Development of Spring Hinge Models to Simulate Structural Elements of Spherical Graphite Reinforced Concrete

LARYSA SHCHERBYNA[1], ANATOLII BOBRAKOV[2], DMYTRO SAVELIEV[3], SERHII BRAICHENKO[4], OLEKSANDR NIKOLAIEVSKYI[5]
[1,2]Department of Civil Engineering and Project Management, Zaporizhzhia Polytechnic National University, 64 Zhukovsky St. Zaporizhzhia, 69063, UKRAINE
[3]Department of Engineering and Rescue Machinery, National University of Civil Defence of Ukraine, 94, Chernyshevska St., Kharkiv, 61023, UKRAINE
[4]Department of Construction Industry, Lviv Polytechnic National University, S. Bandery St., 12, Lviv, 79013, UKRAINE
[5]Department of Mathematical Disciplines and Innovative Design, Private Higher Educational Institution "European University", Vernadskogo boulv. 16-v, Kyiv, 03115, UKRAINE

Abstract: The goals of the study were the formation of a model of concentrated plasticity based on spherical graphite fibers. The goal was to present indicators of the cyclic behavior of structural elements due to the lack of consideration in modern scientific research of the issue of increasing the technical level and reliability of structures due to the addition of innovative materials during the development of structural elements. Taking into account the fundamental shortcomings in construction in the conditions of installing an excess amount of reinforcement, as one of the main mechanisms for achieving strength and reliability. The aim of the study was to develop a method of improving the quality of structural elements using innovative materials through building spring hinge models. The study involved the mathematical simulation, comparison, and system analysis. The result of the work is a developed spring hinge model for simulating reinforced concrete structural elements. The work emphasizes that the obtained experimental model converges to reference data and does not reflect a significant error with the increased number of cycles. It is emphasized that the model degrades with significant calibration, while the numerical strength and hysteresis behaviour matches the experimental data at higher deformation levels. The model of concentrated plasticity based on spherical graphite fibers was developed for the range of indicators of the cyclic behaviour of structural elements. The main characteristics of the reinforced concrete structural elements under consideration in the framework of the study are provided in a table in order to visually separate the groups of structures according to the main parameters. A non-linear model of a spring hinge is graphically shown, which shows the moment of movement of the spring when a monotonous load is applied. An urgent need to build a system of indicators of the structural elements' cyclic behaviour was emphasized. A concentrated plasticity model based on spherical graphite fibers was built for this purpose. A beam-column was chosen as a reinforced concrete structure, which is based on a zero-length spring pivot hinge at the end of each individual element. This spring pivot hinge is a uniaxial material model with a moment-rotation dependency. Such a dependency is the fundamental basis of the spring hinge model used to simulate reinforced concrete structural elements. The comparison chart of reference and cyclic strength of a spherical graphite reinforced concrete beam is presented graphically. Prospects for further research involve the development of an empirical system of equations depending on the section geometry and the properties of the structure material based on prognostic variables from the list of potential variable characteristics.

Key-Words: Spherical graphite, strength, rotation, model, plasticity, beam-column, hinge, spring, stiffness, reinforced concrete.

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1 Introduction

A stable development and the implementation of the principles of stable improvement of any sustainable production depends on the knowledge of the Lead Engineer and the mechanisms of implementation of scientific opinion within the framework of a certain field. An important direction of the technological process is the creation and wide application of new structural elements using innovative materials in order to increase the technical level and reliability of structures, taking into account the thresholds of strength, reliability, and direct economic performance of the manufacturer, [1].

Reinforced concrete structural elements have seismic characteristics that fully depend on the ability of each structural element of the general frame for non-elastic deformation, [2]. In turn, concrete, as a material, consists of a filler, a binder, and water. Its fragility affects the deformation resistance of all structural elements, leading to damage or destruction during seismic impacts, [3]. Considering this fact, reinforcement is a promising direction for increasing the strength of concrete, but excessive reinforcement leads to global problems in construction.

The formulation of complex technology for increasing the strength and quality of structural elements is undoubtedly promising given the modern development of the field of construction technologies, the technological progress in the world, the introduction of nanotechnologies and nanomaterials.

This research aims to formulate a method of improving the quality of structural elements using innovative materials through the creation of spring hinge models.

The aim involved the following research objectives:

- Examine the reinforced concrete structural elements for their properties and specifications;
- Build a concentrated plasticity model based on spherical graphite fibers according to the range of indicators of the cyclic behaviour of structural elements;
- Develop a mathematical model of a spring hinge to simulate reinforced concrete structural elements.

