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SERVICEABILITY LIMIT STATE PARAMETERS FOR HIGH STRENGTH CONCRETE STRUCTURES

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Abstract. High-strength concrete structures become more and more widespread in construction practice due to certain advantages. At the same time the current Russian and foreign standards for the design of reinforced high-strength concrete structures are not rigorous enough, since it is based on the conceptual provisions for reinforced concrete structures made of ordinary concrete. The article analyzes the basic provisions for calculation of high-strength concrete structures for serviceability limit state and compares it with the available experimental data. The study points out not only significant quantitative discrepancies in design and experimental values of stiffness and crack resistance parameters of such structures, but also indicate inadequacy of physical phenomena laid in the basic design provisions adopted in the current Russian and foreign standards by analogy with the physical nature of deformation of reinforced concrete structures made of ordinary concrete. The paper proposes to adjust the deformation model for calculating the parameters of serviceability limit state for high-strength concrete structures based on the results of experimental investigations.

Keywords: high-strength concrete, reinforced concrete structures, cracks, serviceability limit state, spacing between cracks

ПРОБЛЕМА НОРМИРОВАНИЯ ПАРАМЕТРОВ ПРЕДЕЛЬНЫХ СОСТОЯНИЙ ВТОРОЙ ГРУППЫ ДЛЯ КОНСТРУКЦИЙ ИЗ ВЫСОКОПРОЧНОГО ЖЕЛЕЗОБЕТОНА

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Аннотация. Конструкции из высокопрочного железобетона благодаря определенным достоинствам находят все более широкое распространение в строительной практике. В то же время действующие российские и зарубежные нормативные документы по проектированию бетонных железобетонных конструкций из высокопрочных бетонов, построенные на основе концептуальных положений норм проектирования железобетонных конструкций из обычных бетонов являются недостаточно строгими. В статье приведен анализ основных положений расчета конструкций высокопрочного железобетона по предельным состояниям второй группы в сопоставлении с имеющимися опытными данными. Отмечаются не только значительные количественные расхождения в расчетных и опытных значениях параметров жесткости и трещиностойкости конструкций из такого железобетона, но и неадекватность физической природы явлений, заложенных в основные расчетные положения принятые в действующих российских и зарубежных нормах по аналогии с физической природой деформирования железобетонных конструкций из обычных бетонов без соответствующего обоснования. Даны предложения к корректировке деформационной модели для расчета параметров предельных состояний второй группы конструкции из высокопрочного железобетона основанные на результатах экспериментальных исследований.

Ключевые слова: высокопрочный бетон, железобетонные конструкции, трещины, вторая группа предельных состояний, расстояние между трещинами

INTRODUCTION

The main issues in the design of structures made of new types of concrete, including high-strength concrete and fiber-reinforced concrete, are their safety and decrease in metal consumption. For this purpose, it is necessary to develop and improve new design models which correspond to the real operation regime of structures made of such materials under different types of stress state. The absence of effective models accounting for the specifics of deformation and fracture of reinforced high-strength concrete structures leads not only to the design of structures with unreasonable reserves of bearing capacity and, accordingly, material consumption, but also to the decrease of their safety. Imperfection of deformation models included in regulatory documents significantly affects the quality of structural design.

The analysis of basic provisions of the new Russian Building Code SP311.1325800 for the design of high-strength concrete structures according serviceability limit state criteria showed that it offers a methodology for determining the parameters of serviceability limit state using the same theoretical and methodological basis as for ordinary concrete structures. Such an approach is not apricated in the publications available today in Russian [1-4] and foreign literature [5-7], where deformation models and methods for calculation of high-strength concrete structures are proposed on the basis of modern experimental studies of such structures. Thus, tests of high-strength concrete beams [1,2,4,8] show that, as a rule, there is only one main crack in the tensile zone. And failure occurs along this crack. The similar character of cracking is observed in fiber reinforced concrete structures [9,10,11]. If we proceed from the traditional model of deformation of reinforced concrete components with cracks proposed, which was developed for concrete of relatively low strength, then this model assumes the formation of a network of cracks in the tensile zone and, accordingly, the strains of concrete and reinforcement in the areas between the cracks and in the crack are reduced to some mean values through the coefficient proposed by Murashev. However, if one or two cracks are formed in the tensile zone of a high-strength concrete structure, such a physical model does not reflect the physical aspect of the problem under consideration. Here, as shown in [8,12], it is necessary to attract more perfect models of deformation of reinforced concrete components with cracks adequately describing the physical phenomenon under consideration, including new hypotheses and more rigorous relationships of fracture mechanics adapted to high-strength concrete structures.

