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The analysis of the reinforced column head with S-T method in order to identify the cracking reasons

Analiza głowicy słupa żelbetowego metodą S-T w celu ustalenia przyczyn zarysowania

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Abstract. In the paper the case of cracking of the precast reinforced concrete column's head was described. The head is the support for a roof steel truss of a production hall on the first side and a roof reinforced concrete beam on the second side. The steel truss is supported on the detailed shelf whereas the beams is supported on the rectangular corbel. Because of the head's cracking (the width of more than 0,5 mm) the reasons' analysis was carried out. It was stated that the reinforcement was calculated and detailed wrongly. On the basis of S-T method the correct way of the element's reinforcing was proposed.
Keywords: S-T method; column; corbel; reinforcement; reinforced concrete.

Streszczenie. W artykule opisano przypadek zarysowania głowicy prefabrykowanego słupa żelbetowego. Głowica stanowi podparcie kratownicy stalowej stropodachu hali produkcyjnej z jednej strony i belki żelbetowej stropodachu z drugiej. Kratownica stalowa opiera się na wykształtowanej półce, natomiast belka żelbetowa na prostokątnym wsporniku. Ze względu na zarysowanie głowicy (o szerokości przekraczającej 0,5 mm) przeprowadzono analizę jego przyczyn. Stwierdzono, że błędnie obliczono i ukształtowano zbrojenie. Na podstawie metody S-T zaproponowano poprawny sposób zbrojenia elementu.
Słowa kluczowe: metoda S-T; słup; wspornik; zbrojenie, żelbet.

Corbels of reinforced concrete columns are critical elements of the structures. Their failure may have significant consequences. Researchers have been paying a lot of attention to these elements for many years (i.a. [1]). The experimental research and numerical studies are aimed at enabling safe and economical detailing, designing and reinforcing of the corbels. The computational approach to designing corbels in Poland has evolved over the years, which is reflected in the standards. In the analysed case, the reinforcement of the corbel differs from that currently used. Among other things, due to diagonal reinforcement, which is not required by current guidelines. An area of a reinforced concrete column that also requires a special approach at the design stage is an irregularity in the height of the cross-section, which is also the place where another structural element is supported. The following part of the article describes the problem that occurred as a result of improper design of the column head reinforcement with an irregularity of the height of the cross-section on the one side and a rectangular corbel on the other.

Description of the problem

The head that is the subject of this article is formed in a precast reinforced concrete column. This column is an internal (interaisle) column and, on the one side, supports the flat roof of the production hall (level +6,60), and on the other side, the intermediate floor (level +3,09) and the flat roof of the office part (level +6,72). The flat roof of the production hall has a lightweight structure (sandwich panels on steel trusses). The loads are transferred from the steel truss to the column shelf (undercut) at the point of an irregular stiffness. The reinforced concrete, slab-ribbed intermediate ceiling and the flat roof of the office part have a partially precast structure. Filigran slabs are arranged along the hall and supported by girders constituting a transverse load-bearing system. The girder is based on the column head corbel. Like the Filigran slabs, the girder is filled with a concrete topping cast in-situ. The forces transferred from the steel truss and reinforced concrete girder are 154 and 126 kN, respectively.

The column was designed in accordance with the Polish Standard for the design of concrete structures of 1999 [2], applicable at the time of the investment execution. Fig. 1 shows the way of detailing the geometry and reinforcement of the column head. The width of the column cross-section is constant and amounts to 400 mm. C20/25 concrete, St3SX plain steel with a characteristic yield strength of f_{yk} = 240 MPa (designation – ∅)

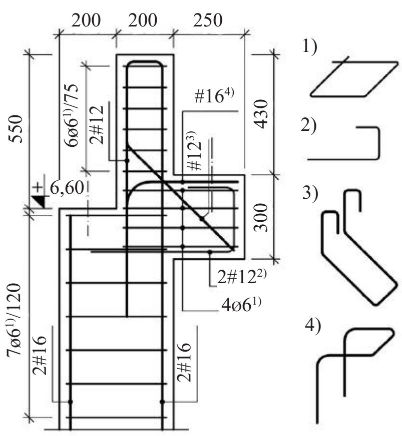

Fig. 1. The geometry and reinforcement of the column's head: 1) two-legged stirrup; 2) contour reinforcement; 3), 4) loop consisting of two rebars
Rys. 1. Geometria i zbrojenie głowicy słupa: 1) strzemię dwucięte; 2) zbrojenie konturowe; 3) i 4) pętla składająca się z dwóch gałęzi prętów

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and 18G2-b ribbed steel with f_{yk} = 355 MPa (designation – #) were used.

