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Petro Krasnitskyi, Maksym Lobodanov, Zinovii Blikharskyi

ANALYSIS OF SOFTWARE PACKAGES APPLYING IN THE INVESTIGATION OF THE DAMAGE EFFECT TO REINFORCED CONCRETE BEAMS ON STRENGTH AND DEFORMABILITY: THE REVIEW

Department Of Building Construction And Bridges,
Lviv Polytechnic National University
maksym.m.lobodanov@lpnu.ua

Currently, on the world market, there are trends in the construction of a large number of monolithic and prefabricated reinforced concrete structures, and individual parts of these structures are operated with damage or defects, and the causes of these damages are quite diverse. In modern conditions, such work can be facilitated and analyzed in more detail with the help of specialized software, which can include all the necessary characteristics of material behavior and include existing defects or damage. This problem of damage to reinforced concrete structures will become extremely relevant in Ukraine, especially after the completion of a full-scale armed attack by the Russian Federation, and therefore, the study of various types of damage and defects that will affect the load-bearing capacity and strength of reinforced concrete elements require a quick and high-quality analysis of this damage, and most likely aggregates of damage.

Key words: finite element method; nonlinear calculation; reinforced concrete beams; damage to reinforced concrete; residual bearing capacity; stress-strain state.

Introduction

To date, the bulk of buildings and structures have been built using reinforced concrete structures, and some of them are operated in a damaged state. These defects or damage can occur at different stages of operation, and the causes of such damage are completely different: inaccurate placement of reinforcement during the manufacture of the element, which subsequently leads to a change in the stress-strain state of the element compared to the design solution; cases of mechanical damage occur during transportation or installation of a reinforced concrete element; the use of a reinforced concrete element outside of its intended purpose or a change in the load on the element that does not correspond to the accepted load in the calculations; the action of an aggressive environment or damage from the action and other natural phenomena. There is a need to study and evaluate the residual bearing capacity of the damaged element and determine the real bearing capacity. Since the complexity of structures is currently different, one of the ways to study such structures is to build a SE model of a damaged structure and conduct a nonlinear analysis, which in turn allows you to take into account various behavioral aspects of the material or other non-standard cases and find the most optimal solution to this problem. Development and implementation of the most convenient and most accurate algorithm for nonlinear calculation of structural elements will allow to find the right solution quickly, reliably and economically, and such an issue is quite important for scientists today. The basis of the presented theoretical studies is the existing method of calculation according to the current norms DBN V.2.6-98:2009, DSTU B V.2.6-156: 2010.

The research material

The purpose and task of the study is to reproduce the results of studies of the bearing capacity of a damaged monolithic reinforced concrete element using a numerical nonlinear finite-element calculation based on the general mechanics of various software complexes, namely: LIRA-SAPR and ANSYS**.** Assessment and classification of various types of damage according to norms and various types of scientific research works. The author (Lobodanov et al., 2018) cited the generally accepted classification of damage in reinforced concrete structures (Rilem technical committees, 1991), which was adopted and approved by the technical committee DCC-104 RILEM (International Union of Experts and Laboratories for Testing Building Materials, Systems and Structures), which has been relevant since 1991. In work (Lobodanov et al., 2018), it can be divided into the following subtypes, namely: depending on the degree of damage, depending on the part of the building where the damage or defect occurred, distribution depending on the damage or defect itself, depending on the time of formation and depending on the cause of occurrence.

Taking into account the determination of the residual bearing capacity of bent reinforced concrete structures with damage, the determination of defects or damage in these elements plays a major role. It is stated in (Lobodanov et al., 2019) that the most common defect is the loss of the protective layer by the reinforced concrete structure, such damage usually occurs in the case of chipping of the protective layer of concrete, which in turn is caused by mechanical damage during transportation or installation or during operation or caused by the action of corrosion or fire influences Another factor that can cause the loss of the protective layer of a reinforced concrete structure is the delamination of the concrete clamps, which is also caused by the effects of fire or the pressure of new formations of salt, ice, or in case of violation of the rules of operation, as an example – the structure is jammed.

