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METHODS FOR CALCULATING THE CONCRETE CORE OF LOOPED REINFORCEMENT JOINTS WITHOUT REINFORCEMENT

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Abstract.

The article presents a comparative analysis of four methods for calculating the concrete core of looped reinforcement joints without additional reinforcement, including the NIIES Hydroproject method based on Mohr's strength theory, the strut-and-tie model proposed by Singaporean researchers, the BS EN 1992 (Eurocode 2) methodology, and a modified method developed by the authors. The study primarily focuses on analytical techniques to assess the load-bearing capacity of loop joints under various operational conditions, highlighting the distinct characteristics of each approach. The NIIES Hydroproject method, while structurally comprehensive, places a strong emphasis on the strength of the concrete core, which can influence design safety. In contrast, the Singaporean strut-and-tie model provides an alternative analytical perspective but may not always align with practical applications. The BS EN 1992 approach integrates contemporary structural principles and offers a balanced assessment of loop joints, though it necessitates additional reinforcement considerations. The authors' modified method enhances existing analytical frameworks by incorporating stress adjustments, aligning well with experimental observations while maintaining computational efficiency. A comparative assessment of the four methods is conducted using experimental data for a monolithic beam with loop joints, confirming that the BS EN 1992 methodology and the proposed modified method provide the most reliable results for structural design. The study highlights the importance of accurate and efficient calculation models in ensuring the structural integrity of loop joints in reinforced concrete construction.

Keywords: loop joints, reinforced concrete, stress-strain state, numerical modeling, reinforcement, structural mechanics, finite element method, strut-and-tie model, contact interaction, construction materials.

I. Introduction

The utilization of loop joints in reinforced concrete structures allows for significantly simplifying the installation process and increasing the reliability of connections, which makes them a promising solution for modern construction. With the increasing complexity of designing buildings and structures, especially in seismically active areas and industrial facilities, ensuring the safety of structural connections becomes a priority task. Reinforcement loop joints provide unique advantages over classical connection methods such as welding and coupling joints [I]. They make it possible to achieve high load-bearing capacity with minimal installation costs, which is especially important in the construction of large objects. An important feature of modern requirements for loop connections is the absence of additional reinforcement of the concrete core, which allows for a significant increase in the productivity of the installation of volumetric reinforcement frames.

There are various methods for calculating the bearing capacity of structures with loop joints, each of which has its own features and areas of application. To date, special attention is paid to the development of analytical and numerical methods that allow for to reliable assessment of the strength of hinge joints under static loads. However, there are still unresolved issues concerning the choice of a rational calculation methodology depending on specific operating conditions.

This paper is devoted to a comparative analysis of different approaches to the calculation of loop joints, including analytical methods and numerical models based on strut and tie models and the finite element method.

II. Overview of the main methods of calculation of structures with loop joints

To accurately calculate the hinge joints of reinforcement in monolithic reinforced concrete structures, several techniques are used, each with its own features and limitations, but in general, they are divided into analytical and numerical methods.

Analytical methods are one of the most common and are based on the determination of forces in the reinforcement and concrete core of the joint, taking into account the geometry of the loop and the characteristics of the materials. The main approaches include estimation of stresses in concrete and reinforcement using equilibrium equations [I-IV]. In particular, important attention is paid to local stresses from crushing of concrete in the loop zone and tensile forces occurring in the reinforcement during load transfer.

Analytical models make it possible to take into account the influence of the bending radius of the loop and the value of radial pressure on the concrete core, which is the key to preventing failure from buckling and loss of adhesion. The main advantage of analytical methods is the relative simplicity of mathematical expressions and the speed of calculation of typical structural elements, while the disadvantage of analytical methods is their limited accuracy under cyclic and dynamic effects.

Numerical methods, along with analytical methods, are actively used to analyze joints with complex stress-strain states, including loop joints. The use of software such as Sumulia Abaqus allows the nonlinear material properties as well as the interaction between reinforcement and concrete to be considered [XIV-VIII]. In this approach, the assembly is modeled in great detail to identify critical fracture zones.

Numerical methods provide high accuracy of results, but require significant computational resources and time, both for model setup and for performing calculations. Nevertheless, their application is justified in the design of high-risk buildings, where the requirements for reliability are particularly high.

This paper will focus on analytical techniques that offer engineering methods for calculating structures with loop joints.

