Theoretical analysis of RC beams reinforced with high strength rebar’s and steel plate

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Abstract. The article introduces the comparative results of the deformability and fracture resistance of steel reinforced concrete beams with combined reinforcement obtained on the basis of laboratory tests with the results of computer-aided mathematical modelling of such structures. The results were compared for the purpose of mathematical model testing and its further usage in the study of the optimal reinforcement percentage in steel reinforced concrete beams with combined reinforcement. Results obtained on the basis of the proposed mathematical model show sufficient correlation with the experimental data up to the stage of structure strength exhaustion. As the result it enables to evaluate the features of destruction of the tested samples with the sufficient accuracy, namely, their load-carrying capacity, cracks formation, to analyze stresses in both steel bars and tapes, monitor deflections and deformations during the loading of the tested beams. Deviation of the experimental values for steel reinforced concrete beam with the combined reinforcement from the data obtained according to mathematical model: up to 5.0% for fracture resistance; up to 14.3% for deformability.

1. Introduction

Nowadays, compressed-bended, bended and non-centrically compressed elements are the popular topic of scientific research [1-10]. One of the most popular materials for such constructions is reinforced concrete [11-16].

However, the influence of both the time factor, as well as various external impacts could result in certain defects and damages [17-22]. Methods for reconstruction and strengthening of such structures are widely studied [12-16, 23]. Recently, the development of new constructions with the use of various high-strength materials has reached high topicality [25-28]. Therefore, it is important to investigate the research of reinforced concrete beams with high-strength steel bars and external steel plate.

The new modern trend in civil engineering is designing construction objects and their structural elements using mathematical modelling. Modelling of the designed structure performance subjected to load with the use of computer provides an opportunity to study and design non-typical structures of arbitrary geometric forms on more detailed scale, taking into account both the compatible work of materials with different physical characteristics, as well as the geometric and physical nonlinearity of performance of the material.
The comparative analysis of results obtained from the experimental data and mathematical modelling on a computer (with the use of finite element methods and consecutive approximations considering the actual deformation diagrams of materials) introduced in the article [24] confirmed that mathematical modelling of the work of steel-concrete structure, reinforced by set of steel bars of different classes corresponds to the actual construction performance. Therefore, the computer calculation method with the usage of software “Lira” proposed in the above-cited previous study [24] requires further detailed investigation and more thorough testing of the results. Mathematical modelling is performed considering the physical nonlinearity and actual deformation diagrams of materials “$\delta - \varepsilon$” using the nonlinear deformation law No. 14 of the Lira software. The introduced method allows obtaining stress values, the development of deformations along the cross-section height on all load levels. The article compares the results of experimental deformability and fracture resistance study of steel reinforced concrete beams with combined reinforcement, with the mathematical modelling results. The comparison was made to test the mathematical model for its usage in further study of steel reinforced concrete structures with combined reinforcement.

2. Definition of the study purpose and objectives
The purpose of the work is to obtain a mathematical model, tested in real experimental studies, in order to further use it to develop proposals for the rational reinforcement of structures with combined reinforcement.

3. The main part of the study
The first part of the mathematical modelling results validation with the experimental data was previously considered and discussed in [24]. These studies present the results of comparison of mathematical modelling with experimental studies in terms of stress development and strength of steel reinforced concrete beams with combined reinforcement. Not less important are similar studies of fracture resistance and deformability of such structures.

Preliminary experimental studies [24] examined the work of eight steel reinforced concrete beams with a cross section of 0.12x0.24m, with a calculated span of 2.4m subjected to load. The linkage of the outer tapes was ensured by the use of U-shaped anchors welded to the sheet. The design of reinforcement frames is shown in Figure 1.

![Figure 1. The reinforcement frame construction for tested samples.](image)

In order to reduce the absolute error value during preliminary tests were used duplicate twin-beams made from one concrete mix. Such an approach made it possible to obtain high-quality source material for further experiment and were shown in [24].

4. Results of the experimental study
The obtained results of theoretical calculations according to the mathematical model with sufficient accuracy coincide with the experimental data, which could confirm the possibility for its further usage
for the calculations of steel-concrete structures, reinforced by the reinforcement set, in which the external tape works with the adhesion to concrete due to anchors, as well as without adhesion to concrete within the span.

As could be seen from the results, the values of bending moments which cause the normal cracks formation obtained with the use of numerical model have good similarity with the experimental data, respectively the deviation does not exceed 5.0%. The data is presented in table 1.

The computer calculation with the use of software “Lira” according to finite elements method, considering the actual deformation diagrams “δ – ε” of materials corresponds to the performance of the actual structure strengthened by the reinforcement set with external tapes.