In work (Klymenko et al., 2012), the stress-strain state of bent reinforced concrete elements was developed and simulated with the help of the "LIRA 9.6" software complex using piecewise linear dependence. According to the author of this work, after a consistent analysis with the help of stress isopoles, it is possible to form a fairly reliable assessment of the influence of structural factors on the load-bearing capacity of a reinforced concrete element and to predict the nature of further deformations and physical damage.

In work (Klymenko et al., 2014), the residual load-bearing capacity of bent reinforced concrete elements was determined in damaged T-shaped beams with the help of the software complex "LIRA 9.4" and the possibility of reproducing different types of damage in this software complex was analyzed:

- part of the shelf is damaged and expressed due to the relationship b_{eff1}/b_{eff2}, where b_{eff1} – amount of damage; b_{eff2} – the size of overhanging shelves;
- depth of damage a_1, expressed through the ratio of the shelf damage angle to the thickness a_1/h_{f1};
- damage angle β, expressed in terms of the ratio of the angle of damage to the angle of inclination of the shelf and is equal to 90°.

In the thread (Subramani, 2014), the author analyzes the nonlinear numerical analysis of a reinforced concrete beam using specialized ANSYS software and investigates the behavior of a bent reinforced concrete element during the first fracture. A comparative analysis was carried out to verify the correctness of the values of deflections and stresses that occur in the reinforced concrete element and came to the conclusion that in a full-scale experiment, when the first cracks appear, it is difficult to predict the behavior of the co-construction, however, with the help of the existing functionality in the ANSYS software, it is possible to simulate the approximate vector of appearance cracks and depict the schematic cracking of a reinforced concrete beam

In the source (Halahla A., 2018), the author explains the reasons that may arise as a result of the appearance of cracks in reinforced concrete elements and as an alternative to predicting and preventing the appearance of cracks, significant efforts have been invested in the development of specialized software complexes for the automated recognition of cracks in digital format.

The author (Klymenko et al., 2013) analyzed the impact of damage to the girder beams on the value of their destructive load. The obtained experimental data were processed by the method of removing the coefficients of the regression equations and a mathematical model was formed, according to which it is possible to estimate the influence of the damage factors studied in this work on the initial parameters of the beam, the geometric interpretation is shown in Fig. 1 and 2, where $F_{ULS}-$ external load under which the beam collapses.

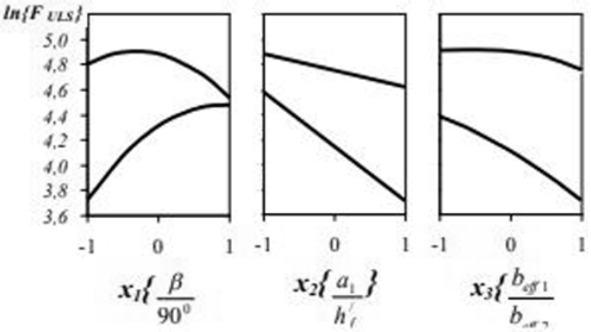

Fig. 1. One-factor dependencies of the influence of various factors on the beam strength indicator (*Klymenko et al., 2013*)

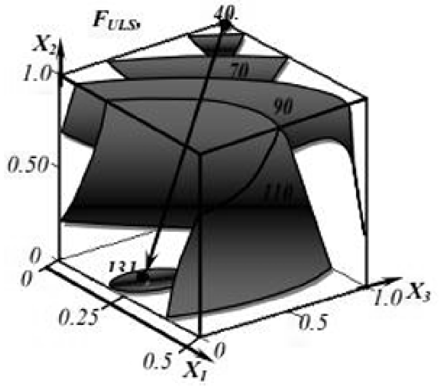

Fig. 2. The graph of the joint influence of various factors on the destructive load of beams (*Klymenko et al., 2013*)

As a result of the work shown, the linear dependence in Fig. 3, between the change of the damage depth and the destructive load, which is the main factor that will affect the load-bearing capacity of the bent reinforced concrete member of the T-profile.