Another important specific feature established experimentally for deformation of high-strength concrete structures [1,2,10] is a relatively small range of deformation in serviceability stage from the bending moment of crack formation to failure one. If low-strength concrete structures have the range of 0.7-0.8 of the capacity, then this range for high-strength structures does not exceed 0.25-0.4. This imposes serious limitations on the analysis of such structures according to the serviceability limit state and its criteria.

To take into account the mentioned and other peculiarities of deformation of high-strength concrete structures in calculation for the serviceable limit state, a more advanced calculation apparatus should be used. It should allow considering the specificity of the noted and other physical phenomena of deformation and cracking of such material. Here, as mentioned in [12], the calculation relationships for determining the level spacing between cracks and the crack opening width can be used within the framework of the general methodology, taking into account the deformation effect in a single crack [8,9] and more rigorous relationships of the semi-analytical model for determining the stiffness of structures in the zone of normal and inclined cracks [3,5, 12-14].

Thus, the purpose of this study is to substantiate the necessity and efficiency of transition to more rigorous and experimentally confirmed models of deformation of high-strength concrete structures for updating regulatory documents, in particular, Russian Building Code (SP311.1325800) in the part concerning the calculation of such structures for serviceability limit state.

Physical and design models of stiffness and crack resistance of high-strength concrete structures. According to the current Russian Building Code (SP 311.1325800) for the design of high-strength concrete structures, the design of such structures for the serviceability limit state should be carried out using the same requirements as for reinforced concrete structures made of ordinary concrete with some adjustment of the deformation modulus and elastic-plastic moment of resistance of the section, taking into account the increased strength of high-strength concrete. It follows that the physical model of deformation and cracking in the tensile zones of high-strength concrete structure remains the same as for ordinary reinforced concrete. As the data of experimental studies [1,2,4,5, 10] and the results of numerical investigations of high-strength concrete structures [4, 9] show, the knowledge obtained in the last decade about physical phenomena of deformation, crack formation and opening in such structures qualitatively differs from those parameters under loading of ordinary concrete structures. Thus, it has been found that instead of a network of irregular cracks formed during testing of structures made of low-strength concrete, single so-called discrete cracks are formed in structures made of high-strength concrete [2,3,4, 5, 10] (Figure 1a-c). In beams with deformable transverse contour in the most stressed tensile zone, several cracks may appear (Figure 1d-f), but only one of which increases sharply in opening width as the load grows, and fracture happens along this crack.

This cracking process qualitatively changes the Murashev deformation model traditionally used in design. In this model, the key hypothesis is the hypothesis of mean strains (or stresses) in the reinforcement located in the tensile zone. Meanwhile, for high-strength concrete structures, the crack opening process can be described more rigorously by a model in which the strains in concrete and rebars are determined for a block between cracks, if there is a network of irregular cracks, or by a model for a block in the zone of a single crack, if there is a single crack in the structure. In accordance with this model [12, 14], the strains of tensile concrete $\varepsilon_{bt}(x)$ are determined from the equilibrium of the block located between the section with a crack and the section passing at a distance $t_* + x$ from the crack (Figure 2):