Description of the investigated methods

Analytical methodology based on the works of NIIES Hydroproject [XI-V] proposes to consider several failure mechanisms, the main one being the shearing of the concrete core along the inclined sections connecting the counter-loops. This analytical model is based on Moore's theory of strength, which forms the basis of the calculation methodology. The general scheme is shown in Figure 1.

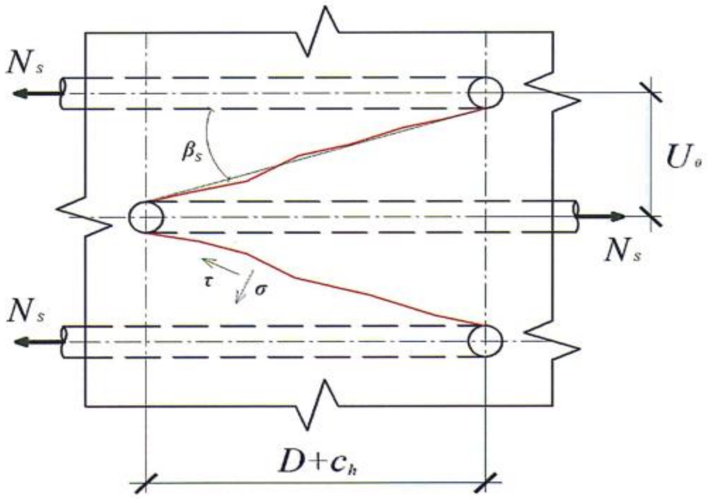

Fig. 1. Force diagram and cracking pattern for shear failure along inclined sections.

Calculation of loop joints at shear on inclined sections is made from the condition:

$$N_{cl} > N_s \tag{1}$$

$$N_{cl} = \gamma_l \cdot S_s \cdot k_c \cdot ([\tau] \cdot cos\beta_s + [\sigma] \cdot \sin\beta_s), \tag{2}$$

Where:

β_s – shear angle (see Fig. 1), determined by the formula:

$$\beta_s = arctg\,\frac{U_0 - d}{D + c_h}; \tag{3}$$

S_s – area of the inclined section, determined by the formula:

$$S_s = \frac{S_{cl}}{cos\,\beta_s}; \tag{4}$$

[σ] – mean normal stresses in the inclined section:

$$[\sigma] = \frac{1.35R_{bt}}{1-k_R+2\cdot\sqrt{k_R}\cdot ctg\beta}, \tag{5}$$

Where:

$$k_R = \frac{R_{bt}}{R_b} \tag{6}$$

$[\tau]$ – mean tangential stresses in the inclined section:

$$[\tau] = [\sigma]\cdot ctg\beta \tag{7}$$

Researchers from Singapore have proposed a strut-and-tie model to calculate loop joints in central tension, which represents the joint as compressed and tensile strips [III, XIII].

The assumed operation scheme of the node is shown in Figure 2.

The ultimate tensile force absorbed by the loop joint is proposed to be determined by the equation:

$$P_u = \frac{0.6f_{cu}l_0^3h}{(s/2)^2+l_0^2}, \tag{8}$$

Where s - distance between the loops, h - height of the structure, l_0 - overlap length of the counter loops, f_{cu} - cubic strength of concrete.

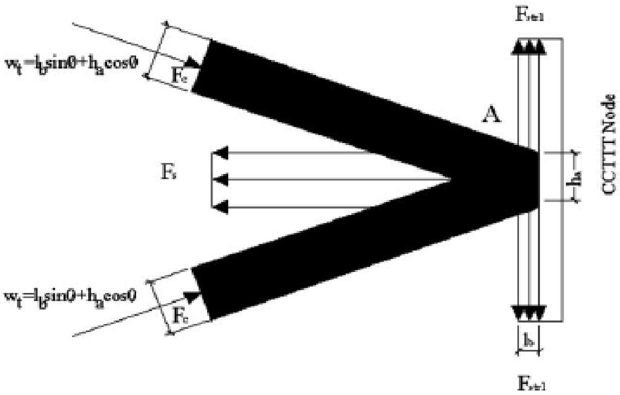

Fig. 2. Force distribution in the loop joint zone

Based on the equation of equilibrium, the ultimate tensile force at the node can be represented as the normal component F_s of the strut force F_c, which follows:

$$P_u = 2F_c\cdot cos\,\theta, \tag{9}$$

Where the cosine of the angle is determined by the formula:

$$cos\,\theta = \frac{l_0}{\sqrt{l_0^2+s_0^2}} \tag{10}$$

Then, the problem is summarized by determining the compressive strength of the strut, which is expressed by the dependence:

$$F_c = A_{cn} \cdot f_{cn} \tag{11}$$

where Acn -cross-sectional area of the strut; f_{cn} - effective compressive stress across the strut surface;