Already "macroscopic"analysis of the shapes of the reinforcing bars allows us to conclude that they were not detailed correctly. The following are evident:

- too large spacings of the horizontal reinforcement under the shelf (equal to the spacing of the column stirrups);
- lack of diagonal rebars at the corner of the shelf (where diagonal stress should be expected [3]);
- questionable suspension of the corbel with the diagonal loop #12 to the upper part of the low-stiffness column (cross-section dimensions h×b=200×400 mm).

These errors resulted in cracking of the column head at the corner of the shelf (maximum crack width – approx. 0.5 mm), as shown in the picture. It is not without significance that the stirrups (according to the trends of the time) made of plain steel. Such rebars have much worse crack-bridging capabilities.

The cracking on the left side of the column's head

Zarysowanie lewej strony głowicy słupa

Computational analyses

In order to precisely explain the causes of cracking the column head, in-depth analysis was performed. Even though the column head works in a cracked state, first, finite element method calculations were performed for a linear elastic material in a plane state of stress. This analysis provides a lot of valuable information about stress distribution and can be considered a starting point for further analysis. Fig. 2 presents the crosses of the directions of the principal compressive and tensile stress [4]. Fig. 2 clearly shows the tensile stress that acts in the horizontal direction in the area of a step change in stiffness (left side) and the corbel (right side).

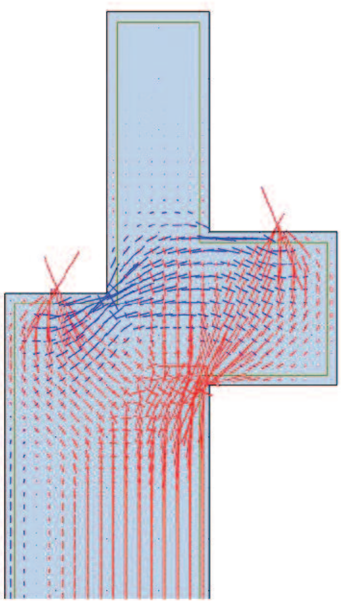

Fig. 2. The crosses of the principal stresses directions

Rys. 2. Krzyże kierunków głównych naprężeń

Moreover, the diagonal tensile stream is visible at the corner of the undercut on the left side. It should be noted, however, that there are no tensile stress in the direction of the diagonal loop used. It can therefore be concluded that it would be much more advantageous to use this reinforcement lower, on the other side. The compressive stress streams flow diagonally from the points of application of the forces to the column core.

In the analysed column, areas of type B and D should be distinguished. Areas B are those in which the application of the Euler-Bernoulli theory gives results that are satisfactory from an engineering point of view. In areas where we are dealing with any discontinuities, both in relation to loads (e.g. concentrated forces) and geometry (e.g. step change in stiffness, corbel), a special approach should be used. The head of the presented column can certainly be considered a D-type area. It is assumed that area D extends to a distance equal to the height of the column cross-section from the point of discontinuity.

For further calculations, in the post-cracking phase, the S-T *(strut-and-tie)* method was used for area D. This method involves virtually introducing into the considered element a truss consisting of S-type compression bars *(representing concrete)* and T-type tension bars (representing reinforcement). The basic type of compression bar (S-type) is a bar with straight and parallel edges. The method also allows for the introduction of straight bars into the model, but with non-parallel edges, so called bottle-shaped struts (see [5]). T-bars are reinforcement and the concrete surrounding them. However, this concrete has no effect on the load-bearing capacity, only on the deformation of the bar (and consequently also on cracking). The bars meet in nodes, the type of which must be previously declared. The method distinguishes the following basic types of nodes: CCC – a node in which no tension bar is anchored, CCT – a node in which compression bars and one tension bar (or two colinear tension bars) are connected, CTT – a node in which they are connected two tension bars and one compression bar. Depending on the type of joint, the appropriate concrete strength is calculated. In such a truss model, the S, T bars and nodes are analysed. The S-T method allows not only the calculation of D areas, but also of entire elements. The most common use of the S-T method in this area is observed in solving plates loaded in-plane (with openings as well). A more detailed description of the method with comments can be found, among others, in [3, 5, 6]. An example of the application to the designing of reinforced concrete nodes of cast in-situ frames was presented in [7].