Another most common defect in reinforced concrete bent elements is corrosion of internal reinforcement. This damage consists in the fact that during the corrosion of the armature, its volume increases directly on the armature itself, which as a result leads to the appearance of cracks and a violation of the integrity of the protective layer of the structure (Ghlaghola et al., 2002) (Fig. 3).

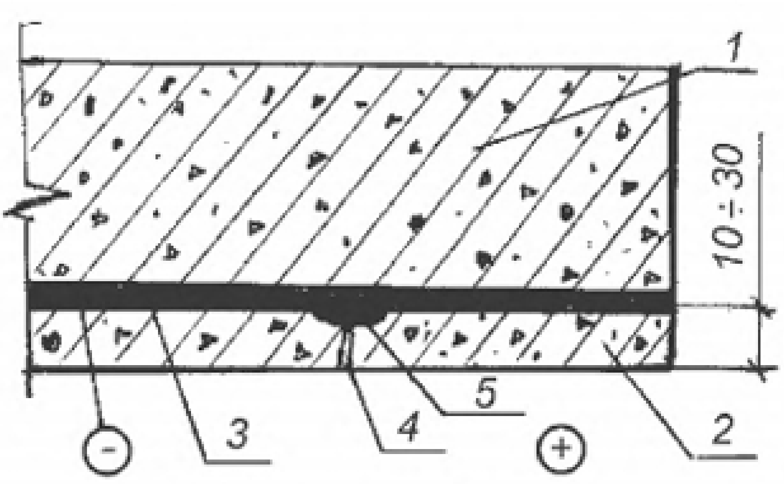

Fig. 3. The beginning of reinforcement corrosion: 1 – beam; 2 – protective layer; 3 – structural reinforcement; 4 – crack; 5 – corrosion area (Ghlaghola et al., 2002)

This process occurs in a hidden form with a decrease in the bearing capacity of the reinforced concrete structure. The most common reason for the appearance of corrosion is the presence of chlorides in the concrete or the ingress of oxygen directly to the reinforcement itself, accordingly, the required diameter of the reinforcement adopted according to the calculation decreases, which in turn leads to a decrease in the bearing capacity of this reinforced concrete structure and its destruction.

The influence of the action of an aggressive environment is described in work (Khmil et al., 2009), where the following aspects of the influence of an aggressive environment are highlighted, namely: the process of destruction of reinforced concrete bent elements in a sulfur environment, where corrosion of the concrete itself occurs, which can then further develop into corrosion of the reinforcement, which leads as given above to the reduction of the necessary area of reinforcement, and with the action of corrosion on concrete, the area of the concrete section also decreases, which leads to a decrease in the working height, a decrease in the area of the compressed zone of concrete, and as a result, stresses in the concrete and reinforcement increase, which at one point leads to destruction. The influence of an aggressive environment in the local zone, described by the author in (Blikharsjkyj et al., 2011), is different from the action of an aggressive environment described in (Khmil et al., 2009), in that the action of an aggressive environment took place in the compressed zone of the reinforced concrete section. The authors of the paper (Petrov et al., 2015) investigated the influence of displacement of the reinforcement of the element during its manufacture, which in turn leads to the appearance of torque and the appearance of spiral cracks.

Having analyzed and researched all the most frequent types of defects and damage of reinforced concrete elements, it is a very important aspect of modeling the damaged element along with the damage using the finite element method and then conducting a numerical nonlinear finite element calculation taking into account all the behavioral characteristics of the materials on the basis of a certain calculation complex. Account all the behavioral characteristics of the materials on the basis of a certain calculation complex.