The cross-sectional area is defined as:

$$A_{cn} = h \cdot w_t \tag{12}$$

Where h - construction depth; w_t - effective width of the inclined strut. And the effective compressive stress is proposed to be determined by the empirical dependence:

$$f_{cn} = 0.51 f_c \tag{13}$$

Where f_c - cylindrical compressive strength of concrete.

The effective width of the strut w_t is determined by:

$$w_t = \frac{P_u}{2h(0.51 f_c)\cos\theta} \tag{14}$$

The strut-and-tie model was developed in the updated edition of the British Annex to Eurocode 2 [II]. The model assumes the calculation of a loop joint both with and without straight inserts when tensile forces act on the joint. The general scheme of the model is presented in Figure 3.

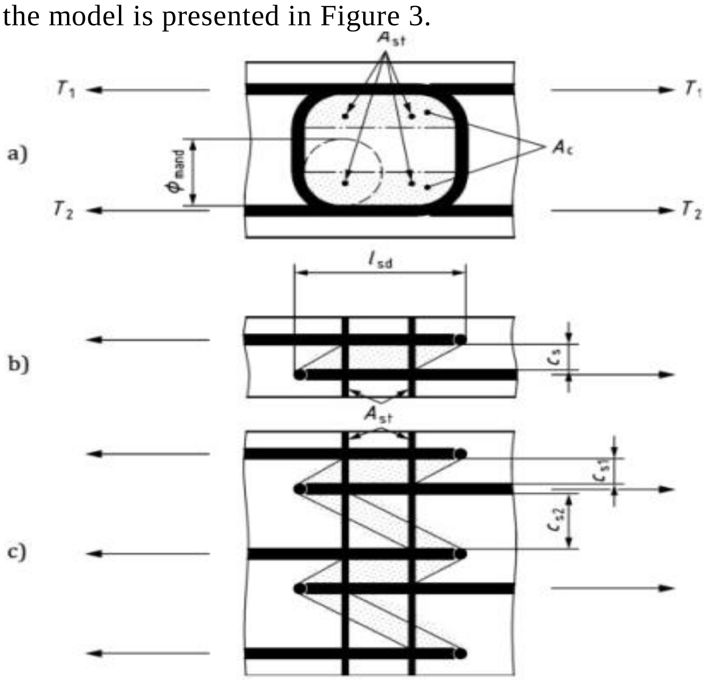

Fig. 3. Calculation model of a loop joint according to Eurocode [III].

It is proposed to take as the main design criterion the strength of concrete between the counter-direction loops, which is proposed to be determined by the formula:

$$T_{Rd,c} = 0.2 f_{cd} \cdot A_c \cdot \left(\frac{d_{dg}}{l_{sd}}\right)^{\frac{1}{3}} \cdot \left(\sqrt{k_{st} + \left(\frac{c_s}{l_{sd}}\right)^2} - \frac{c_s}{l_{sd}}\right). \qquad (15)$$

An important distinctive feature of the methodology is the need to take into account the reinforcement of the core, the minimum area of which is determined by the formula:

$$A_{st} \geq 0.5\sqrt{f_{ck}} \cdot \frac{A_c}{f_{yk}}. \qquad (16)$$

Additional tensile stresses or “secondary shear forces” are generated when the loop joint is subjected to tensile forces in one or both branches of the reinforcement loop [V], perpendicular to the joint, which are absorbed by the concrete tensile strength. The result of the secondary shear forces exceeding the concrete tensile strength is the tensile strength observed in the experiments [II, XI], and spalling of the protective cover of concrete at the side edges.

The tensile part of the loop generates concentrated radial pressure as shown in Figure 4, with the resulting compressive stress fields of the joint balancing each other in the case of symmetrical forces on both sides of the joint, or the unbalanced edge section resulting in concrete spalling from the side face.

