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Original Article

Methodology for Calculating the Risk of Defects in Multi-Story Construction Using Fault Tree Analysis

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Abstract - *Improvement of the system of quality control organization during the construction of multi-storey buildings is an urgent task of scientific research, the solution of which will improve the quality of construction projects and reduce the duration and financial costs of defect elimination. The main types of risks associated with probability defects in construction work and their impact on project implementation and the quality of construction structures are examined. To bridge this gap, this paper proposes assessing the probability of defects. The methodology of constructing and analyzing fault trees is recommended. The probabilities of fault tree incidents are calculated using expert assessments and statistical data analysis from construction project records. A formula for assessing project implementation damage, based on the impact of defects on the project timeline and additional costs for their correction, is proposed. To assess the probability of defects, a fault tree was constructed in the article using the example of constructing load-bearing monolithic structures for multi-storey buildings. The article develops a method of reducing the risk of defects in construction works by adopting organizational and technological decisions based on fault tree analysis. The developed methods were implemented to construct a multi-storey building in Moscow. Based on the article's results, applying a defect risk management methodology using fault tree analysis has been justified. A conclusion has been drawn regarding the prospects for further research into the risk-based approach in construction quality management systems.*

Keywords - *Risk-based approach, Construction control, Construction quality management, Fault tree analysis, probability of defects.*

1. Introduction

Construction quality management is one of the most important areas of scientific research [1, 2, 3]. Analysis of building inspections shows that most defects originate during the construction phase [4] rather than during operation. Construction quality requirements are defined in various regulatory documents, project documentation, and material and equipment usage instructions. There are methods of quality control using the 3D camera, which perform point cloud construction and determine the presence of a defect [5, 6]. Using (3D) keypoint detection to identify rebar defects in the construction industry, [7] and monitoring of construction quality control by the egocentric video recording method [8]. Such technology allows for identifying defects compared to traditional methods but does not prevent them. Implementation of multilevel construction quality control helps to reduce the number of defects in construction works but does not completely solve the problem [9]. Construction companies, adhering to resource-saving principles [10], strive to create an effective quality management system that enables high-quality projects with rational human and financial resource expenditures. The primary goal of a construction quality management system is to prevent defects. Soft computing methods (artificial neural networks) are also used in research. It is possible to predict construction quality, manage factors that affect it, and avoid defects [11]. Scientific research is being conducted to predict construction quality based on initial project values [12]. Green artificial intelligence and its integrity in construction robotics have been employed for construction quality control, as well as for cost and duration prediction [13]. These works do not analyze the specific causes of defects and their impact on project implementation. The feedback control system for fresh concrete integrates worker position and vibrator parameter data to visualize the concrete in the helmet, as well as the instructions needed to reduce concrete defects [14]. Integrated sensors and 3D printers allow for the control of the quality of building structures [15]. The method of interpretability provides machine learning results on constructive errors, improving management decision-making [16]. These studies improve quality at a certain stage of construction - the placement of concrete mix. However, the use of 3D printers is limited in monolithic construction and cannot currently compete with traditional methods due to significantly inferior performance. Also, improving the quality of monolithic structures requires a comprehensive approach and consideration of operations at all stages of their construction. The use of information modeling technologies for defect management has also been explored [17, 18]. Construction quality management in digital technology can greatly improve the detection of hidden work defects, prevent defects before construction, and ensure compliance during construction [19]. Information modelling technologies allow for effective monitoring of construction and improving quality due to instant access to the project model and elements of augmented reality.

However, these technologies do not establish a link between defects and their causes and do not allow for evaluating the criticality of defects and their impact on quality. This task must also be addressed considering resource-saving principles and a balance between other efficiency criteria, such as project duration and cost. To address these issues, the authors propose a risk-based approach [20, 21]. The goal of this article is to build a model for managing the quality of concrete work in the construction of monolithic structures for multi-story residential buildings. The article addresses the following tasks:

Developing an approach to assessing the risk of defects, identifying the most significant defects in monolithic structures, classifying incidents leading to defects in concrete work, constructing a fault tree for monolithic structures, calculating its probabilities, and developing organizational and management solutions to prevent incidents that lead to defects. The final task is implementing the model into the quality management system for constructing monolithic structures to avoid defects and enhance construction quality. The model has been implemented in the construction of monolithic structures in Moscow.