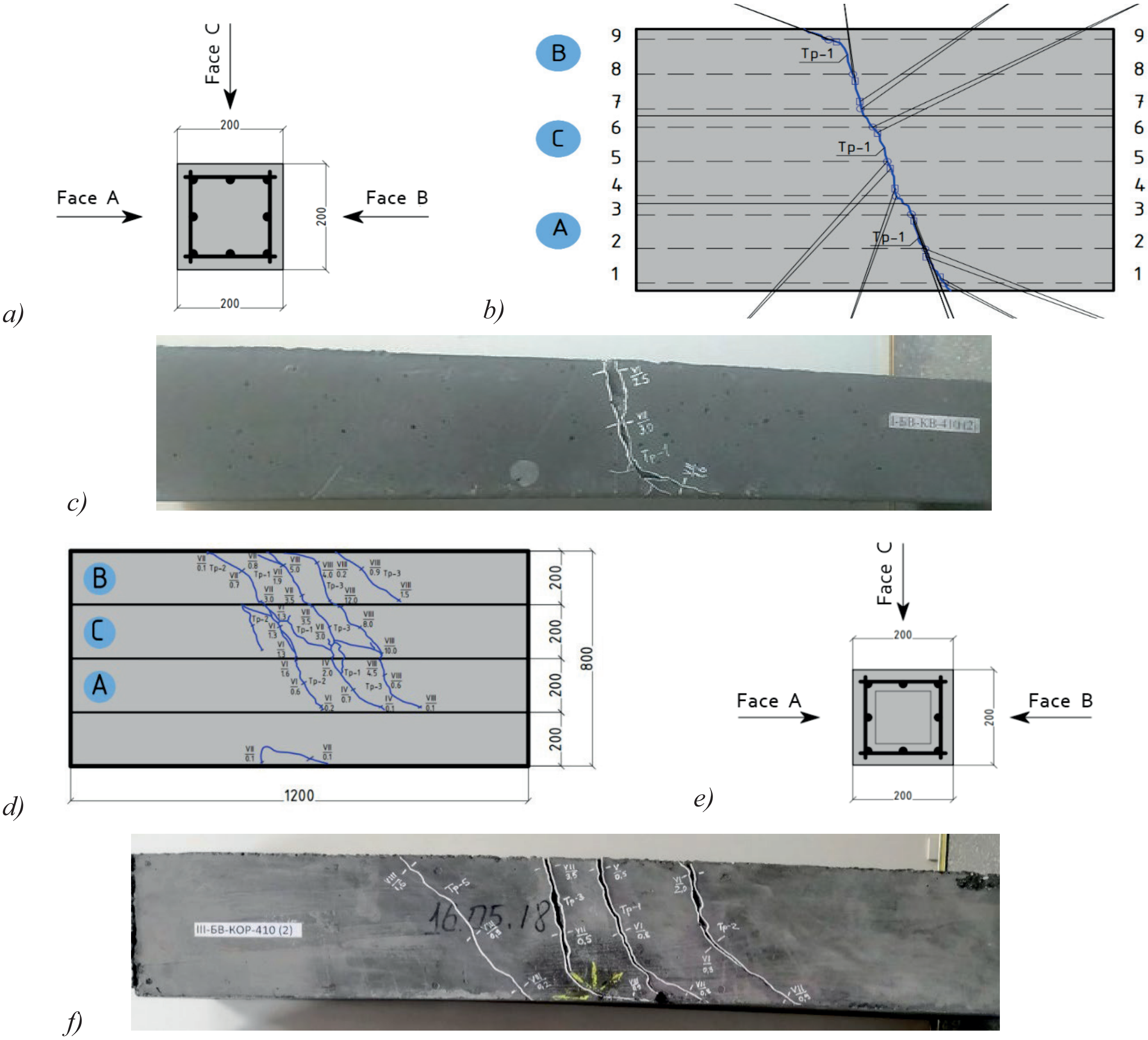
$$\varepsilon_{bt}(x)\big|_{x=0,5l_{crc-t_*}} = \varepsilon_{bt,u} \quad . \tag{1}$$

According to this block model, the mutual slip strains of reinforcement and concrete are determined by the formula:

$$\varepsilon_g(x) = \varepsilon_s(x) - \varepsilon_{bt}(x) \tag{2}$$

where $\varepsilon_s(x)$ is the strain in steel rebar; $\varepsilon_{bt}(x)$ is the strain in concrete at the section x.

An important particularity of the physical phenomenon of cracking in reinforced concrete structures is the so-called deformation effect, which is experimentally established at crack opening. In existing Russian [16,17] and foreign [18-20] regulatory documents, the crack opening width is calculated at the level of the rebar axis by the strains of concrete and reinforcement in the area between adjacent cracks and using the triangle profile for crack opening. The calculation model introduces such a parameter as the distance between cracks lm,crc. In this case, the profile of the crack itself changes linearly from the maximum opening at the level of the reinforcing bar with a decrease in the width of the opening as it moves away from it in the direction of the compressed zone (Figure 3a). Based on numerous experimental studies of the crack formation and crack opening in reinforced concrete structures with different geometry and reinforcement parameters, [21, 27], the study provides substantiated results of the analysis of this process and a refined SCC model [21] of the effective crack opening width in slender and deep beams. It considers two types of external cracks in flexural elements subjected to pure bending: primary flexural cracks penetrating most of the tensile zone and reaching the neutral axis, and local secondary cracks of smaller size located near the tensile reinforcement, respectively. It also differentiates approach to the types of cracks in deep and slender beams (Figure3b). The basic idea of the SCC model proposed in [20] is to predict the mean crack spacing in an RC element from the strain profile of the tensile reinforcement. This model allows predicting the mean spacing between primary $l_{m,crc}$ and secondary $l_{m,crc,s}$ cracks. As observed by the authors of the model, who had analyzed the experimental data, the primary crack width profile in deep beams follows a bilinear shape, while the traditionally accepted model (see Figure3a) uses a linear primary crack width profile. In deep beams, the crack opening width increases linearly between the crack depth levels representing the vertices of the primary (point 1) and secondary (point 2) cracks (see Figure 3b).