2 Literature Review

The studies on the implementation of innovative mechanisms for the simulation of reinforced concrete structural elements are becoming more relevant in the context of current development. In [1] the author revealed the functionality of fracture mechanics in relation to reinforced concrete structures, including composite and plane-stressed ones. The author carried out simulations of parallel deformation schemes of reinforced concrete based on the fracture mechanics principles, and quantified the effects of components on the overall strength of the structure.

In [2] the researcher dealt with the mechanism of testing the shear strength of high-strength concrete elements. The researcher experimentally studied the deformed state of concrete and reinforcement near the shear area of individual high-strength concrete elements. Her research helped the author to improve the calculation of the strength of high-strength concrete and reinforced concrete elements destroyed by shearing.

A number of authors, [3], proposed an approach for determining the technical condition of reinforced concrete structures under force and high-temperature impacts. Based on the analysis of field survey results, the authors obtained important data on characteristic defects and structural damage, as well as their impact on further work; data on changes in physical and mechanical properties of materials during their use; a mathematical model was developed which allowed evaluating and forecasting the technical condition of structures.

The study, [4], deals with solving the scientific problem of establishing the actual stress-strain state of reinforced concrete flexural, as well as compressive & flexural structures strengthened under the load, and the creation of calculation methods for designing and evaluating the reliability and residual life of those structures. The study experimentally determined the coefficients of the operating conditions of additional reinforcement and concrete of reinforced concrete structures strengthened under the load, which differ significantly from the values recommended by the design standards.

In [5] the authors proposed a scheme for time integration of the system of equations with a Lagrange grid. It became the basis for conducting numerical experiments. As a result, they came to the conclusion about the quality and appropriateness of using reinforced concrete structures in the fortification construction for operation under high-speed impact. The fundamental basis of the research is conducting numerical studies to explore the processes of deformation and destruction of reinforced concrete elements with various types of reinforcement under high-speed impact, as well as the development of recommendations for their design and implementation into construction practice.

The works of the following foreign authors are worth noting. The authors presented and analysed two practical solutions for the structure restoration by establishing the level of bearing capacity of short reinforced concrete cantilevers of the structure's supports, [6], which have undergone certain degradation during their work. In [7] the researchers proposed a new finite element model to simulate reinforced concrete beams shear-strengthened carbon fiber reinforced polymer plate under cyclic loading. The authors developed a spring element for simulating a fracture zone based on a virtual crack in the sub-concrete material. Was evaluated by reinforced concrete structural members, [8]. Was developed a new type of environmentally efficient steel fiber reinforced concrete with waste graphite, [9]. The authors proved that steel fibers are a type of material for strengthening concrete, and waste graphite is used to partially replace sand aggregate. In [10] the researchers studied the degradation of concrete with compression cracks, the effect of tensile reinforcement, and bond-slip to improve the prediction of the reactions observed in reinforced concrete elements under various loads. The authors created a model that predicts the characteristic features of the multiaxial behaviour observed in experiments on simple and reinforced concrete elements subjected to various loads.

The structural facade panel and lighting support were simulated, [11], to study their behaviour under wind pressure. The developed numerical simulations were calibrated against available data from the literature. This simulation revealed information potentially useful for planning further experimental tests. In [12] the researchers developed a structure that attaches to a reinforcing bar for a reinforced concrete structural element containing an anchor end designed to be fixed in the anchor chamber of the former reinforced concrete structural element. The developed design allowed for increasing the overall strength.

Moreover, we are presented with analytical results which showed that high ductility frames showed slightly better lateral load performance compared to low ductility frames, [13]. Besides, analytical studies revealed that the structural steel in the column, regardless of the cross-section shape, is the most important parameter for increasing the bearing capacity of the frame in the transverse direction. In [14] the researchers studied the principles of using CNTs as reinforcement in reinforced concrete structural elements. The authors carried out mathematical modelling of mechanical oscillations of the main structural element of reinforced concrete support, and identified its weaknesses, [15]. In [16] the researcher focuses on the applicability of truss models and the brace and bond method for the analysis and design of reinforced concrete beams and structural walls with an opening that had a complex flow of internal stresses, as well as the development of a design procedure for these beams and walls based on the model.