Design using the S-T method is iterative, so it is convenient to use computer programs. The analysis was performed using the freeware CAST [8]. This program allows you to enter all calculation parameters yourself, thus ensuring a balance between operations performed automatically and those controlled by the user. As a consequence, the user has the opportunity to significantly interfere in the course of calculations and perform them based on any assumptions (e.g. according to [9] or [10]). This is important because computational approaches may differ. As an example, we can mention the classification of S-type bars based on the European [9] and American [10] standards. According to the European standard [9], a distinction is made between S bars that are not transversely tensioned or those that are. The American standard [10] distinguishes S-type bars: edge and internal, depending on the location of the bar in relation to the element's contour. Additionally, other features of S bars are also taken into account (e. g. whether the bar reaches the model support or is confined by transverse reinforcement). Based on the classification of the bar, its operating conditions are determined, and then its compressive strength.

On the basis of Fig. 2. the calculation model shown on Fig. 3 was proposed. Due to low explicit horizontal loads they were assumed as 20% of the vertical loads. The compressed bars were marked with dashed lines, whereas the tensioned bars with continuous lines. The tensile bars of the truss represent the main reinforcement of the corbel, diagonal loop and transverse stirrups. The S-T analysis was performed according to [10]. Due to the crack width limitation to 0,3 mm the yield strength of the reinforcing steel was assumed according to [2] correspondingly to the applied diameters (Table 1). On Fig. 4 the load effort of each bar is shown.

Based on the S-T analysis, a reinforcement arrangement for the considered head was proposed (Fig. 5a). Dashed reference lines mark the reinforcement, which does not result from static and

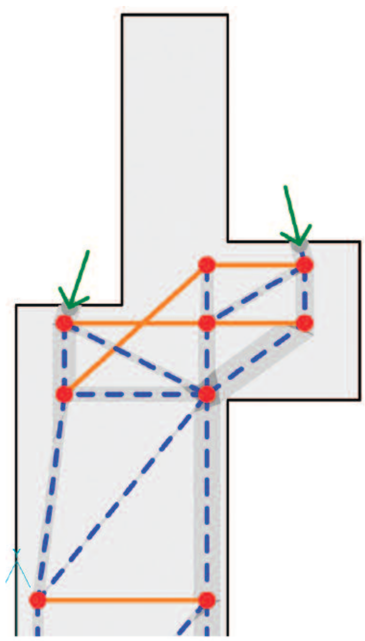

Fig. 3. The S-T method model
Rys. 3. Model metody S-T

Table 1. The properties of the column's head reinforcement
Tabela 1. Właściwości zbrojenia głowicy słupa

Reinforcement	Grade of steel	Bar diameter	Yield strength acc. to [2]
Main	18G2-b	#14	310
Diagonal	18G2-b	#16	285
Transverse (stirrups)	St3SX	ø12	210

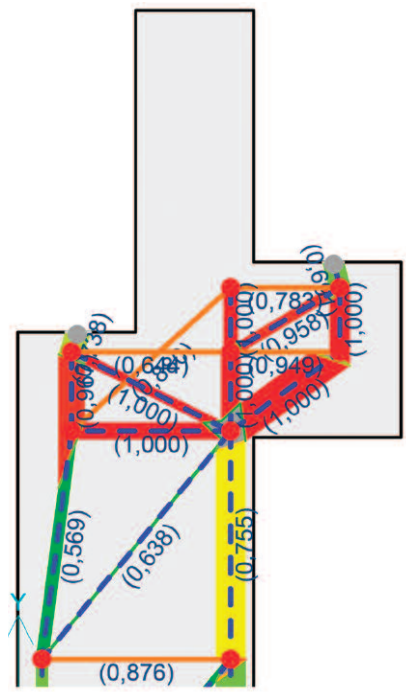

Fig. 4. The effort in the S-T model
Rys. 4. Wytężenie prętów w modelu metody S-T

strength calculations, but from detailing requirements. To highlight the differences, the reinforcement included in the project was shown again (Fig. 5b). Only bars important from the point of view of the purpose of this work are described. An important difference (as already mentioned in this article) is the lack of diagonal reinforcement at the corner of the undercut on the left side. In my own proposal, the diagonal bars of the corbel on the right side were omitted. Moreover, the stirrups in the proposed reinforcement method connect the left part of the column to the corbel. However, the project does not include such reinforcement.