a)

b)

c)

d)

e)

f)

Figure 1. Cross section of a solid beam (a), a pattern of a single crack sweep (b) and a general view of a crack from a side face (c); d,e, f - the same for a box section beam

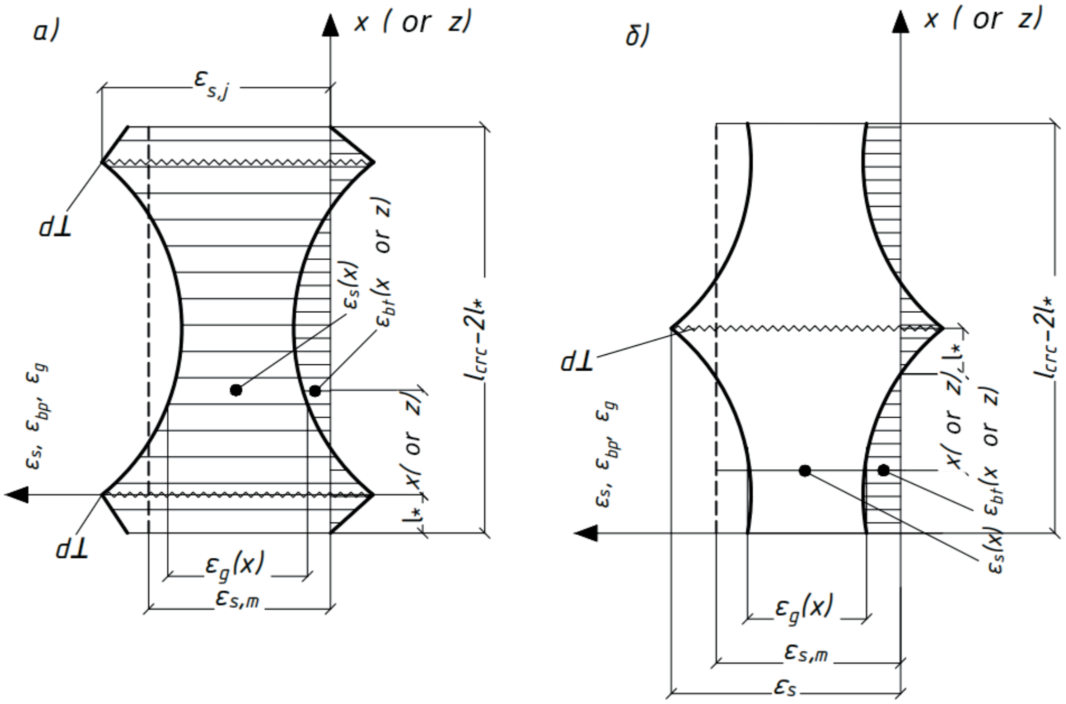


Figure 2. Diagrams of strain in concrete ε_{bt} (x or z), steel rebars ε_s (x or z) and mutual slip strains ε_g (x or z) in the block between adjacent normal or inclined cracks at presence of network of cracks (a) or at appearing of a single crack (b)