In work [17] authors analysed the studies carried out on retrofitted RC beams using a traditional method such as stitching (hook method), and also studied the relative effect of these methods on the load-bearing capacity of beams with bending deficiency by retrofitting. Using the closed-form solution of the equilibrium equation and the Jacobi auxiliary equation was determined the equilibrium forms of the beam and their stability, [18]. The author provided a solution for a cantilever beam with a spring hinge that is subjected to a tensile force. In [19] the researchers calculated the spring hinge model through the Lagrange equation, which describes alveolar structures and their morphometric characteristics. The scientists considered the spring hinge as a torsional harmonic oscillator and derived the equations of motion and its natural frequency. The damping effect and external torque were also taken into account.

Authors studied and experimentally confirmed the moment-rotation response of a tape spring hinge in quasi-static folding and deployment processes, [20]. Fluidity theory, derived from a combination of the Theory of Thin Shells and the Tresca criterion, is introduced to control loop fluidity during the folding and deployment processes. In [21] the researchers proposed a calculation model of the static stability of multi-spring hinged columns (linear analysis).

So, with all the mentioned scientific achievements, the issue of developing spring hinge models for modelling structural elements of spherical graphite reinforced concrete remains open and requires detailed study, which is the subject of this research.

3 Research Method

The research was preceded by a survey of several scientific achievements such as their analysis, structuring (Table 1), monitoring of basic and variable structural elements, their composition, and characteristics.

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Dmytro Saveliev, Serhii Braichenko,
Oleksandr Nikolaievskyi

Table 1. The main characteristics of the reinforced concrete structural elements under consideration in this study, [8]

No.	Type	$L_{s,}$ mm	b, mm	h, mm	L_s/d	p_l, %	E_c, MPa	f_c, MPa	f_t, %	f_y, %	f_u, %	Δ_c/L_s, %
1	S1	500	100	100	6.10	1.73	18000	80	6	410	620	14
2	S2	500	100	100	5.88	1.67	18000	80	6	410	620	15
3	S3	610	406	254	3.00	1.23	16000	44	4.4	669	807	12
4	S4	610	406	254	3.00	1.23	16000	41	4.4	669	807	11
5	S5	685	100	250	2.98	1.11	16000	46.4	3.5	440	730	5
6	S6	685	100	250	2.98	1.74	16000	50.3	3.5	445	710	10
7	S7	760	127	178	5.04	0.74	16000	45	3	445	690	8.5
8	S8	760	127	178	5.04	0.74	16000	45	3	445	690	6
9	S9	813	165	203	5.04	1.45	16000	45	3	455	675	16.6
10	S10	813	165	203	5.04	1.45	16000	45	3	455	675	11.9

The purpose of analysing the generated data and their interpretation became the fundamental basis of mathematical modelling was to create the main spring hinge model to simulate structural elements of spherical graphite reinforced concrete. The system analysis was used to establish structural relationships between variables or elements of the general structure, their influence on each other, and the general strength metrics. The comparison method was applied to form the cyclic response of reinforced concrete structural elements to force and drift with and without the use of spherical graphite. The principles of changing the properties of structural elements, their material, geometric characteristics, and cross-sectional properties with a comparable one were confirmed in accordance with the research base.

The fundamental metric for the selection of research results is based on a clear understanding of the types and characteristics of failures, that is, the structuring of the main failures of structural elements from reinforced concrete and the need to improve / strengthen their qualities.

4 Results

Mathematical modelling is the basis of the modern system of experimental research to a greater extent. Its essence is the mechanism of changing the initial object of research into a mathematical model.

In view of the rapid pace of innovative developments in the field of construction and modern technological features of the formation of material complexes to obtain highly effective structural elements of reinforced concrete, it is proposed to reinforce it with spherical graphite fiber, which will increase the ductility during tension and form improved impact toughness during compression (Fig. 1).

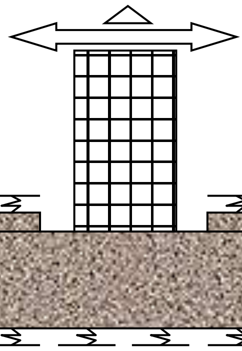

Fig. 1: Continuum spring hinge model, plane stress state of elements (author’s development based on, [19])

The model of uniform distribution of spherical graphite fiber in the ductile matrix (Fig. 2) is able to prevent the reduction of structural strength, cycle degradation, and clamping. However, it is worth emphasizing that the model is not capable of clearly predicting failure modes and initial rigidity.