2. Materials and Methods

The priority of construction control processes should be determined based on the risk associated with defects in these construction activities. In previous works, the authors considered two main types of damage caused by defects in construction structures: damage to the quality of the structure and damage to the project implementation. In both cases, the level of risk of defects in construction structure A can be calculated using the following formula: [22]

$$R(A) = \sum_{i=1}^{i=N} P(D_i)U\,(D_i). \quad (1)$$

Where:

- $P(D_i)$ – Is the probability of the I-defect in construction activity A
- $U(D_i)$ – Is the damage caused by the I-defect in construction activity A.

For the risk of defects affecting the quality of the construction structure $R_Q(A)$ damage is determined by the sum of damages for each quality indicator of the construction structure, as shown in Figure 1. The damage caused by the i-defect is determined by the sum of damages caused by this defect for each quality indicator.

$$U_Q(D_i) = U_{Q1}(D_i) + U_{Q2}(D_i) + U_{Q3}(D_i) + U_{Q4}(D_i) + U_{Q5}(D_i). \quad (2)$$

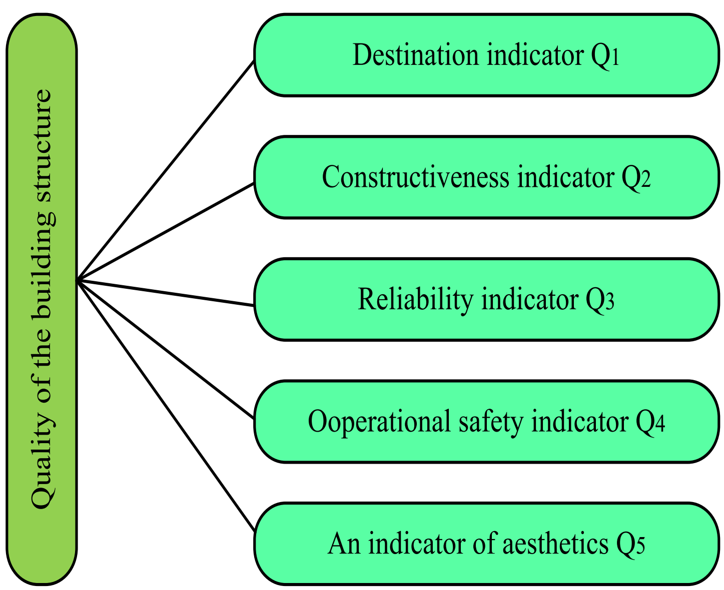

Fig. 1 Indicators of the quality of the building structure

Damages from defects in construction work for the realization of the project $R_P(A)$ are various and can be expressed by the following components.

- The increase in the duration of the construction process due to the time needed to correct defects and the resulting shift in construction deadlines (C_t);
- Additional labour costs for workers to correct defects and Engineering and Technical Personnel (ETP) labour costs for re-acceptance of work after defect correction (C_T);
- Additional material resource costs for the correction of defects (C_M)

It is important to note separately the damage caused by latent defects that were not identified during the handover and acceptance phase. These defects usually manifest themselves only after the completion of subsequent works and often during the operational phase of the building. Correcting such defects involves the cost of dismantling and reassembling the structures completed after the hidden works (C_{p}). For example, to rectify defects in the masonry of the external walls, it will be necessary to dismantle and reassemble the façade cladding and the internal wall finishes of the building. The calculation of the damage due to a defect should take into account the potential damage due to such defects in concealed works not detected in time, taking into account the probability that this defect will not be detected during the handover and acceptance process, $P(D_i^n)$. The unifying characteristic of these types of damage is cost, so the damage to the project implementation. $U_P(D_i)$ This can be represented as follows:

$$U_P(D_i) = C_t + C_T + C_{\text{M}} + P(D_i^n)C_{\text{p}}. \quad (3)$$

The probability of defects from (1) is the same for both risks. This value can be determined through expert surveys and/or by analyzing statistical data from the construction control service, general contractor, customer, and state supervision. In this article, defect probabilities are calculated using the construction and calculation of a fault tree.