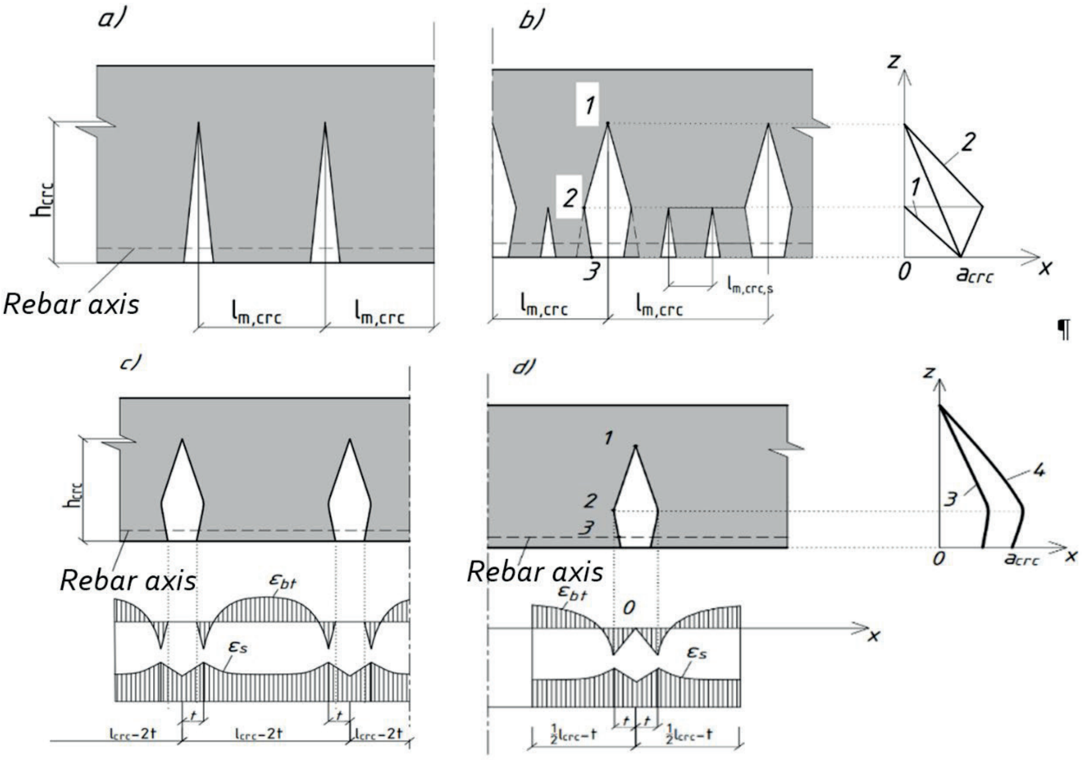


Figure 3. Model of cracks in bending element: a - according to the method [17,18]; b - according to the method [21]; c, d - according to the method [12]

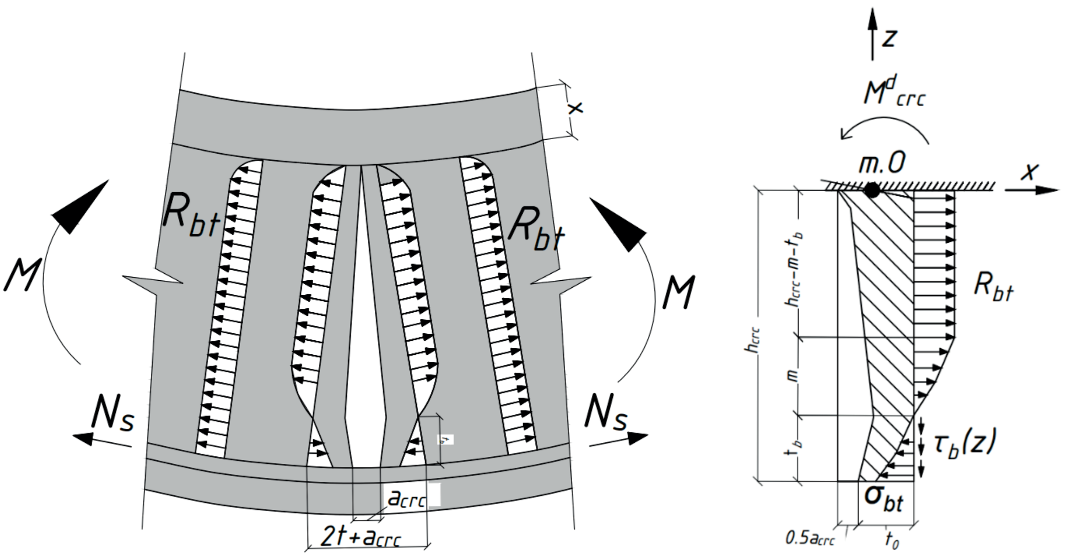
Within this interval, the crack width is determined by the spacing between primary cracks. Further, the crack width growth rate decreases due to the appearance of secondary cracks. For very deep beams, the growth rate may even become negative, i.e., the width decreases and the crack width profile takes the shape of a fish. The SCC crack model is an experimentally based approach with a minimum number of empirical parameters. In addition to the mean strains, a single empirical parameter characterizing the strain profile of the reinforcement is introduced. According to the authors [20] in contrast to the Model Code 2010 [20] and Eurocode 2 [19] methodologies, the proposed calculation model is free from the empirically determined effective deformation region of concrete under tension.