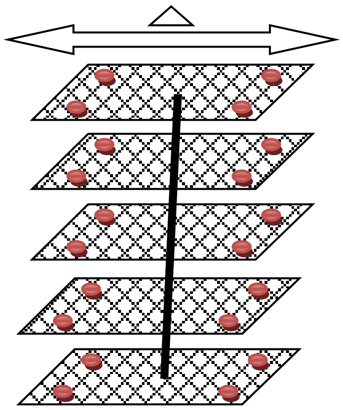

Fig. 2: A model of uniform distribution of spherical graphite fibers in a plastic matrix

The concentrated plasticity model based on spherical graphite fibers (Fig. 3) allows for obtaining the indicators of the cyclic behaviour of structural elements. The length of the plate hinge (L_p) enabled predicting the possibility of displacement at the very beginning of the reinforcement destruction. The given model takes into account the cyclical degradation of strength and rigidity of the structure due to changes in the hysteresis parameters of the steel material model.

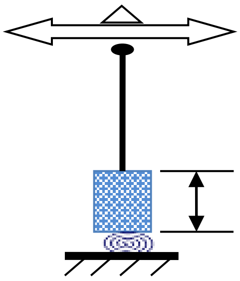

Fig. 3: The concentrated plasticity model based on spherical graphite fibers

The building of spring hinge models is focused on concentrated plasticity, their use is aimed at the study of inelastic behaviour in some areas of the hinge due to their computational efficiency and extreme interpretation simplicity, [20].

The use of calculation models with numerical stability is effective in the advanced nonlinear analysis of reinforced concrete structural elements and seismic design of structures. Spring hinge models are based on direct structural variables that include rotations and moments, with due regard to the method of capturing the cyclic response of the structural components of the overall structure.

A beam-column was chosen as a reinforced concrete structure, which is based on a zero-length pivot spring hinge at the end of each individual element. The given pivot spring hinge is a uniaxial material model with the moment M - rotation θ dependence, where the moment M is the force applied to the rod, and the rotation θ represents the deformation, which is calculated as the displacement of the top, Δ, divided by the length of the shear span L_s.

The spring performs bending movements (Fig. 4 shows the trajectory of movements with a blue line) under the influence of a monotonous load, forming a cyclic curve in which the elements lose strength, rigidity, and deformation capacity within the non-elastic area; the threshold values of moments and rotation are shown by a red dashed line.

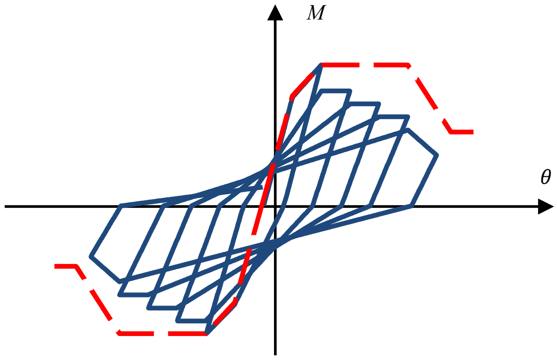

Fig. 4: Spring hinge nonlinear model

Fig. 5 illustrates the mathematical model of a spring hinge for simulating reinforced concrete structural elements.

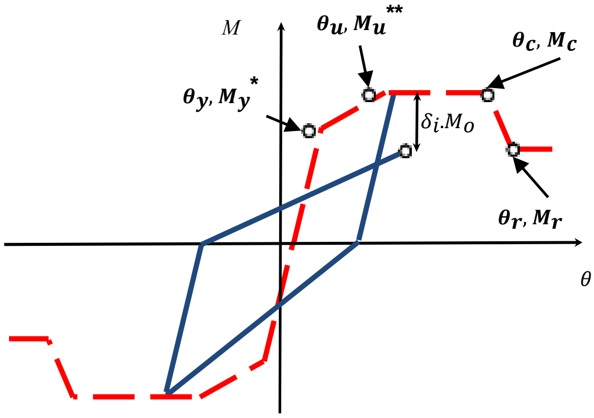

Fig. 5: The mathematical model of a spring hinge for simulating reinforced concrete structural elements

Torque:

$$M_y = C_c\left(d - {}^{c}/_{3}\right) + C_s(d - d') - T_{c1}\left(d - c - {}^{2e}/_{3}\right) - T_{c2}\left(h - c - {}^{e}/_{2} - d'\right)$$

where C_c, C_s – internal compressive forces;

c – neutral axis;

T_{c1}, T_{c2} – tensile forces along the depth of the cross-section

The value of the threshold moment at which the reinforcement has maximum hardness:

$$M_u = C_c\left(d - {}^{0,85c}/_{2}\right) + C_s(d - d') - T_{c1}\left(d - c - {}^{2e}/_{3}\right) - T_{c2}\left(d - c - e - {}^{d'}/_{2}\right)$$

Threshold angle of rotation

$$\theta_y = {}^{1}/_{2}\,\phi_y/L_s$$

ϕ_y – rotation curvature;

L_s – span length.