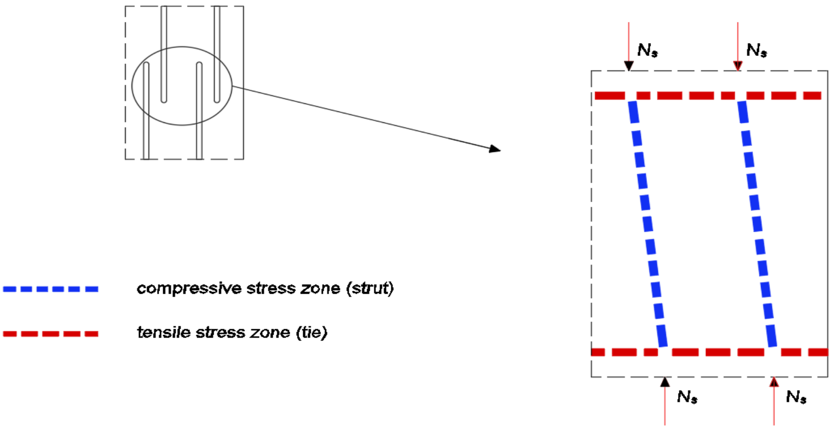

Fig. 4. Pressure equilibrium of two pairs of loop joints.

Secondary shear forces are less of a problem in the interior of the structure, where they are balanced by adjacent pairs of loops.

Hence, failure between the loops of an edge pair of loops can lead to spalling of the side protection layer. This occurs if the tensile crack between the loops extends beyond the splice zone to the edge of the structure or is joined by a normal crack parallel to the splice zone (Figure 5). As a result, the anchorage of the outer loops is significantly reduced.

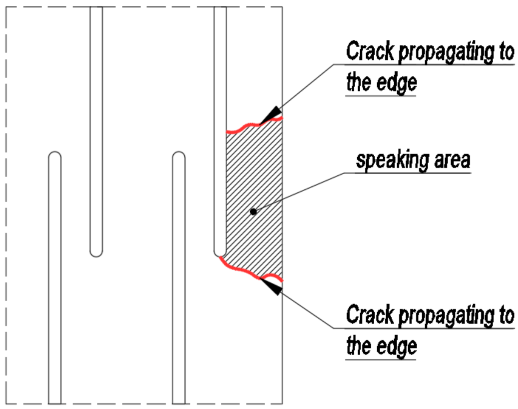

Fig. 5. Failure scheme of the edge section of the structure with a loop joint

Hence, the loop joint extreme to the free edge of the structure is partially switched off from operation, and the load is transferred to the adjacent sections of the loop joint, and, as numerical experiments have shown, the influence of this effect is reduced when the number of joints is large.

The version of the strut-and-tie model of resistance of loop joints proposed by the authors of this paper is convenient for describing the interaction of the counter-directional loops shown in Figure 4, resulting in the forces shown in Figure 6, which can be described by equilibrium equations.

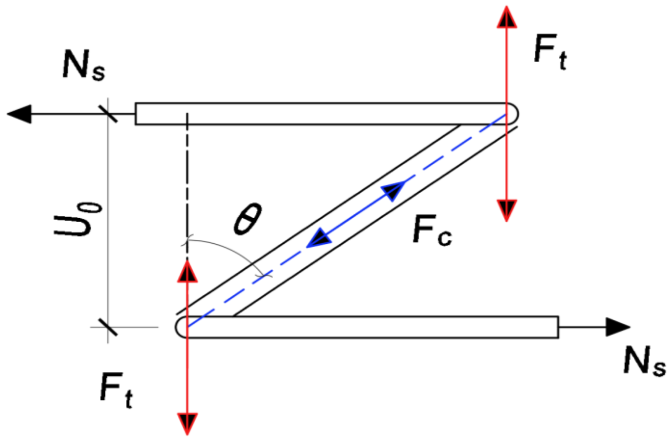

Fig. 6. Strut-and-tie model of a loop joint

The proposed model describes the mechanism for transferring the force N_s from one reinforcing bar through the concrete of the joint core to the other bar.

