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DEFECTS OF PRETENSIONED CONCRETE BEAMS WITH OPENINGS IN THE SUPPORT ZONE

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Abstract
Pretensioned concrete girders and ceiling ribs are designed often with web openings situated in the support zone. This solution is motivated by the necessity of hiding technical installations inside the ceiling or roof of unusable space.
Several times authors of this paper have met maps of cracks appearing with various intensity near the web openings. Usually, just simple analysis shows lack of bearing capacity of compressed concrete struts or rarely insufficient area of transverse reinforcement.
Paper presents general description of design rules, some exemplary cases of girder defects and provides repair methods.

Streszczenie
Strunobetonowe dźwigary dachowe i belki stropowe często projektuje sie z otworami w środniku strefy przypodporowej. Wynika to z konieczności prowadzenia instalacji technicznych w nieużytkowej przestrzeni stropu lub dachu.
Autorzy artykułu kilkukrotnie spotkali przypadki różnej intensywności zarysowań środników w sąsiedztwie otworów. Prawie zawsze już prosta analiza obliczeniowa wykazywała przekroczenie nośności ściskanych krzyżulców betonowych, rzadziej również niedobory zbrojenia poprzecznego.
W artykule przedstawiono ogólne zasady projektowania belek osłabionych otworami oraz opisano wybrane przykłady uszkodzonych dźwigarów i wybrane metody napraw.

Keywords: **Pretensioned concrete beams; Support zone; Web openings; Shear.**

1. INTRODUCTION

Technical installations in modern buildings occupy more and more space. At the same time, the network of pipes, cables and ducts should not interfere aesthetics and appropriate usability of the object. Usually installations are provided in the roof or ceiling space. This gives relatively easy access in case of emergency, however, it limits usable height of the interior. Popular solution, allowing, partially or completely to avoid this problem, is passing the installations through the openings made in ceilings or roof structural ribs. Due to the relatively large cross-sections of some ducts (e.g. smoke exhaust or air-conditioning), designed opening should have sufficiently high cross-section.

In the past, the webs of ribs were perforated to reduce their weight. Many types of beams made in the seventies of the last century had holes in the web, but they were situated near the middle of the span in the "useless" zone. In modern beams openings are situated near the supports. It facilitates arrangement of horizontal installations and their connection with the vertical ducts usually fixed to the columns and walls. Unfortunately, the web in these area plays essential role for the transfer of shear forces and redistribution of the prestressing force in the cross-section. The opening creates a natural barrier disrupting the distribution of diagonal compression and tensile forces, which may result in reduction of bearing capacity due to shear and tendency to the occurrence of uncontrolled cracks. In the extreme situation [1], it may provide a horizontal splitting of the beam and separation of the prestressed part from the rest of the section.

During their professional work, authors of this paper several times met prestressed girders with strongly cracked support zones weakened by openings. Those damages occurred in spite of the formally correct design and good realization.

2. EXAMPLES OF DAMAGES

Examples of failures are shown in Figure 1. The most frequently observed were cracks near the openings, usually starting at their lateral surfaces. The length of most cracks was relatively small (several centimeters affecting only the web). The width of cracks fluctuated around 0.1 mm, but locally, especially at the edge of the hole, exceeded 0.5 mm. The worst damage occurred in ribs where relatively intensive shear was induced by the locally supported roof girders (almost constant distribution of shear along the entire length). In this case, some of the cracks reached the neighboring opening. The angle of inclined cracks varied within 31÷37°.

The common feature of all cracked beams was relatively thin web (120 mm) and low distance between the openings (approximately equal to their double diameter).

It should be noted, that for all the beams, applied reinforcement near the openings has been correctly formed and had sufficient area. Also design analysis at the glance was correct. Finally discussion of the accuracy of the shear angle identified the problem of capacity underestimation.

3. PRINCIPLES OF DESIGN

Nowadays two methods of designing the beams weakened by openings are in common use. Developed by the Vierendeel frame analogy model and truss model based on a modified Morsch approach.

3.1. Truss model

The idea of this method is to search for the truss scheme enabling safe transfer of the internal forces. For small openings, usually it is possible to find a scheme which allows the transfer of shear forces without additional transverse reinforcement in the chords [2]. In theory, this method provides an opportunity to optimize the structure, with the ability to define the scheme of their static work, through an optimized truss shape. Optimization include also the arrangement of the openings, to minimize the effect of capacity reduction.