3. Results

The risk of defects in construction control for construction work R(A) can be used to indicate the effectiveness of construction quality management. The risk of defects calculated according to formula (1) for project realization is an a priori value without any additional information about a given construction project. The damage calculated by formulas (2) and (3) will be constant for a given structure and project and will depend on the type and quantity of defects. However, the probability of defects is a value that can be influenced by a greater number of factors.

The probability of a defect can be adjusted in the event of additional information about the project, such as the high qualification of the contractor's workers, a strong portfolio of the contractor in relation to these types of work, high-quality project and organizational-technological documentation, etc. Thus, by influencing the probability of defect occurrence, both risks of the construction process A for the quality of the construction structures $R_Q(A)$ and for the implementation of the project $R_P(A)$ can be reduced. This is one of the main tasks of construction project quality management – to prevent the appearance of defects by reducing the probability of their occurrence. In this study, to calculate the probability of defects in concrete works during the construction of monolithic structures in multi-story residential buildings, it is proposed to use a fault tree model (failures) leading to defects. This model has proven effective in various industries for analyzing and addressing the causes of unfavourable events [23]. For constructing the fault tree of monolithic structures during the construction of residential multi-story buildings, the most significant defects were identified: D_1 -Irregularities and chips on the concrete surface, D_2 - Cracks in concrete, D_3 - Deviation of geometric characteristics and positioning, D_4 - Non-compliance with concrete strength, D_5 - Surface voids, pores, and exposure of reinforcement, D_6 -Violation of work joint requirements during concreting. The authors then classified incidents leading to the occurrence of defects, as shown in Table 1.

Table 1. Classification of incidents leading to defects in monolithic structures

Defects	Incidents	Cause of the defect (incident)
D_1	I_1	Bending or displacement of the formwork during concreting
	I_2	Inaccuracy in geodetic layout
	I_3	Improper the levelling of the mixture during the paving
	I_4	Improper formwork installation
D_2	I_5	Improper concrete curing
	I_6	Loading of structures before reaching strength
	I_1	Bending or displacement of the formwork during concreting
	I_7	Premature removal of the formwork
D_3	I_1	Bending or displacement of the formwork during concreting
	I_4	Improper formwork installation
	I_2	Inaccuracy of the geodetic layout
D_4	I_8	Improper during manufacturing at the factory
	I_9	Improper compaction of the mixture

	I_{10}	Exceeding the permissible height for pouring the mixture into the formwork
	I_{11}	Failure to comply with the time and conditions for pouring.
	I_{12}	Improper during curing and maintenance of concrete
D_5	I_9	Improper compaction of the mixture
	I_{10}	Exceeding the allowable drop height of the mixture into the formwork
	I_4	Improper formwork installation
	I_{13}	High reinforcement percentage
D_6	I_{14}	Insufficient manpower and/or equipment
	I_{15}	Interruption of the concreting process due to weather conditions
	I_{16}	Concreting stopped due to a delay in receiving the mix from the factory.

The next step in constructing the fault tree is to determine the probabilities of incidents leading to defects. To accomplish this task, an expert survey was conducted. The survey involved specialists from contracting organizations that perform monolithic works with more than 10 years of experience in construction. For each incident, the experts assessed the probability, followed by statistical processing of the results, excluding outliers. Based on the research, a fault tree for monolithic structures was constructed, as shown in Figure 2. In this tree, each incident I_i can lead to a defect. In the tree shown in Figure 2, this is indicated by an "OR" gate. The probability of a defect is equal to the sum of the probabilities for each incident.

$$P(D_i) = 1 - \prod_{i=1}^{n}(1 - P(I_I).$$

The results of the defect probability calculation based on the Analysis of the constructed fault tree are shown in (Table 2). Moreover, the overall probability of defect occurrence during concrete work was P(D) = 0.68.

To verify the defect probability value, calculated based on the fault tree analysis, the authors calculated the probability of defects in monolithic structures based on statistical data obtained from the Analysis of inspection records of the construction control service on 10 multi-storey residential building construction sites.