It should be realized that in the years of implementation of the analysed project (around 2000), foreign articles, standards and computer programs were not yet widely available. Moreover, time pressure plays an important role in the civil engineering industry. As a result, designers do not have time to explore new design methods (and the S-T method was certainly considered such at that time). It was therefore possible to design the left side of the head as an area with a step change in stiffness (calculation algorithm shown in [3]) and the right side as a corbel according to [2]. For comparison, the reinforcement was also designed in accordance with these assumptions (Fig. 5c). However, the diagonal corbel rebar was abandoned, as it does not fulfil its role due to the low stiffness of the part of the column above the corbel. It can certainly be said that this reinforcement is qualitatively and quantitatively similar to that obtained using the S-T method. All three reinforcement proposals are presented in a table (Table 2).

The main reinforcement of the corbel in all three cases can be considered comparable. A higher value than for the S-T model of the entire head was obtained according to [2] (also according to the design). However, it should be noted that this bigger value was obtained after applying the condition for the minimum reinforcement percentage (0,4%). The reinforcement required with the strength formulae according to [2] was 3,01 cm^2, which is very close to the value obtained for the S-T bar model of the entire head. The design did not take into account diagonal stress at the corner and the reinforcement there was not detailed appropriately. Such reinforcement calculated using two methods (S-T and the one presented in [3]) is comparable. The horizontal reinforcement (stirrups) in the column was made incorrectly due to too large spacing under the undercut and discontinuities (separation of stirrups under the undercut and the corbel). Two of the own versions proposed similar total reinforcement in the form of stirrups. It should be noted, however, that in the case of the S-T method, the horizontal reinforcement below the undercut is clearly bigger. Above the undercut, only a stirrup is provided to fulfil detailing rules. This is due to the fact that the horizontal tension is assigned to the truss bar representing the main reinforcement of the corbel.

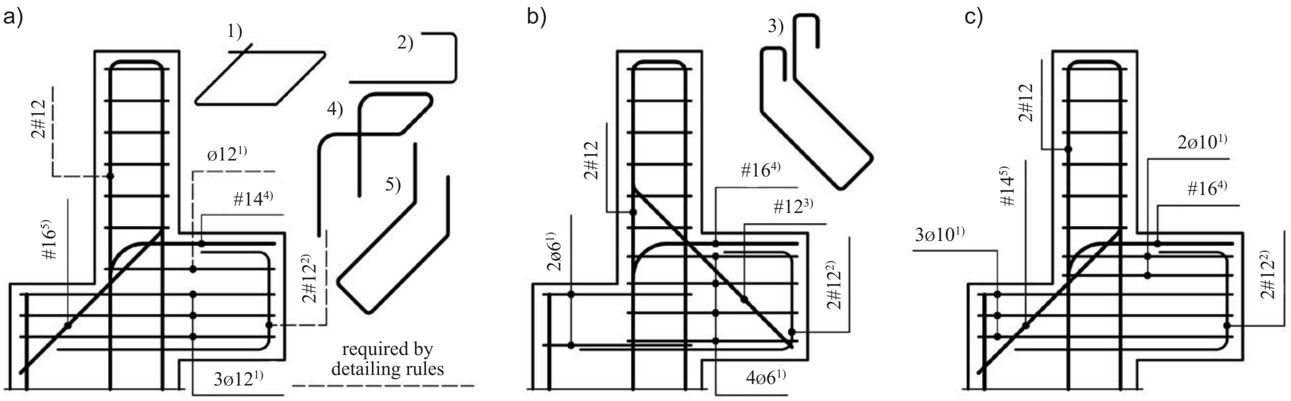

Fig. 5. The reinforcement of the column's head acc. to: a) S-T method; b) the design; c) [2] and [3]
Rys. 5. Zbrojenie głowicy słupa wg: a) metody S-T; b) projektu; c) [2] i [3]

Tab. 2. The list of the provided reinforcement areas for the considered cases [cm²]
Tabela 2. Zestawienie zastosowanych pól przekroju zbrojenia w rozpatrzonych przypadkach [cm²]

Reinforcement	Acc. to the S-T method	Acc. to the design	Acc. to [2] and [3]
Main	3,08	4,02	4,02
Diagonal	4,02	–	3,08
Transverse (stirrups) above the shelf	2,26	1,12	3,14
Transverse (stirrups) below the shelf	6,78	1,12	4,71

Summary

The situation necessitated the use of strengthening. Due to limited access to the column head and the constant „clean" production process in the hall, traditional strengthening methods had to be abandoned. Despite the fact that they are common, proven, willingly used by contractors and supported by rich experimental and theoretical material (e.g. [11, 12]). It was decided to use a carbon sheet embedded in epoxy resin, which was wrapped around the head of the column (Fig. 6). A unidirectional sheet with a polyester matrix with a carbon fibre weight of 400 g/m², a tensile strength of 5100 MPa and a longitudinal modulus of elasticity of 265 GPa was used. The usefulness of this method for strengthening reinforced concrete corbels has been demonstrated, among others, by: in research [13]. In accordance with the guidelines developed therein, the sheet was applied in two layers. The application was greatly facilitated by the fact that the corners of the column were chamfered, which allowed avoiding the troublesome grinding of concrete, which caused heavy dust.