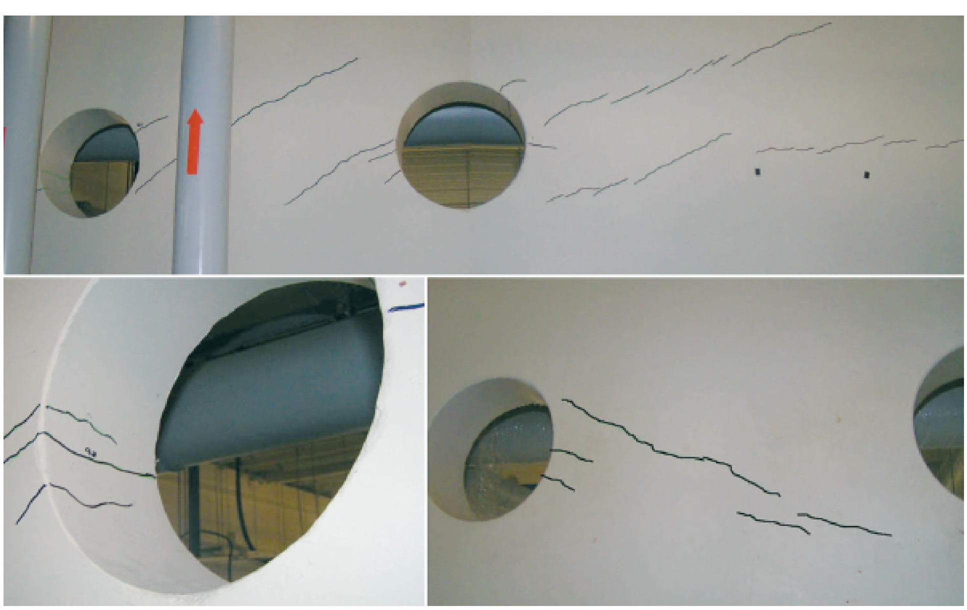

Figure 1.
Observed crack pattern for described beams

Usually, for medium sized openings this is possible to build a truss model similar to the model created for the full web, and the differences are mainly in cross sections of the compressive struts and the angle of their inclination. The situation complicates for relatively large openings, where they do not allow to provide straight struts or ties directly connecting chords, since they always intersect the opening area. Shear force in this case needs to be taken separately by the upper and bottom chord [3].

The method described below can be applied for openings classified as small and medium-sized. Placement of openings should allow passing of diagonal compressive struts between the openings, as shown in Figure 2.

Commonly for designing, a high value of the angle Θ is considered as a safe assumption. For a dense arrangement of openings it leads to a significant reduction of the cross-section area of compressed strut (passed between openings). This leads to the situation, where, for beams with relatively thin webs, not reinforcement, but the resistance of compressive strut can be significant for the shear capacity.

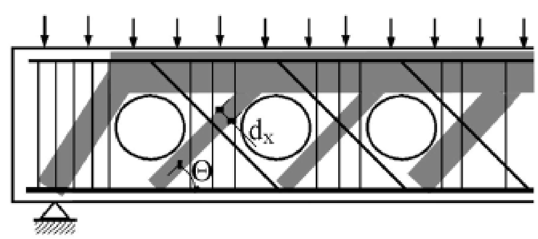

Figure 2.
Strut&Tie model

Shear resistance due to the diagonal compression, according to [4] may be calculated using the formula:

$$V_{Rd,max} = \alpha_c v f_{cd} b_w d_x \sin\Theta, \qquad (1)$$

where:

α_c is a factor considering the influence of prestressing,

$v = 0.6(1 - f_{ck} / 250)$, where f_{ck} given in MPa is the characteristic concrete compressive strength,

f_{cd} is the design compressive strength of concrete,

b_w means width of the web,

d_x is the depth of the diagonal strut, which can be passed between the openings.