Table 2. Defect probabilities of monolithic structures based on the fault tree analysis results

Defect Name	Probability of Defect Occurrence
D_1- Irregularities and chips on the concrete surface	0.16
D_2- Cracks in concrete	0.21
D_3- Deviation of geometric characteristics and positioning	0.14
D_4- Non-compliance with concrete strength	0.22
D_5- Surface voids, pores, and exposure of reinforcement,	0.16
D_6- Violation of work joint requirements during concreting	0.13

Table 3. Probabilities of defects in monolithic structures based on statistical data processing from inspection registers

No	Name of the Defect (Di)	$P(D_i)$
1	D_2- Cracks in concrete with an opening width of more than 0.2 mm	0,09
2	D_5- Areas of unconsolidated concrete	0,15
3	D_3- Vertical deviation, straightness, horizontality of structure, deviations of the cross-section dimensions	0,15
4	D_1- Irregularities and chips on the concrete surface	0,15

Addressing the causes (incidents) of defects in the construction process A will lead to a reduction in the risk to the quality of these construction structures $R_Q(A)$ and a decrease in the risk of defects affecting the implementation of the construction project $R_P(A)$. Analysis of the fault tree in Figure 2 revealed that incidents I_1, I_2, I_4, I_9, and I_{10} are the causes of multiple defects simultaneously.

Addressing these incidents is preferable for reducing the overall probability of defects. The authors have identified a set of organizational and managerial solutions to address the incidents leading to defects. The list of these solutions is presented in (Table 4). The developed methodology was implemented during the construction of Building 2 of a residential complex in Moscow, with a total area of 110,000 m². To prevent the occurrence of defects, based on the conducted research, organizational decisions were made during the design of technological processes for the construction of monolithic structures: S_8, S_2, and S_5.

To reduce the probability of incidents I_1, I_9, I_1, I_9, and I_{10}, operational control should be strengthened during concrete placement (S_3). For this purpose, the foreman and supervisor monitor all technological processes during concrete placement, and the surveyor controls the positioning of the formwork.

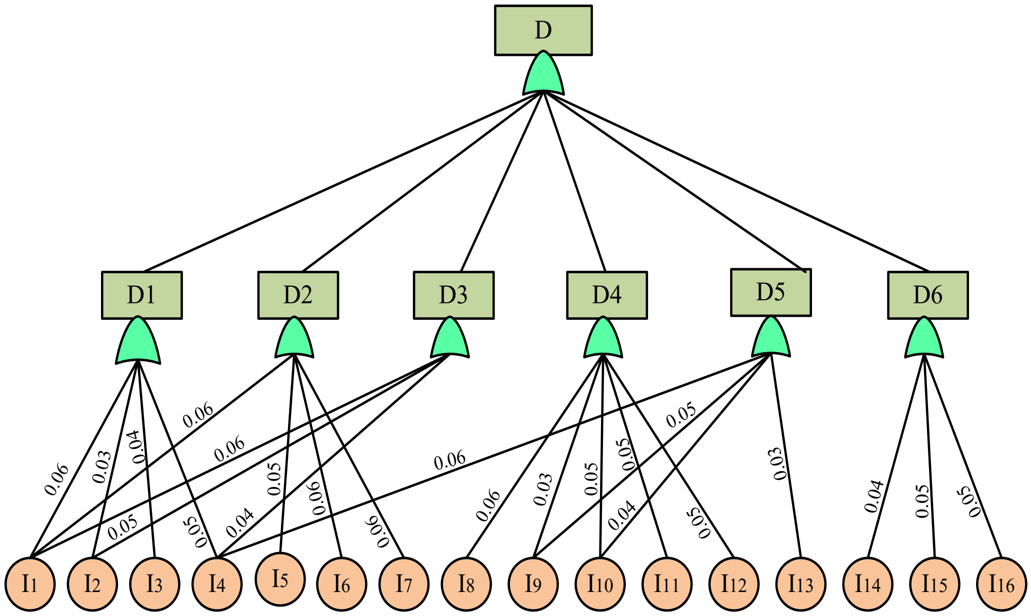

Fig. 2 Fault tree for monolithic structures

Table 4. Organizational and technological solutions to reduce the probability of incidents

