads to a 28.96% decrease in bond strength, which indicates a significant influence of temperature on the adhesion properties of rein-forcement and concrete.

The maximum value of bond strength before heating was observed in specimen 7, which was equal to 30.80 MPa. After heating, the maximum value of bond strength was recorded for specimen 10, which was equal to 21.71 MPa. The minimum value of bond strength for the specimens before heating was 19.83 MPa (specimen 2), and 8.88 MPa after heating (specimen 11).

Table

Results of the experiment on determination of bond strength

№	**Maximum force, kN**	**Bond strength, MPa**	**Average bond strength, MPa**
Samples before heating			
1	21.03	20.91	24.47
2	19.93	19.83	
3	22.74	22.62	
4	22.91	22.79	
5	27.19	27.05	
6	25.78	25.65	
7	30.96	30.80	
8	23.95	23.82	
9	26.90	26.76	
Samples after heating			
10	21.82	21.71	17.38
11	8.92	8.88	
12	20.19	20.08	
13	22.57	22.45	
14	14.74	14.67	
15	12.11	12.05	
16	19.73	19.63	
17	18.53	18.43	
18	18.61	18.51	

S o u r c e: made by D.S. Baryak

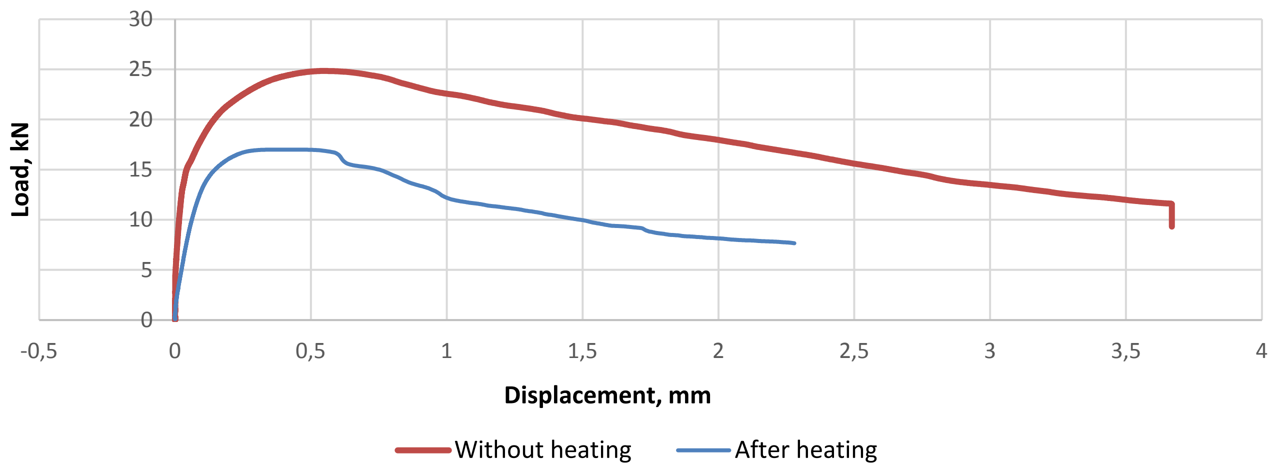


Figure 4. Graph of experimental results

S o u r c e: made by D.S. Baryak

The obtained results indicate a critical decrease in the reinforcement-concrete bond strength under the influence of temperature. This is consistent with studies [12–14], where the decrease in bond strength at temperatures of 350–400°C was 25–40%, confirming the significant effect of heat on the degradation of adhesion properties of reinforcement and concrete. In [15], it was observed that the heating rate has a significant effect on bond degradation, with moderate heating rates used in this study giving comparable results to those reported previously. In addition, data from [16; 17] indicate that the use of corrosion-resistant reinforcement partially compensates for the temperature-related bond loss, but this study shows that with standard A500C reinforcement, temperature effects lead to bond degradation regardless of the corrosion layer. Thus, the obtained experimental data not only confirm the existing studies, but also supplements them by taking into account pre-corrosion, which was previously considered to a limited extent. This emphasizes the relevance of the work and its contribution to the study of the influence of temperature on the bond between reinforcement and concrete.

4. Conclusion

1. The tests showed a 30% decrease in the reinforcement-concrete bond strength after heating to 400°C relative to unheated specimens. This confirms the significant influence of temperature on the adhesion properties of corrosion-damaged reinforcement.

2. The analysis of the stress-displacement plots shows that heating leads to a decrease in the ultimate stress and changes the nature of the system behavior. For heated specimens, an earlier drop in stress after the peak is observed, which indicates a decrease in the load capacity.

3. In unheated specimens, the bond with concrete is provided by plastic deformations of concrete between the protrusions of the reinforcement surface profile. In heated specimens, this interaction is weakened and the bond is more dependent on friction against corrosion products, resulting in a sharper bend in the graph at the point of maximum load.

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