

Durability of Concrete Reinforced by Specific Rebar

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Abstract. Design of reinforced concrete is based on assuming that applied rebar has no corrosion damages at its surface. However, conventional construction practice allows the rebar embedded into concrete to have surface rust. Being transported in open railway cars, by river or marine transports, being in warehouses of intermediate traders and then affected during this time by an atmospheric precipitation and sometimes even aggressive agents of the environment (for example, being in direct contact with remains of chlorides which are earlier transported in the same cars), rebar arrives to construction site with corrosion defects of different types and various extents. Corrosion damages are caused not only by the conditions of its transportation and storage, but also by poor quality of the steel itself. This may lead to dangerous consequences such as sudden collapses of building constructions without preliminary visible deflections and deformations. One of the reasons of sudden structure collapses related to steel quality is strong structure heterogeneity stressed out by the slag immerge at the surface from the bar's core. The emergence of slag to a surface of the rebar is especially noticeable in rebar produced by a multilane casting method. The solution of durability problems of reinforced concrete structures is based on competent design, identification and application of necessary methods of corrosion resistance for steel rebar, quality control in producer facilities as well as on the construction site of the consumer, increase in durability of bonding of rebar with concrete, and sufficient choice of primary and secondary anticorrosive protection for rebar and concrete.

1 Introduction

Durability of reinforced concrete is a function of applied material quality, including rebar quality. Despite the growing applications of composite reinforcement, steel rebar continues to be used heavily and is in great demand.

Broad range of new materials, functional complexity of projects, heightening of the civil and industrial facilities, development of remote locations including Arctic regions, growth of unique engineering projects, growth of hazardous process plants, on one hand, along with difficulties and a high expense of on-time, adequate solution on natural cataclysm and

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disasters, on the other hand, force engineers and researchers of reinforced concrete to consider problems of projects and materials quality, completeness of normative documentations, structures reliability and suspended environment. Therefore, quality of steel rebar is a key factor influencing durability of concrete structures and their performance during designed life cycle.

2 Background (Peculiarity of multilane casting technology)

The current trend in steel rebar production is aimed at the wide distribution of the multilane continuous casting method with a cross-section from 75x75 mm to 700x700 mm in place of the traditional casting into common molds. Existing metallurgical mini-plants, where this method is used, have significant economic advantages over large integrated metallurgical plants of the full cycle [1, 2]. However, there are features that, along with the advantages, have a negative effect on the properties of the resulting reinforcement, including durability and reliability of structures, where the steel has been applied.

Continuous cast-steel is inferior in quality of macrostructure to the cast-steel obtained from the traditional ingot technique. This occurs since during the rolling of the ingot, its head part is removed, where the main metallurgical defects, slag particles and other contaminations are concentrated. In addition, a large number of thermal effects of ingot and then the workpiece heating with high deformation stress of the cast structure, basically eliminates the dendritic micro-inhomogeneity of the steel and ensures a deeper homogenization of the structure along with the rolling of the cross-section. When using the multilane continuous casting method, metallurgical defects and contamination remains in the workpiece, adversely affecting the steel properties. Furthermore, there is no intensive deformation stress of a cross-section reduced workpiece, which causes the presence of contamination localizations and, as a result, a degeneration of the mechanical and functional properties of the produced rebar. Further separation of the billet into several bars, the so-called slitting process, can exacerbate the negative effect of local impurities on the quality of the reinforcement. The multilane continuous casting expenditure and the subsequent slitting of steel billets into rods of smaller diameters is economically very justifiable, but they necessitate further studies of operational, (including corrosion resistance), physical and mechanical properties of the rebar in order to improve the quality of the rebar and, consequently, reliability, performance and safeness of the reinforced concrete structures. during designed life cycle.

3 Corrosion resistance test method

According to the requirements of GOST R 31383, steel rebar is tested for corrosion resistance. The samples of the reinforcement are placed in a hot solution of nitrate salts with a continuously acting bending load applied equal to 0.9 of the conditional yield strengths of steel $\sigma_{0.2}$.