Significant impact on the width d_x has a value of the angle Θ, therefore, it is important to establish the correct value of this angle. Theoretically, a designer can control the behavior of the shear zones defining the cotangent of the angle within $1.0 \leq \cot\Theta \leq 2.0$. Observations of the cracks inclination carried out by the authors, as well as comparative FEM analysis indicate, that for prestressed beams, angle Θ typically varies in the range of $31° \leq \Theta \leq 37°$, which corresponds to the cotangent of the $1.28 \leq \cot\Theta \leq 1.66$. Numerical analysis showed one more phenomenon (important from a design point of view) – prestressing reduces the value of the angle of about 5÷10° (compare Fig. 3). The reasons for this can be found in the additional role of compressive strut, which is the transfer of the prestressing force to the upper chord.

The best way for the searches of the angle Θ is the use of the finite element method. Unfortunately, the inconvenience of such analyzes, associated not only with accessibility of the programs and more complicated design process, but also with the correct modeling of the prestressing force, limits their widespread use in practice. Slightly less accurate, but also safe, can be solution based on the standard code formulas, with the analysis of two extreme situations: minimum cotangent of the inclination angle: $\cot\Theta = 1.0$ for the calculation of the reinforcement and maximum $\cot\Theta = 2.0$ for the control of the capacity of concrete in compression struts.

3.1. Vierendeel frame model

For large, especially the elongated or densely placed openings, creation of truss scheme can be quite laborious task for engineering use. In this case the

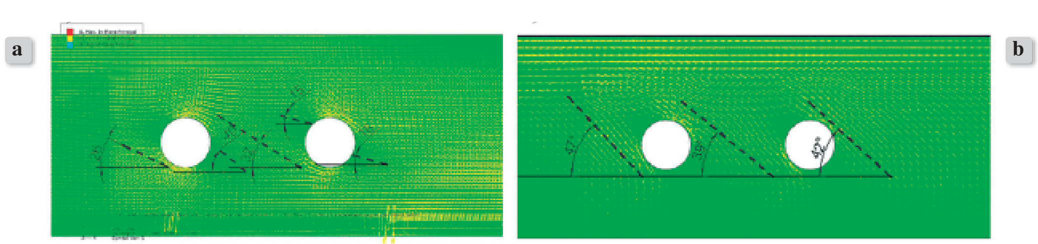

Figure 3.
Inclination angle of compressed strut: a) pretensioned, b) RC beam

Vierendeel model is recommended. Its special feature is the use of the simple frame static scheme (Fig. 4), in which shear force is distributed between the upper and bottom chord. The rest of the analysis can be provided in the conventional way – according to the distribution of internal forces. Chords are treated as elements subjected to simultaneous bending, compression/ tension and shear. Shear force could be simply shared between the upper and lower chord according to the ratio of their bending stiffness [5], or, in the case of small holes, while the effect of bending can be omitted, according to the cross-sectional area of chord [6].

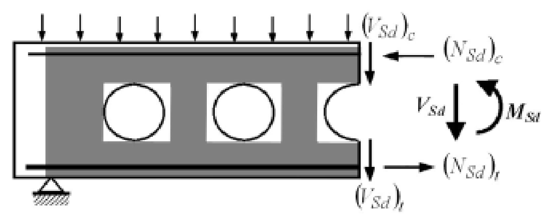

Figure 4.
Vierendel's model

4. FORMING THE SUPPORT ZONE

2.1. Size and location of openings

Opening disrupt the natural transmission of internal forces, the range of those disturbance depends on the size of the opening. Only for openings classified as small, effect can be omitted during design process. There is no clear classification criteria of openings with regard to their size. According to Corley and Somes [7], opening may be considered as large when its diameter exceeds 25% of the depth of beams web. More adequate and efficient criterion proposes Mansur [8]. He believes, that when opening is small, it does not affect the beam type behavior. According to this criterion, the definition of the opening depends not only on the size of the opening, but also on the type of loading – for the segments where bending dominates opening should be placed in the way that does not limit the area of the compression zone, while in areas where bending is accompanied by shear – opening should not disturb the transfer of the diagonal compressive force caused by shear. For a group of openings following condition should be ensured:

$$V_{Rd\,\max} \geq V_{Ed}, \qquad (2)$$

where:

$V_{Rd\,\max}$ is a maximum shear resistance, limited by the crushing of compression struts (formula (1),

V_{Ed} means shear force at the relevant section.