The tension in the reinforcing bars causes the formation of a compressed section of concrete through which the force is transmitted to the reinforcing bar in the opposite direction. As can be seen from Fig. 6, this section is located under some angle θ, which theoretically can vary from close to 0 degrees up to 90 degrees, and any non-zero value of the angle will result in tensile forces, which are equal to N_s

at θ=90 degrees and tend to zero at θ→0. Hence, the equations for determining the compressive forces Fc and tensile forces Ft are as follows:

$$F_t = N_s \cdot ctg\theta \tag{17}$$

$$F_c = N_S \cdot cos\,\theta \tag{18}$$

These analytical dependencies have a good correlation with the results of experimental studies [II], in which, with increasing the distance between the loops, the load-bearing capacity of the connection decreased.

For the compressed strut, it is proposed to apply the reduction factors of compressive strength depending on the stress state [III]. Hence, the ultimate resistance of concrete of the compressed strip is proposed to be defined as:

$$R_{st} = k_c \cdot R_{cube}, \tag{19}$$

где:

R_{cube} – cubic compressive strength of concrete;

k_c – reducing the angle coefficient θ.

For the case of a loop joint, due to the peculiarities of its stress-strain state and the availability of experimental data, it is proposed to determine the reduction factor through a logarithmic regression function:

$$k_c = 0.3608 \cdot ln(\theta) - 0.6168 \tag{20}$$

Hence, the ultimate force in the compressed strut F_{st} :

$$F_{st} = k_c \cdot A_{st} \cdot R_{st} \tag{21}$$

Where A_{st} is the cross-sectional area of the compressed strip, defined as the product of the effective width w_{st} by the effective depth h_{st}.

For a loop joint, it is proposed to simplistically define w_{st} as d_s and h_{st} as S=(D+C)·cosθ.

$$A_{st} = k_s \cdot S \cdot d_s \tag{22}$$

Where:

k_s – empirical coefficient that considers the non-uniformity of stresses at the core of the joint and is taken as 0.75 in bending and 1.4 in tension.

In further calculations, it is proposed to define the equal strength coefficient of the loop joint as:

$$k_r = \frac{F_{st}}{F_c} \tag{23}$$

If the value of k_r is greater than or equal to one ($k_r \geq 1$), the joint is considered equal to the mating working reinforcement, and the bearing capacity of the element is proposed to be determined according to the generally accepted formulas for reinforced concrete elements at the full value of the design resistance of the working reinforcement.

If the value of k_r is less than one ($k_r < 1$), the joint is considered to be unequal strength, and the kr coefficient should be multiplied by the load-bearing capacity determined by the generally accepted formulas for reinforced concrete elements.

The proposed analytical method has demonstrated high accuracy in predicting the bearing capacity of looped joints under central tension. However, its applicability is currently limited to specific structural and loading conditions. The following considerations define the domain of applicability:

- Loading Conditions: The method is formulated for centrally applied static tensile loads. It does not account for eccentric loading, which may induce bending moments in the joint zone. For eccentrically loaded joints, additional stress components should be considered, and the method may underestimate internal forces.
- Cyclic Loading: The proposed model assumes monotonic loading and does not incorporate degradation mechanisms associated with fatigue or seismic conditions. Therefore, its direct application to joints subjected to cyclic or dynamic actions is not recommended without further calibration.
- Loop Configuration: The method is validated for symmetrical loop configurations in a single reinforcement layer. For cases with asymmetrical loops, multiple loop layers, or 3D joint geometries, the current formulation may not fully capture the stress distribution and requires further development.

These limitations should be considered when applying the method in structural design, and further research is required to extend its validity to more complex boundary conditions.

To address scale invariance and facilitate design across different geometries, the proposed method can be reformulated using non-dimensional parameters. The primary geometric and material parameters can be expressed as:

$$\overline{d_s} = \frac{d_s}{D} \tag{24}$$

$$\bar{C} = \frac{C}{D} \tag{25}$$

$$\bar{s} = \frac{s}{h} \tag{26}$$

Where:

$\overline{d_s}$ – ratio of loop diameter to concrete core width, $\bar{C}$ – cover thickness ratio, $\bar{s}$ – relative loop spacing.

The bearing capacity of the diagonal strut becomes:

$$F_{st} = k_c \cdot k_s \cdot D^2 \cdot (1 + \bar{C}) \cdot d_s \cdot \cos\theta \cdot R_{cube} \tag{27}$$

The proposed method is well-suited for integration into practical design environments, such as spreadsheets or design modules. Due to its explicit analytical form and small number of input parameters, the model can be implemented using standard engineering tools (e.g., Excel, Mathcad, or Python-based scripts).