This proves that the design model allows us to estimate with sufficient accuracy the strength and deformability of steel reinforced concrete structures with combined reinforcement.

Table 1. Comparison of the experimental, theoretical according to FEM and calculated normative values of the bending moments which correspond to the fracture formation in the tested beams.

| Notation of the beams | Experimental $M_{cr}^d$, kNm | $M_{cr}^d - M_{cr}^{DBN}$, kNm | $M_{cr}^d - M_{cr}^{DBN}$, % | FEM $M_{cr}^d$, kNm | $M_{cr}^d - M_{cr}^{FEM}$, kNm | $M_{cr}^d - M_{cr}^{FEM}$, % |
|----------------------|-----------------------------|--------------------------------|-----------------------------|-----------------------------|--------------------------------|-----------------------------|
| B - I - 1            | 6.9                         | 5.92                           | 14.2                        | 7.04                        | 2.0                            | -1.5                        |
| B - I - 2            | 7.15                        | 6.12                           | 18.0                        | 7.71                        | -3.6                           | -3.4                        |
| B - II - 1           | 8.00                        | 6.12                           | 18.0                        | 7.71                        | 3.4                            | -4.0                        |
| B - II - 2           | 7.46                        | 5.26                           | 18.1                        | 11.2                        | 1.9                            | 1.9                         |
| B - III - 1          | 11.67                       | 5.26                           | 18.1                        | 11.2                        | -4.0                           | -5.0                        |
| B - III - 2          | 10.99                       | 6.1                            | 18.0                        | 6.1                         | 1.9                            | -4.6                        |
| B - IV - 1           | 39.16                       | 7.12                           | 11.9                        | 37.2                        | -5.0                           | -5.0                        |
| B - IV - 2           | 39.00                       | 10.1                           | 21.5                        | 37.2                        | 1.9                            | 2.5                         |

In the deflection definition the satisfactory coincidence of results was obtained at all stages of structure loading (see Table 2).

The deviation of the results with deformations of beams according to computer simulation and experimental data at 0.7$M_{dr2}$ does not exceed - 14.3% (Table 2).

Table 2. Comparison of experimental, theoretical according to FEM and calculated according to DBN.V.2.6:2009 deflections values for he tested beams.

| Notation of the beams | Deformation from 0.4$M_{dr2}$ | Deformation from 0.7$M_{dr2}$ |
|----------------------|-------------------------------|-------------------------------|
|                      | $f_1^d$, mm | $f_{1FEM}^d$, mm | $f_{1FEM}^d - f_1^d$, % | $f_2^d$, mm | $f_{2FEM}^d$, mm | $f_{2FEM}^d - f_2^d$, % | $f_2^d$, mm | $f_{2FEM}^d$, mm | $f_{2FEM}^d - f_2^d$, % |
| B - I - 1            | 2.21            | 2.1              | -5.0                        | 4.55            | 5.2              | 2.0                          |
| B - I - 2            | 2.35            | 4.1              | -10.6                       | 5.08            | 9.8              | 3.8                          |
| B - II - 1           | 4.81            | 3.0              | -14.8                       | 9.56            | 9.8              | 2.5                          |
| B - II - 2           | 3.98            | 8.2              | -14.9                       | 20.32           | 22.1             | 8.8                          |
| B - III - 1          | 8.25            | 8.2              | -0.6                        | 20.32           | 22.1             | 8.8                          |
| B - III - 2          | 9.64            | 14.9             | 21.57                       | 21.57           | 2.5              | 4.0                          |
| B - IV - 1           | 1.94            | 2.1              | 8.2                         | 4.55            | 4.4              | -3.3                         |
| B - IV - 2           | 2.08            | 1.0              | 4.55                        | 4.4             | 6.0              | 3.3                          |
Results of the mathematical modelling confirmed that the designed calculation model gives an opportunity to evaluate deformations and fracture resistance of steel reinforced concrete beams with combined reinforcement with the sufficient accuracy.

5. Conclusion
The proposed mathematical model gives an opportunity to take into account the influence of physical non-linearity of actual deformation diagrams of materials on deformability, fracture resistance and performance of structures with the set of reinforcement.

The results obtained on the basis of the proposed mathematical model show sufficient correlates to the experimental data up to the stage of structure strength exhaustion. As the result it enables to evaluate the features of tested samples destruction with the sufficient accuracy, namely their carrying capacity, cracks formation, to analyze stresses in both steel bars and tapes, monitor deflections and deformations during the loading of the tested beams.

Deviation of the experimental values for steel reinforced concrete beam with the combined reinforcement from the data obtained according to mathematical model: up to 5.0% for fracture resistance; up to 14.3% for deformability.

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