In (Tjitradi et al., 2017), the author investigates the failure behavior of concrete with the help of simulations in the ANSYS software package using the finite element method and comparing different types of finite elements. The author (Patil et al., 2013) conducts a comparative experimental and analytical study of 3 experimental samples of reinforced concrete beams of different lengths, after the experiment it was found that the analytical calculation values were smaller than the experimental values: for the first sample by 20 %, for the second by 17 % and for the third at 16 %. The author (K. Hasan et al., 2020) studied various types of transverse reinforcement in reinforced concrete beams with the help of a finite element model in the ANSYS software complex. After the analysis, the welded frame showed much better characteristics. In the work (Ibrahim, 2009), the simulation of reinforced concrete beams of rectangular cross-section was carried out, reinforced with external fiberglass reinforcement, using the method of finite elements, implemented in the PC "ANSYS". In (Bosniuk et al., 2021), a comparative analysis of the bearing capacity of a reinforced concrete structure was carried out using the ANSYS software complex. The following finite elements were used in the construction of the finite element model: for concrete – SOLID 65, and for reinforcement – Link8. SOLID65 – typically this finite element is used to model concrete while Link8 will be used to model rebar properties. This final element is determined by 8 nodes and has 3 degrees of freedom in the x, y and z directions. Link8 is a finite element used for modeling reinforcement. This element also has 3 degrees of freedom in the x, y, z directions, but this element contains only 2 nodes. Both end elements interact well with each other and undergo plastic deformations. In this work (Wierzbik-Strońska et al., 2021), a comparative analysis of a damaged reinforced concrete beam due to temperature effects was carried out. All calculations were performed according to Eurocode 2: Design of concrete structures. When building the model, the parameters of the reinforced concrete beam from the first series of tests (sample No. 1) were used. During all experiments, temperature changes were recorded at control points every minute. However, given the large volume of data, in Table 1 shows only the results recorded with a step of 5 minutes. For comparison, similar data are obtained from the calculation results file in the ANSYS program (Table 1).

Analysis Table 1 shows that the results of experimental studies of a reinforced concrete beam-wall and its numerical analysis in the ANSYS program for the first 10 minutes are quite significantly different at all control points, but later this difference stabilizes and, until the end of the experiment, does not exceed 10.0 %.