Name of the Incident	Organizational and Technological Solutions to Reduce the Probability of Incidents
I_1- Bending or displacement of the assembled formwork during concreting	S_1- Strengthening operational and acceptance control of formwork assembly S_2- Replacing the formwork with newer models S_3- Operational control during concrete placement
I_2- Inaccuracy in geodetic layout	S_4- Improving the qualifications of survey engineers S_5- Using high-precision geodetic instruments
I_4- Improper formwork installation	S_1- Strengthening operational and acceptance control of formwork assembly S_2- Replacing the formwork with newer models S_6- Improving worker qualifications S_7- Verification and control of formwork installation accuracy (executing as-built geodetic formwork diagrams)
I_9- Improper compaction of the mixture	S_6- Improving worker qualifications S_8- Using modern technologies and equipment for concrete placement S_3- Operational control during concrete placement
I_{10}- Exceeding the allowable drop height of the mixture into the formwork	S_6- Improving worker qualifications S_8- Using modern technologies and equipment for concrete placement S_3- Operational control during concrete placement

Table 5. Comparative analysis of the quality of building construction after applying the model

No	Indicator Name	1st Building	2nd Building
1	The volume of monolithic reinforced concrete structures, m^3	85483	109798
2	Number of defects	251	152
3	Defects per 1000 m^3	2,93	1,38

This example of using the model presents a comprehensive improvement in the quality of monolithic construction by reducing the probability of incidents that lead to the largest number of defects. The developed model can be used to analyze the causes of defects and influence the factors that lead to them. During the construction of a waste incineration plant in the Moscow region, at the stage of erecting the underground part of the building from monolithic reinforced concrete, the predominant number of defects, D5- 70% of all defects, was recorded (Table 6). According to the developed model, to reduce the probability of the occurrence of defect D5, it is necessary to reduce the probabilities of incidents I9, I10, and I4, as per Table 1. The prevention of these incidents was minimized by applying organizational and management solutions, according to Table 4.

These measures allowed for reducing the occurrence of defects (22% of the total number of defects), which is reflected in the statistics of prescriptions for this object during the construction of the above-ground part of the building (Table 6).

Table 6. Comparative analysis of the quality of incinerator building construction after applying the model

No	Indicator Name	The Underground Part	The Above-Ground Part
1	D_1- Irregularities and chips on the concrete surface	2	10 (15%)
2	D_2- Cracks in concrete	0	7 (11%)
3	D_3- Deviation of geometric characteristics and positioning	11 (25%)	26 (40%)
4	D_4- Non-compliance with concrete strength	0	3
5	D_5- Surface voids, pores, and exposure of reinforcement,	30 (70%)	14 (22%)
6	D_6- Violation of work joint requirements during concreting	0	5
	In total:	43	65

4. Discussion

This article presents an approach for assessing the damage caused by defects, which allows for evaluating the significance of defects and, consequently, determining the risk of defects. This article is the first to use a fault tree to calculate defect probabilities in monolithic reinforced concrete structures. The obtained probabilities are approximately consistent with defect probabilities determined from statistical data, indicating the correct determination of defect probabilities based on the probabilities of the incidents leading to them. Using fault trees allows for analyzing the causes of defects and addressing them to reduce their probability.

The constructed model enables the determination of defect risks and adopting of rational organizational decisions to reduce them. This contributes to preventing defects, as experimentally confirmed during the construction of a residential complex in Moscow. Another distinctive feature of the proposed model is the automatic identification of possible causes of defects with an indication of their probability. This advantage of the model makes it possible to make decisions to prevent defects during further construction, especially in cases where there is no reliable information about the causes of defects, as experimentally confirmed during the construction of an incinerator building in the Moscow region. The system's effectiveness in managing the quality of monolithic reinforced concrete structures, which is based on the construction and Analysis of a fault tree, has been verified.

5. Conclusion

This article demonstrates approaches to solving problems in the organization of construction control for multi-story buildings through the application of a risk-based approach. Two main types of damage from construction defects are identified, and methods for their calculation are presented. The article concludes that it is possible to reduce the risk of defects by decreasing their probability. A fault tree model is proposed to reduce the probability of defects, which should be constructed for each type of structural defect. The article presents the results of constructing a fault tree for monolithic reinforced concrete structures, analyzing and calculating defect probabilities. Measures to reduce defect risks are proposed, and their implementation in the construction of a residential complex in Moscow is described. Further research should include more detailed fault tree construction, identifying dependent causes at different levels, calculating probabilities at tree branches and nodes, analyzing fault trees, and developing measures to address the root causes of defects.

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