The use of more precise tools in the experimental studies by V.I. Kolchunov [8], I.A. Yakovenko [22], A. I. Demyanov [15] et al of crack opening width in tests of structures made of concrete of different strength and with different types of stress state allowed to identify that the physical nature of the investigated phenomenon of crack opening in reinforced concrete structures has more universal regularities and should not be separated to specific concrete structures. This nature can be described by the model of the so-called deformation effect or the effect of discontinuity in reinforced concrete structure near the steel rebar [12]. The nature of concrete strain patterns obtained in the mentioned studies, as well as in the studies of other researchers [23-26] show that in the zones adjacent to the crack, concrete tensile strains turn into compressive strains. The tangential bond stresses also change sign and the pattern of strains in the rebar in the area between the cracks changes respectively (see Figure 3c). Avalanche-like opening of cracks along the triangular profile which is typical for a concrete element, is restrained by rebars in reinforced concrete elements. This can be considered as a concentrated deformation effect after the continuity violation. Thus, the crack profile is complex and can be described as an ellipse curve, with the maximum opening above the level of the reinforcement bar. As a result, in a two-component system of reinforced concrete matrix with a crack in the vicinity of cracks, a reaction appears at the contact between concrete and reinforcement called the effect of continuity violation or deformation effect.

The theoretical solution of the problem under consideration is developed using clearly structured and interrelated design assumptions that incorporate the mechanics of reinforced concrete and fracture mechanics [12, 15, 22]. The perturbation of the stress-strain state in the vicinity of the crack is found by using the model of the so-called double-cantilever element (DCE), which relates the constants of the concrete strain diagrams to the ductility of this element (Figure 4). The pliability function is derived from the expression of the energy release rate at crack opening

$$\varphi_{bu} = \lim_{\delta A \to 0}\left[\frac{\delta W - \delta V}{\delta A}\right] = \frac{dW}{dA} - \frac{dV}{dA} \tag{3}$$

where δW is the additional work done over the element when the crack propagates by a small distance δA; δV is the additional work done on the element as the crack propagates by a small distanceδA; A is the area of crack surface.



a) b)

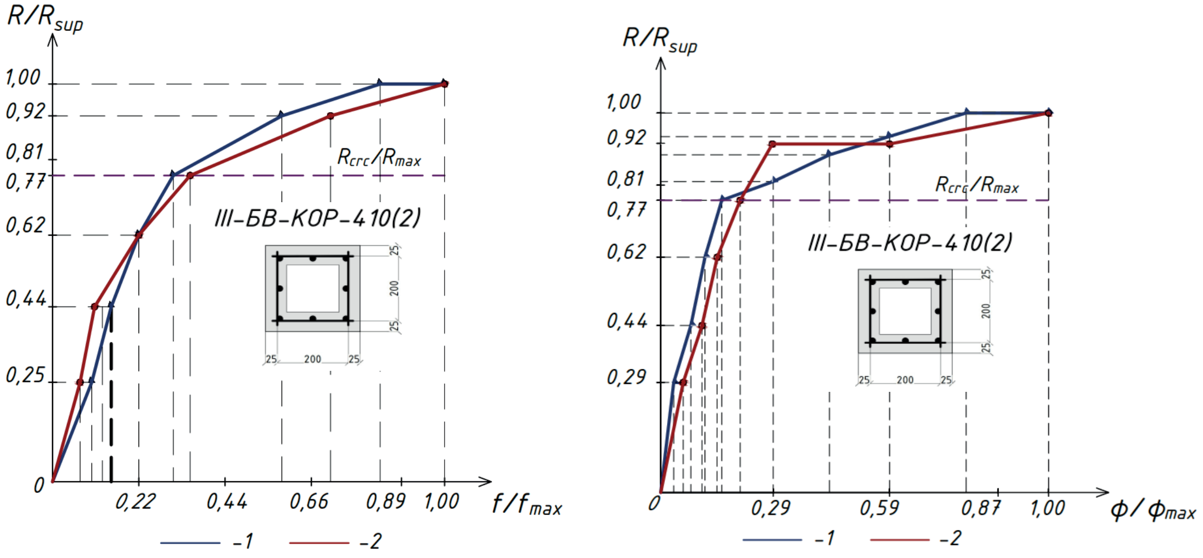
Figure 4. Model of double-cantilever element (DCE) in reinforced concrete beam: stress-strain state in the vicinity of the crack (a); model of double-cantilever element (b)

Providing the relation between the constants of fracture mechanics and traditional mechanics of reinforced concrete structures, the equivalent experimental characteristic σ_{bt} amenable to standardization is used. As a result, the physical resistance model (PRM) called the double-cantilever element model is universal for single and discrete cracks. Having all the components of the stress state such as stresses in the compressed and tensile concrete along the crack sides (σ_{bt}, R_{bt}), tangential stresses in the contact zone of the tensile reinforcement and concrete (τ_{bt}) (see Fig. 4), it allows modeling theoretically the deformation effect in transverse [25], inclined [26] and spatial [1, 2] cracks in a reinforced concrete element made of concretes of different strengths without introducing additional experimental parameters and without using hypotheses about the mean crack opening width.