The following inputs are required:

- Geometric dimensions: rebar diameter ds, core width D, concrete cover C, and loop inclination angle θ (eq. 27);
- Material property: concrete compressive strength Rcube;

- Design type flag (tension vs. bending) to assign empirical factor k_s ; Based on these inputs, the designer calculates the bearing capacity of the core strut using Equation 27.

This allows for quick evaluation of joint capacity, preliminary sizing of loop reinforcement, or checking of existing designs. The method is especially suitable for incorporation into internal design standards or parametric design tools used in structural engineering practice.

III. Comparative analysis of calculation results

All four methods can be interpreted within a common physical framework based on the equilibrium of internal forces within the joint core. Generally speaking, the bearing capacity is determined by the interaction between the loop anchorage force and the compressive stress field in the concrete core.

Both the proposed method and Eurocode 2 adopt an equilibrium-based approach, explicitly considering the strut action within the core. Ong and Hao introduce an empirical, friction-based mechanism, whereas the NIIES Hydroproject method combines core compression and friction but lacks an explicit force balance.

Despite their differences, all methods aim to estimate the maximum force that can be transferred across the joint via direct compression, confinement, or anchorage mechanisms. This shared structure enables meaningful comparisons and benchmarks to be made, as shown below.

Analytical methods of calculation of structures with loop joints provide engineers with an opportunity to take into account important parameters affecting the reliability of joints. Let us compare the four methods presented in this article.

The methodology of NIIES Hydroproject, based on the Mohr strength theory, provides for the determination of the bearing capacity of the joint through the concrete strength conditions for inclined sections. The main attention is paid to the calculation of stresses arising in the concrete core.

The methodology of Ong and Hao is based on the estimation of forces transmitted through the concrete core. The calculated values were significantly higher than the experimental values (by 31%), indicating an overestimation of the bearing capacity. However, the methodology is suitable for preliminary calculations and optimization of structures.

The BS EN 1992 methodology is based on modern approaches to the design of reinforced concrete structures, including consideration of loop geometry and material interaction. The calculation results are close to the experimental values (less than 2% deviation), which makes this methodology preferable for the calculation of tensile structures. Among the disadvantages of this methodology, we note the high complexity of calculations and the need to take into account the reinforcement of the concrete core.

The method proposed by the authors is characterized by the use of modified design coefficients that take into account the nonlinear stress state of concrete. The calculated values are close to the experimental values (deviation of about 2%). The methodology demonstrates high accuracy in the design of structures.

To compare these methods, consider a monolithic beam with a loop joint 160 mm high, 460 mm wide, with a loop spacing of 50 mm under the action of central tension. The prism strength of concrete is equal to 36.2 MPa, and the strength of reinforcement is 580 MPa. According to the results of the full-scale experiment [II], the ultimate tensile force was 257 kN.

Table 1: Comparison results

Calculation method	Bearing capacity, kN	
	experiment	calculation
Methodology of NIIES Hydroproject	257	335
Methodology Ong, Hao (Singapore)	257	336
Methodology BS EN 1992 (Eurocode)	257	261
Proposed methodology	257	252

Table 2 summarizes the underlying assumptions and analytical structures of the four analyzed methods. Although the methods differ in their design logic and physical mechanisms, they can be mapped onto a shared structural framework, facilitating direct comparison and implementation.

Table 2: Comparison of Loop Joint Calculation Method

Criterion	Proposed Method	Eurocode 2	Ong & Hao	NIIES Hydroproject
Physical basis	Force equilibrium via a diagonal concrete strut in the joint core	Strut-and-tie model with confinement reinforcement	Friction mechanism with empirical calibration	Empirical combination of core compression and friction
Core reinforcement required	Not required	Required (transverse reinforcement assumed)	Not considered	Not considered
Geometric sensitivity	Yes – loop spacing, concrete, and rebar strength	No – depends mainly on concrete strength	Partial – based on loop spacing and concrete strength	Partial – based on loop spacing and concrete strength

Load transfer mechanism	Diagonal compression in concrete core	Compression and anchorage	Friction along contact surfaces	Core compression and friction, empirically combined
Practical implementation	Easy – closed-form formula suitable for Excel or software modules	Possible, but limited to code-compliant detailing	Difficult – uses empirical tables and coefficients	Spreadsheet-based, but lacks parametric flexibility

IV. Discussion

For comparative analysis, various methods of calculating the bearing capacity of a monolithic beam with a loop joint under central tensile action were considered. The experimentally determined value of the ultimate tensile force, which amounted to 257 kN, was taken as the reference solution. The obtained calculated results showed the following:

– The value of ultimate tensile force determined by the method of NIIES Hydroproject was 335 kN, which is 23% higher than the experimental value. The methodology was based on the results of tests of beams with loop joints in bending and in tension gives some overestimation of strength.