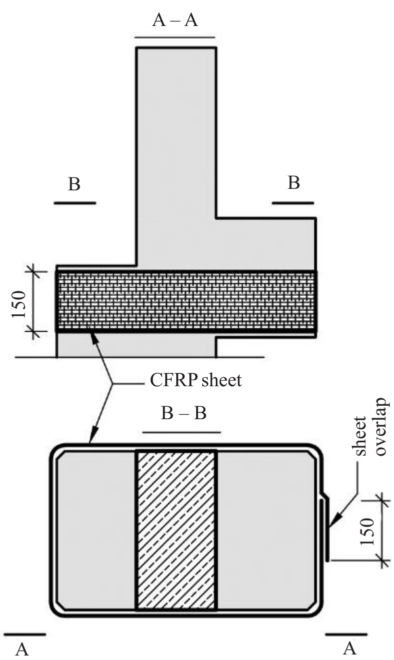

Fig. 6. The proposed way of strengthening
Rys. 6. Proponowany sposób wzmocnienia

The analysis was aimed at identifying the causes of the column head failure. On its basis, it was presented how to correctly calculate and detail the reinforcement. The seemingly typical geometry, as it turned out, caused problems for the designer, resulting in severe cracking. Designing the right side as a separate corbel and omitting the left side in the design process (treating it as a regular column section) was a mistake. It should be emphasized that any irregularities in the structure (such as step changes in dimensions) should always be treated individually. The presented analysis may be useful when designing the reinforcement of similar column heads. It is also intended to encourage designers to use the S-T method.

Literatura

[1] Nagrodzka-Godycka K. Wsporniki żelbetowe. Badania, teoria, projektowanie. Monografia nr 21. Gdańsk: Wydawnictwo Politechniki Gdańskiej; 2001.

[2] PN-B-03264:1999. Konstrukcje betonowe, żelbetowe i sprężone.

[3] Starosolski W. Konstrukcje żelbetowe według Eurokodu 2 i norm związanych – Tom 3. Warszawa: Wydawnictwo Naukowe PWN; 2019.

[4] Marsh K. Autodesk Robot Structural Analysis Professional 2016: Essentials. New York: Marsh API LLC; 2016.

[5] Knauff M. Obliczanie konstrukcji żelbetowych wg Eurokodu 2. Warszawa: Wydawnictwo Naukowe PWN; 2020.

[6] Abbood I. S. Strut-and-tie model and its applications in reinforced concrete deep beams: A comprehensive review. Case Stud. Constr. Mater. 2023; https://doi.org/10.1016/j.cscm.2023. e02643.

[7] Bagrij P, Styś D. Modelowanie naroży ram żelbetowych w metodzie S-T. Materiały Budowlane. 2015; DOI. 10.15199/33.2015.06.29.

[8] Tjhin TN, Kuchma DA. Integrated analysis and design tool for the strut-and-tie method. Eng. Struct. 2007; http://dx.doi.org/10.1016/j.engstruct.2007.01.032.

[9] ACI 318-19 (22): Building Code Requirements for Structural Concrete.

[10] PN-EN 1992-1-1:2008. Eurokod 2. Projektowanie konstrukcji z betonu – Część 1-1: Reguły ogólne i reguły dla budynków.

[11] Urban T. Wzmacnianie konstrukcji żelbetowych metodami tradycyjnymi. Warszawa: Wydawnictwo Naukowe PWN; 2015.

[12] Urban T, Krawczyk Ł, Gołdyn M. Badania krótkich wsporników żelbetowych wzmacnianych zbrojeniem wklejanym i stalowymi akcesoriami. Badania doświadczalne elementów i konstrukcji betonowych 2019; https://doi.org/10.34658/kbb.2019.22.

[13] Corry R, Dolan Ch. Strengthening and Repair of a Column Bracket Using a Carbon Fiber Reinforced Polymer (CFRP) Fabric 2001; https://doi.org/10.15554/pcij. 01012001.54.63.

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