It is relevant to note that the idea of block models taking into account shear in concrete above the crack tip in combination with the spacing effect and the nagel effect at the level of the tensile reinforcement axis has been recently proposed in a number of foreign publications, for example, in a rather detailed study [27] on the theory of shear cracks in reinforced concrete beams. This model has some similarity with the idea proposed by the DCE model, but the determination of the parameters of this shear theory is based on the use of static-kinematic equations and has less generality, since it is oriented to the use of an increased number of initial assumptions and experimental constants. Such models are usually applicable to special cases of stress states of concrete structures and types of cracks. At the same time, the physical nature of deformation in these models remains within the framework of traditional approaches: the idea of the mean spacing between cracks is retained, the deformation effect of concrete in the crack is not taken into account, the Bernoulli-Navier hypothesis is used to determine the height of the compressed zone of concrete, etc.

It is easy to see that the introduction of the DCE model into the mechanics of reinforced concrete makes it possible to adequately describe both variants of cracking in the tensile zone (see Figure 3 c, d) and to develop a general design model for solving the problems of stiffness, crack resistance and strength of high-strength concrete structures, considering different types of cracks and experimentally established new effects of deformation of reinforced concrete with cracks under different types of stress state.

Another argument to justify the expediency of introducing in the design practice more rigorous models in the assessment of serviceability limit states to take into account the specifics of deformation of high-strength concrete structures can be the experimentally obtained curvatures (strains) and deflections of beams made of such material. Thus, analyzing the qualitative character of the experimental diagrams “relative value of the generalized support reaction vs. relative deflection” and “relative value of the generalized support reaction vs. relative angle of rotation” of high-strength concrete beams experiencing bending with torsion [1,2,10] it is possible to note the following (Figure 5). In these structures, up to the level of 0.75-0.80 of the generalized ultimate support reactions, the change in deflections was close to a linear relationship. At the same time, there were no cracks in the beam structures. The range of nonlinear deformation at increase of loads up to exhaustion of bearing capacity was relatively small and amounted to 0.2-0.25 of the failure loads. At the same time, it is known that in beams made of ordinary reinforced concrete the second stage of stress-strain state is the main operational stage for estimation of parameters of serviceability limit state associated with determination of crack opening width and displacements of elements with cracks.



a) *b)*

Figure 5. Experimental diagrams “generalized reaction vs. relative deflection” (a) and “generalized reaction vs. angle of rotation” (b) of box section high-strength concrete beam experiencing bending and torsion: 1 - by the first indicator, 2- by the second indicator

Considering the extremely small range of deformation of high-strength concrete structures from the moment of crack initiation to failure and the fact that after crack initiation the intensity of nonlinear displacements and, accordingly, crack opening sharply increases. Thus, the failure of such structures is brittle under the considered stress state and reduced deformability of high-strength concrete [28,29]. Apparently, quantitative criteria of limit states of high-strength concrete structures should be revised in the existing standards.

The same conclusion can be drawn from the analysis of the crack opening pattern in experimental high-strength concrete beams (Figure 6) tested in the research [1]. The quantitative values of the width of opening of a single crack 1 (Tp.1) at different stages of loading (indicated by Roman numerals) show that the crack opening width along the axes of reinforcement bars (axes 1-9 on the sweep of beam faces A,B,C) has values two or more times smaller than at distances of two or three diameters (shown in brackets) from these axes. For example, the crack opening at stage IV is 0. 2(0.5), at stage VI is 0.8 (1.7), at stage VII is 3.0 (6.2).

This experimentally confirms the presence of deformation effect and bilinear or curvilinear crack profile shown in Figure 3 b,d. The crack profile specified today by Russian and foreign standards does not consider the deformation effect and significantly overestimates the normalized crack opening width for high-strength concrete structures by more than twice. Ignoring the type of cracks (distributed or single) in high-strength concrete structures also significantly affects the calculated values of displacements, and not to the reserve for the stiffness of structures.