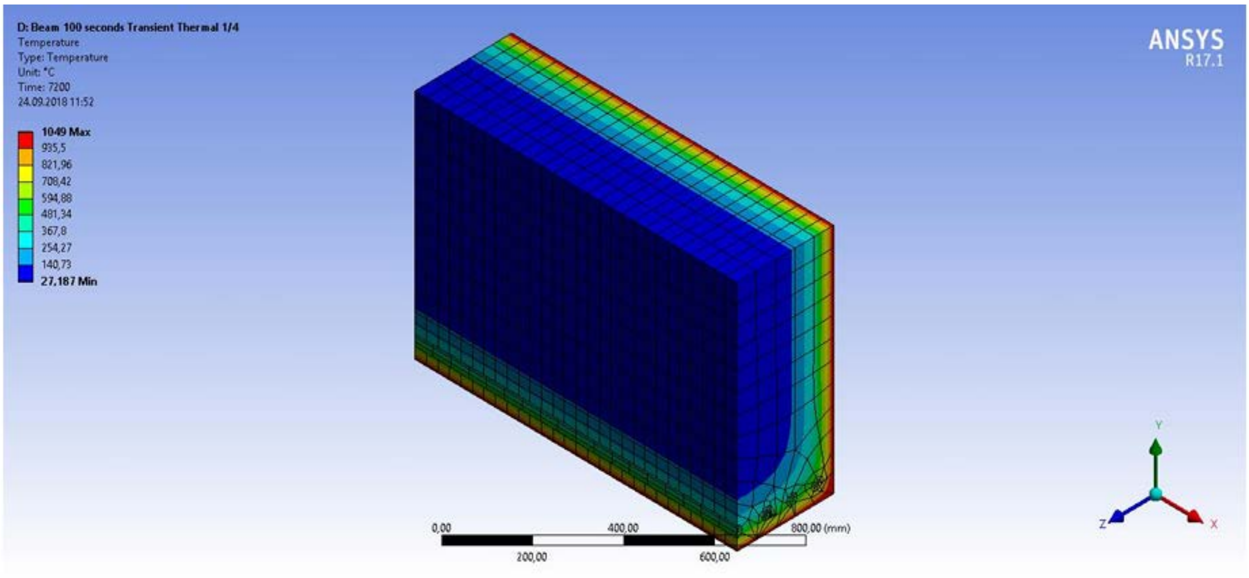

Fig. 4. Calculated CE model taking into account the temperature distribution along the beam (*Wierzbik-Strońska et al., 2021*)

Table 1

Comparison of experimental results and numerical calculation*

Time, m	T1-1	ANSYS	Difference, %	T1-2	ANSYS	Difference, %
0	11	14	21.4	10	13	21.4
5	13	16	18.8	10	13	21.4
10	23	26	11.5	12	15	20.0
15	47	51	7.8	18	20	10.0
20	70	76	7.9	28	31	9.7
25	87	96	9.4	37	41	9.7

* *Wierzbik-Strońska et al., 2021.*

In the author's work (Muryn et al., 2012), a comparative analysis of reinforced concrete beams not reinforced and reinforced with carbon composite strips was carried out in PC "LIRA-SAPR" and experimental and calculated deflection graphs for unreinforced and reinforced beams were given. In the work (Karpiuk et al., 2020), the author reproduced the results of experimental studies of the bearing capacity of uncut and eccentrically compressed beams with the help of numerical nonlinear finite element calculation based on the general mechanics of reinforced concrete using PC "Lira 9.6". Another numerical experiment was performed using the domestic software complex "LIRA CAD 2017" in work (Klymenko et al., 2019). The following aspects are considered in the paper (Karpiuk et al., 2020). As a basis for this calculation, a finite element model was also built, in which finite elements of the CE No. 236 type were used – this is a physically nonlinear universal 8-node parametric CE, its volume is 150 mm^3 with the size of the ribs 5×5×6 mm, the elements are connected to each other by rigid inserts, that is, nodes that are rigid bodies and absolutely small in size with six degrees of freedom. Reinforcement in the beam is also made in similar finite elements with characteristics corresponding to the specified reinforcement. Obtaining data in this software complex takes quite a long time (Fig. 6). The achievement of at least one limit state by the reinforced concrete structure was accepted as a failure criterion: achievement of the limit stresses by the longitudinal or transverse reinforcement; the achievement by the concrete in the compressed zone of a significant number of SE limit stresses at the place of abutment of the sample or above the top of the inclined plane. All calculations were carried out according to current norms DBN V.2.6-98:2009, DSTU B V.2.6 – 156: 2010

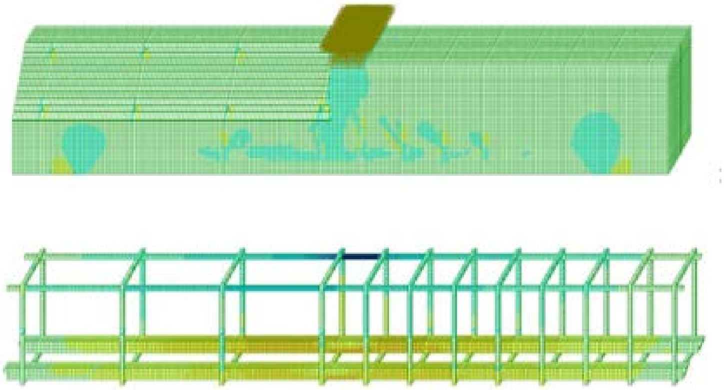

Fig. 5. Calculated CE model of a damaged beam
(concrete and reinforcement) (Klymenko et al., 2019)