The criterion for the resistance of a bar to stress corrosion cracking under load is the time from the beginning of the test to the appearance of the very first crack on the bar surface or a sudden break in the specimen.

4 Experimental results and discussions

Table 1 shows the corrosion test results of steel specimens produced by various technologies, in accordance with the requirements of GOST 10884.

Table 1. Corrosion resistance test results of rebar, diameter 12 mm.

Steel grade	Manufacturer	Mode of production	Corrosive Resistance, hour	Rolling method
A _T -V	Metallurgical works 1	Multilane continuous casting 125x125 mm	less 7	Double Slitting
A _T - V	Metallurgical works 2	Multilane continuous casting 125x125 mm	less 6	Double Slitting
20ГC, A- V	Metallurgical works 3	Ingot weighing 8.5 tons 820x720-715x620 mm	more 100	Double Slitting
500СП	Metallurgical works 4	Ingot weighing 11,6 tons 975x855-827x725 mm	more 200	One rod
500C	Metallurgical works 5	Multilane continuous casting 125x125 mm	46	Double Slitting
500C	Metallurgical works 6	Multilane continuous casting 125x125 mm	34	Double Slitting
500C	Metallurgical works 7	Multilane continuous casting 125x125 mm	more 78	One rod

Note: the names of plants are given conditionally.

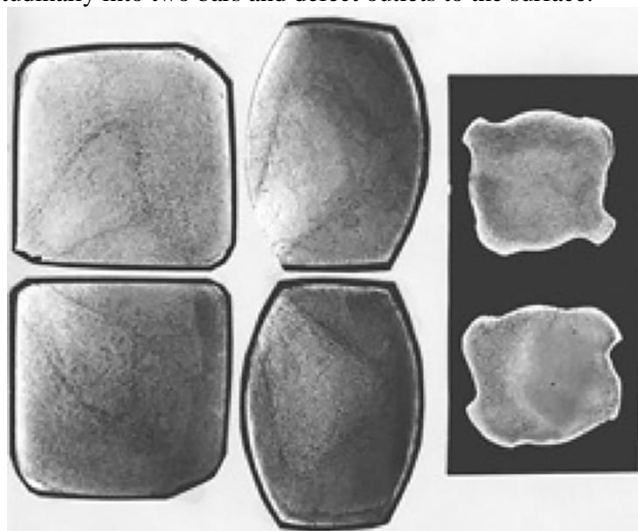
It was found, the total stretch coefficient, and, accordingly, the internal suppreure of the metal structure while rolling the rebar by slitting in 2 rods from the workpiece with a cross section of 125x125 mm, is reduced by an average of 50 times, compared with the rebar rolled from an eight-ton ingot into one rod.

Research Institute of Concrete and Reinforced Concrete by nm. of A. Gvozdev (NIIZhB by the nm. A.A. Gvozdev) of the Research Center "Construction" found that the rebar obtained by rolling into a single rod, has a "corrosion resistance" index significantly higher than in the case of workpiece slitting with a separation into two rods.

It was also revealed that, in terms of the "corrosion resistance" index, the rebar of the plant, conventionally designated in the table as "Plant 4" (rolling from an ingot into one bar) is 20-50 times higher than the "Plant 2" rebar obtained by Double Slitting of the workpiece with a cross-section of 125x125 mm.

Table 1 shows the corrosion resistance of the rebar from the continuously cast piece obtained by slitting, is significantly lower, compared to the rebar obtained from one ingot. It can also be seen, that corrosion resistance of a single rod, produced from rolling continuous-cast billets, almost doubles in comparison with double slitting specimen.

In Fig. 1 shows the internal defects of the specimen's cross-section while workpiece was separated longitudinally into two bars and defect outlets to the surface.



a).

b).