Rotation curvature

$$\phi_y = \frac{M_y}{\alpha E_c I_g}$$

The stiffness reduction coefficient:

$$\alpha = {k_{exp} L_s}/{2 E_c I_g}$$

where k_{exp} – experimental stiffness,

The damage index is found as a function of the deformation and energy damage indices:

$$\delta_i = \delta_{de\,f} + \delta_{energy} = f_1 \left(\frac{d_{max,i}}{d_f} \right)^{f_3} + f_2 \left(\frac{\sum E_i}{E_{mon.main} \cdot gE} \right)^{f_4}$$

where $d_{max,i}$ – maximum deformation within the ith load cycle;

d_f – final deformation;

E_i – total energy absorbing capacity at the ith load cycle

$E_{mon.main}$ – to the threshold of the residual level, the power of energy dissipation on the monotonic main curve;

gE – coefficient of the energy level when loading with cycles;

$f_1 \div f_4$ – degradation rate.

Strength reduction Level:

$$M_i = M_0(1 - \delta_i)$$

where M_0 – reference strength.

Fig. 6 shows the moment of beam rotation and the curve built on the basis of the analysis. Most of the data were obtained from literature as a representation of outlined data about power drift, [7], [16], [19], [21], the minority was the results of manual digitization of charts presented in modern scientific literature.

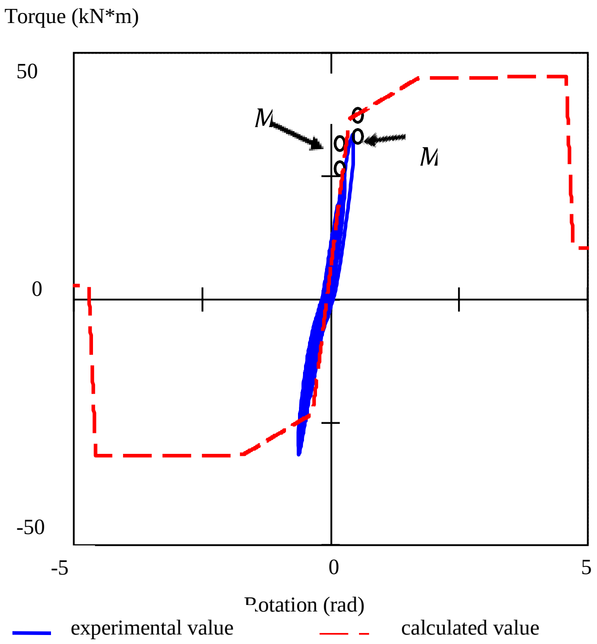

Fig. 6: Comparison chart of reference and cyclic strength of a reinforced concrete beam with spherical graphite

The obtained calculation model converges to reference data and does not reflect a significant error with the increased number of cycles. However, the model with a calibrated value of $f_2 = 0.31$ degrades, while the numerical strength and hysteresis behaviour match the experimental data at higher deformation levels, which indicates the increased deformation resistance of fittings with spherical graphite before the occurrence of complete destruction under conditions of seismic impact.

5 Conclusions

The work describes the reinforced concrete structural elements in terms of their properties and specifications. The model of concentrated plasticity based on spherical graphite fibers was built for the range of indicators of the cyclic behaviour of structural elements. The mathematical model of a spring hinge to simulate reinforced concrete structural elements were developed. So, the research results showcase that the structural elements of spherical graphite reinforced concrete have the maximum increased seismic performance in terms of transverse strength, plasticity, the ability to dissipate energy, and cracking response. In comparison with reinforced concrete structures without spherical graphite, structural elements built in line with the latest technology show increased deformation resistance of spherical graphite reinforcement to complete destruction under seismic impacts.

Prospects for further research include the development of an empirical system of equations depending on the section geometry and the properties of the construction material based on prognostic variables from the list of potential variable characteristic data.

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The authors have no conflicts of interest to declare that are relevant to the content of this article.