Table 2

Comparison of residual bearing capacity results*

Type of beams	Limit load according to simulation results F_u^{lira}, kN	Limit load according to the results of the experiment F_u^{exp}, kN	Limiting transverse force according to simulation results V_u^{lira}, kN	Limiting transverse force according to the results of the experiment V_u^{exp}, kN	Difference $\frac{V_u^{exp}-V_u^{calc}}{V_u^{exp}}$
B1	111.24	121.618	54.51	59.54	8.45
B2	105.6	116.62	51.74	57.14	9.46
B3	90.828	98.294	44.51	48.16	7.59

* *Klymenko et al., 2019.*

The data obtained as a result of the calculation of the load-bearing capacity of the test samples, as well as laboratory studies, allow us to trace the trends of its decrease depending on the amount of damage: the larger the area of damage, the smaller the residual load-bearing capacity of the element. The absolute difference between laboratory data and simulation results is obtained.

Conclusions

By analyzing domestic and foreign literary sources, it was possible to classify damage and defects that occur in bent reinforced concrete structures, the need for modeling damaged reinforced concrete elements in specialized software using finite elements is clearly demonstrated. After analyzing the numerical calculations of two different types of damage in the “ANSYS” and “LIRA-SAPR” software packages, they saw a satisfactory result, where the discrepancy between the results of the theoretical calculation and the experiment is no more than 10 %. And therefore the expediency of conducting additional software analysis of damage data is in demand. Comparing these two complexes, it can be said that each of them has its own set of advantages and disadvantages, which can be further investigated to develop the most optimal algorithm for calculating damaged structures in the setting of numerical nonlinear finite element calculation.

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П. В. Красніцький, М. М. Лободанов, З. Я. Бліхарський,
Національний університет “Львівська політехніка”,
кафедра будівельних конструкцій та мостів

АНАЛІЗ ЗАСТОСУВАННЯ ПРОГРАМНОГО ЗАБЕЗПЕЧЕННЯ В ДОСЛІДЖЕННІ ВПЛИВУ ДЕФЕКТІВ ЗАЛІЗОБЕТОННИХ БАЛОК НА МІЦНІСТЬ І ДЕФОРМАТИВНІСТЬ: СТАН ПИТАННЯ

Згідно із тенденціями сучасного світового ринку будівництво із монолітного та збірного залізобетону надзвичайно популярне через численні різноманітні чинники, які змушують вибирати саме такого типу конструкції для спорудження будинків. Якась частина цих конструкцій експлуатується з пошкодженнями чи дефектами, причини яких різноманітні. Особливої уваги потребують обстеження і реконструкція таких пошкоджених конструкцій, щоб визначити значення надлишкової несучої здатності елемента, оскільки пошкодження та дефекти можуть бути абсолютно різноманітними, а чинників, які їх спричиняють, безліч. У сучасних умовах таку роботу можна полегшити і детальніше проаналізувати за допомогою спеціалізованого програмного забезпечення, яке ураховуватиме всі необхідні поведінкові характеристики матеріалу, братиме до уваги в розрахунках дефекти чи пошкодження. Зважаючи на сьогоднішню ситуацію в Україні, проблема пошкоджених залізобетонних конструкцій буде надзвичайно актуальною, особливо після закінчення повномасштабного збройного нападу російської федерації. А отже, дослідження різних пошкоджень та дефектів, які впливатимуть на несучу здатність та міцність залізобетонних елементів, потребуватиме швидкого і якісного аналізу пошкодження, а швидше за все, комбінації пошкоджень. Проаналізовано класифікацію та вплив пошкоджень, дефектів на несучу здатність пошкоджених згинаних залізобетонних елементів і проаналізовано два варіанти нелінійного аналізу в двох різних програмних комплексах “LIRA-SAPR 2017” та “ANSYS”. Досліджено роботу кожного з цих програмних комплексів, порівняно з експериментальними дослідженнями, та практичність їх використання у реаліях сьогодення.

Ключові слова: метод скінченних елементів; нелінійний розрахунок; залізобетонні балки; пошкодження залізобетону; залишкова несуча здатність; напружено-деформований стан.