– Calculations according to the method of Ong, Hao (Singapore) also showed an overestimated result - 336 kN, which is 31% higher than the experimental value. This result may lead to the risk of calculated overestimation of the actual load-bearing capacity of the structure, which is inadmissible in design.

– The calculation using BS EN 1992 (Eurocode 2) yielded a result of 261 kN, which is closest to the experimental value with a deviation of less than 2%. This indicates a higher accuracy and applicability of the methodology for the design of structures operating in central tensile conditions.

– The result of calculations according to the method proposed by the authors was 252 kN also showed high accuracy with the calculated value of 252 kN, which is close to the experiment (257 kN). This indicates the high reliability of the methodology for joint calculations, especially for preliminary calculations and optimization of structures.

A sensitivity analysis was carried out to evaluate the robustness and parameter dependence of the four calculation methods. This involved performing a parametric sweep of three critical variables:
This generated 27 combinations, labelled as samples 'abc', where each letter indicates the level of one parameter.

- **a** = index of loop spacing $u \in \{30,50,70\}$ mm
- **b** = index of concrete strength $Rb \in \{25,35,45\}$ MPa
- **c** = index of reinforcement strength $Rs \in \{400,500,600\}$ MPa

Table 3 summarises the resulting bearing capacities.

Table 3: Sensitive analysis comparison

№	Proposed methodology	Methodology BS EN 1992 (Eurocode)	Methodology Ong, Hao (Singapore)	Methodology of NIIES Hydroproject	ultimate tensile strength of rebar
	Bearing capacity, kN				
111	189	238	353	344	189
112	192	238	353	334	237
113	192	238	353	334	284
121	189	332	493	449	189
122	237	332	493	449	237
123	253	332	493	449	284
131	189	426	632	547	189
132	237	426	632	547	237
133	284	426	632	547	284
211	182	238	308	305	189
212	182	238	308	305	237
213	182	238	308	305	284
221	189	332	430	395	189
222	237	332	430	395	237
223	240	332	430	395	284
231	189	426	551	478	189
232	237	426	551	478	237
233	284	426	551	478	284
311	173	238	258	286	189
312	173	238	258	286	237
313	173	238	258	286	284
321	189	332	360	367	189
322	228	332	360	367	237
323	228	332	360	367	284
331	189	426	462	443	189
332	237	426	462	443	237
333	269	426	462	443	284

The results show that:

The proposed method demonstrates clear and consistent sensitivity to all three parameters. Higher calculated capacity is achieved through increased concrete and reinforcement strength, as well as reduced loop spacing. This reflects the method's ability to capture actual stress redistribution within the joint core.

In contrast, the Eurocode 2 method depends only on concrete strength. It is invariant to changes in loop spacing and reinforcement grade. This is consistent with the original Eurocode formulation, which assumes sufficient core reinforcement — a condition that is not met in the current context. Therefore, its applicability to joints without additional core reinforcement may be limited.

The Ong & Hao and NIIES Hydroproject methods produce significantly overestimated values, particularly at high material strengths. They are sensitive to changes in parameters, but this may not correlate well with actual physical behaviour, potentially leading to unconservative results.

Overall, these findings suggest that the proposed method not only agrees well with experimental data but also realistically adapts to a wide range of structural configurations. This makes it preferable for the practical design of looped joints without internal core reinforcement.

These conclusions are further supported by the results of the parameter sweep presented above.

Hence, the most accurate results were shown by calculations according to BS EN 1992 and the model proposed by the authors, which makes them preferable for the design of joints operating in central tension. At the same time, the methods of NIIES Hydroproject and Ong, Hao overestimate the bearing capacity, which may lead to insufficient reliability of structures in practice.

Conflict of Interest:

There was no relevant conflict of interest regarding this article.

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