Fig. 1. Outputs of slagged steel to the surface of the workpiece (a) and reinforcing bar (b).

By means of the structural-matrix method [3, 4] to analyze the behavior of the crack-defects in the cross-section of the workpiece and the deformable strip, a mathematical model was obtained that allows analysis and quantitative estimation of the probability of a defect emerging as a crack on the rebar surface, depending on the forming process during a longitudinal rolling.

As the basic data for the calculation, the total area (S_{π}) of liquation defects at initial stage (Fig. 1), was taken in account,

$$S_{\pi} = \sum_{i=2}^n \left(\frac{b_{i-1} + b_i}{2} \cdot l_i \right) \quad (1)$$

where n is the number of sites of segregation;

S_{π} - is the area of the segregation element;

b_{i-1} is the width of the liquation at node $i-1$;

b_i is the width in the i -th node;

l_i is the length of the i -th vector.

The total area of liquation defects is obtained from the template scanning.

The segregation coefficient:

$$K_{\pi} = \frac{S_{\pi}}{S_p}, \quad (2)$$

where S_{π} is the area of the segregation in cross section;

S_p is the cross-sectional area of the rolling.

Obviously, the smaller K_{π} reflects smaller segregation, which as result less its influence on the technological properties of the rolling. To use this index in the matrix model, let's write this formula through the components of the rolling matrix. The rolling matrix consists of several matrices, which in turn might also consist of matrices of low level ($\mathbf{a}_1, \mathbf{a}_2, \dots, \mathbf{a}_n$).

For example:

$$[A] = \begin{bmatrix} [\Phi] \\ [L] \\ [CP] \\ [\Pi O] \\ [\Pi И] \end{bmatrix} \quad (3)$$

where $[\Phi]$ is the matrix of the cross-section form;

$[L]$ is the matrix of liquation (segregation);

$[CP]$ - the properties matrix of the rolling (temperature, plastic properties);

$[\Pi O]$ - matrix of equipment parameters;

$[\Pi И]$ – the equipment profile loss matrix.

The matrix of the form of the liquation $[L]$ is formed and its changes in the process of deformation along the rolling process. The cross-sectional liquation of the workpiece can be specified in the form of a point, cord, in the form of a circle, an oval, or a rectangle. Behavior of liquation during rolling depends on its form. So then, shape of liquation strongly affects the probability of segregation at the surface of the rod and appearance of a rebar defect.

To determine the form of liquation, the coefficient of the liquation form is proposed:

$$K_{\phi\pi} = \frac{\sum_{i=2}^n l_i}{n \max_{i=1} b_i}, \quad (4)$$

where l_i is the length of the liquation elements;

b_i is the liquation width.

From the analysis of the liquation behavior, $K_{\phi\pi}$ can take values in the range from 0.9 to 10. The liquation in the form of a circle (axial segregation) has a coefficient in the range from 0.9 to 2. For values from 2 up to 5 liquation is estimated as an axial elongated shape along the section of the rolling. For values above 5, the segregation cross section takes the form of an axial fuzzy segregation, including a close segregation, in shape to an ellipse or rectangle. The coefficients of the shape, phase separation at the first stage are calculated from the scanned image, then they are corrected considering the comparison of the calculated and actual experimental values. After adjusting the model, it is used for similar calculations when the workpiece of the ingot is deformed to specified cross-section size for various calibrations, including the calibers when rolling by 2 to 4 bars. When the model is configured, the data for scanning the templates (**Fig. 1**) is conditionally taken as the reference point and, conventionally taken as the unit.

The calculated values for the model are confirmed by the experimental data of the NIIZhB by the nm. A.A. Gvozdev. So, when rolling the rebar by slitting into 4 rods from the workpiece, the surface quality can deteriorate by an average of 30% in comparison with rolling the workpiece into one "thread". When dividing a workpiece into three threads - up to 75%, and when dividing a workpiece into 2 threads, the calculated index "corrosion resistance" can deteriorate 8-15 times.