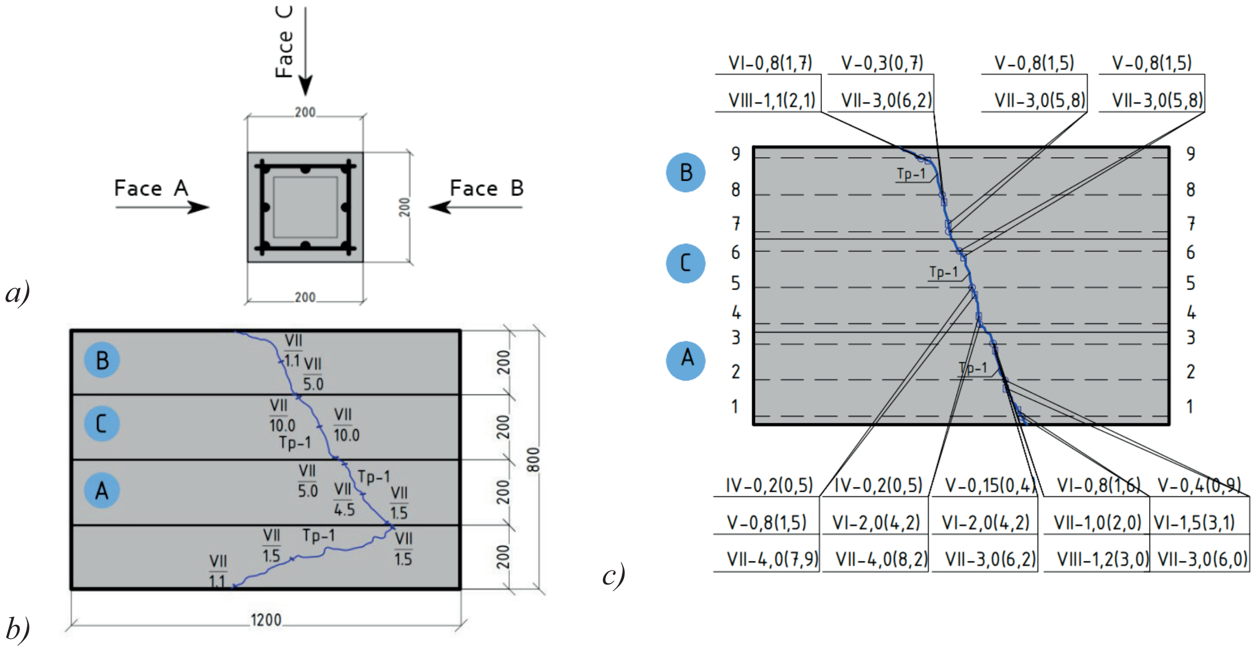


Figure 6. Cross section (a), single crack sweep pattern (b) and crack opening width on the faces of a high-strength concrete beam experiencing bending with torsion

CONCLUSIONS

1. Design models of high-strength concrete structures for serviceability limit state provided in the current Russian and foreign regulatory documents have been developed using conceptual provisions of the design standards for reinforced concrete structures made of ordinary concrete. Thus, they do not strictly enough describe the stress-strain state of structures made of high-strength concrete at the second and third stages of their deformation. They also do not take into account the formation of single cracks in the structures, the presence of the deformation effect in the cracks and changes in the distribution of longitudinal strains in concrete and reinforcement bars in the zone of the crack, the relatively small range of deformation of the section in stage II of stress-strain state.

2. In order to take into account these and other peculiarities of deformation of high-strength concrete structures in the calculation for serviceability limit state, a more advanced calculation apparatus should be used, which allows to account the specifics of deformation and cracking of such material. As shown by the data of experimental studies conducted in recent years with the use of more refined tools, the physical phenomena of deformation, cracking

and crack opening in such structures qualitatively differ from those parameters for structures made of ordinary concrete. Thus, instead of a network of regular cracks formed during testing of low-strength concrete structures, single so-called discrete cracks appear in high-strength concrete structures. This qualitatively changes the deformation model traditionally used in design. The key hypothesis in this model is the hypothesis of strain (stress) averaging in tensile reinforcement. Even the notion of the spacing between cracks used in the design models of serviceability limit state is changed.

3. The physical nature of experimentally determined phenomena of crack opening has more general regularities and is not separated for specific types of structures, specific types of concrete and reinforcement. It can be described by the so-called deformation effect or the effect of violation of the continuity of the concrete matrix in the zone of the reinforcement bar. Theoretical solution of this problem can be constructed using clearly structured and interrelated design assumptions combining the traditional mechanics of reinforced concrete and fracture mechanics. In this case, the perturbation of the stress-strain state in the vicinity of the crack is determined using the model of the so-called double-cantilever element (DCE), relating the constants of concrete strain diagrams to the pliability of this element.

4. In high-strength concrete structures, the strain rate of compressed concrete and reinforcement in the section with the crack increases after the formation of single cracks and, accordingly, the displacements in the structure increase sharply in a relatively short range of load changes. Yielding occurs in the reinforcement bars, i.e., the structure collapses. The operating range of high-strength concrete structures after the formation of single cracks in stage II of stress-strain state is more than twice as short as in beams made of ordinary concrete after the formation of a network of distributed regular cracks.

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