The long-term high performance of reinforced concrete structures depends on the corrosive state of the reinforcement in the concrete. It is known that high alkalinity of the liquid phase of concrete contributes to rebar passivation. However, in the presence of aggressive ions (chlorides, sulfurs and others) or simply water penetrating through the pore space of concrete and microcracks up to rebar surface, it can initiate a corrosion process even while a high value pH-index exists. At the same time, the presence of heterogeneity on the bar surface and particles of the slag rolled into steel adversely affect the corrosion resistance of the rebar and can lead to brittle breaks and structural collapses.

The resulting corrosion product layer is 2-5 times thicker than initial layer of corroded metal, which causes a significant increase of stresses in the concrete at the surface of the reinforcement, exceeding the concrete strength. As result, cracks are formed, leading eventually to the chips of the concrete cover. Further rebar exposure to moisture, atmospheric oxygen, and possible aggressive agents accelerates greatly the destructive process of the rebar and concrete structures.

Surveys of parking garages [5] indicate corrosion losses of rebar's cross-section up to 80%, (**Fig. 2**).



Fig. 2. Corrosion damage to reinforcement with a loss of rebar cross-section up to 80%.

It has been proved that intensive deteriorations of structures surveyed is caused by aggressive action of de-icing salts brought with snow by car wheels. And the service life of this particular parking slabs has become about 7-10 years. During inspection of parking structures, corrosion damage of column rebar was also discovered and showed about 10-15% of its cross-section, which causes a loss of its load-carrying capacity.

Structures safeties are sharply reduced due to the use of low-quality rebar with release of contamination onto surface, the effects of de-icing salts, induced electromagnetic waves influence, and lacking or poor quality of outside concrete protection [6-12].

5 Concluding remarks and recommendations

Further commissioning of a multilane continuous casting method for rebar production with the subsequent slitting of the billet into two, three or four smaller diameter bars must be accompanied by the study and improvement of the operating reinforcement characteristics,

including its corrosion resistance, to ensure reliability over the life cycle of reinforced concrete structures.

- The rebar quality is positively affected by a). an increase of the casting billet's cross-section; b). protection of the metal from oxidation during casting; c). improvement of the cooling rate of the billet during casting, including electromagnetic stirring in the mold. In rolling production, it is recommended to replace the double division into triple. The rolling scheme and calibration in double-slitting must have a maximum number of cell passes (at least 4) from the moment of rolling slitting to the rod depart from the final caliber cell. A significant improvement in surface quality can be achieved by changing the cooling mode after rolling.
- At the construction site a quality control of the steel rebar must be carried out in strict accordance with the requirements of regulatory documents and rules for conducting construction work to exclude the use of reinforcement with corrosion defects in reinforced concrete structures. The works must meet the requirements of CII 63.13330 "Concrete and reinforced concrete structures" and CII 28.13330 "Protection of building structures against corrosion". Reinforcing steel must undergo corrosion tests and be accompanied by a quality certificate.
- Since the cost of rebar is high, reducing the consumption of reinforcement in construction is important. In any project, the cost of reinforcement can be significantly reduced by effective rebar application, such as A500CII, which decreases the anchoring length by 30% due to the improved bonding strength between rebar and concrete. Additionally, the specific view of the A500CII rebar profile makes it possible to provide additional visual control of compliance with the designed requirement to the material used.
- Based on the global experience in the restoration of buildings and structures after man-made accidents and natural disasters (such as: the shopping center in China, the entertainment center in South Korea, in Russia and USA), it is necessary to ensure the safety and reliability of reinforced concrete structures on the basis of the correct solution made in terms of durability and quality of structures and materials used, including the use of new types of reinforcement, at the every stage of the structures life cycle.

Author are grateful to the NIC "Stroitelstvo", personally prof. I. Tikhonov, and to prof. A. Steblov (National Academy of Sciences of Belarus) for essential participation and significant support.

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