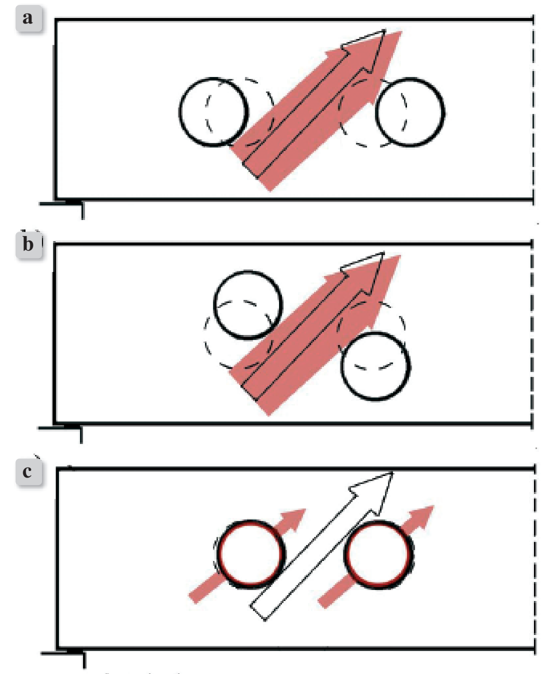

Figure 5.
Optimization by the relocation of openings

Improvement of the transmission of diagonal compressive force can be achieved by the extension of space between the openings (Fig. 5a), their respective vertical movement (Fig. 5b), or adding additional struts into the opening (e.g. steel tube – Fig. 5c).

2.2. Shape of openings

In case of rectangular holes up to five possible locations of cracks can be identified (Fig. 6a). Those are: cracks caused by the localized tension in the corners of the openings due to the framing action of chords (2). Significantly better in this case behaves circular opening (Fig. 6b). Rounded shape also prevents the cracking due the secondary bending of chords (3). Other types of cracks, that is, the horizontal cracks caused by prestressing (1), the vertical cracks due to the normal tensile stress in the chord (4) and diagonal due to shear (5) can occur independently of the shape of the opening.

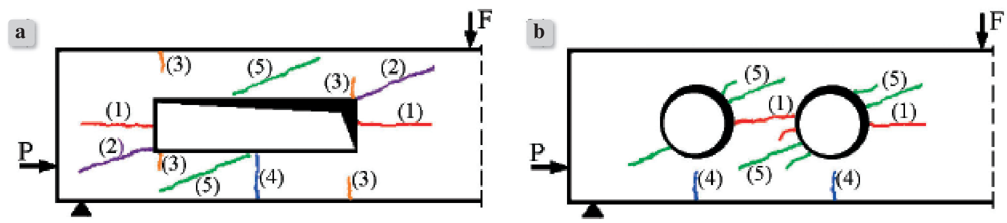

Figure 6.
Possible crack pattern: a) rectangular opening; b) circular opening

2.3. Reinforcing

The correct formation of the transverse reinforcement, although does not prevent the occurrence of cracks around the openings, however, plays a key role for the beams capacity. Properly placed reinforcement is shown in Figure 7. It should contain:

- vertical stirrups, if possible, concentrated at the edge of the openings,
- horizontal bars directly above and below the opening,
- diagonal bars that most effectively reduce the propagation of diagonal cracks around the opening (see Figure 6b (5), in case of small holes this reinforcement plays also the role of shear reinforcement of the chords over and below the openings.

In case of large openings, particularly rectangular, proper shear reinforcement of chords should be ensured – preferably in the form of short stirrups.

In prestressed beams, it is strongly recommended to use the upper strands to prevent the phenomenon of splitting the beam in the horizontal plane by the crack between the openings [9].

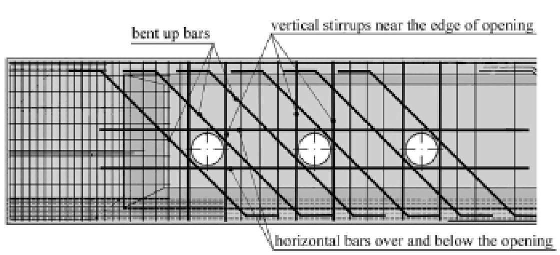

Figure 7.
Exemplary reinforcement of shear zone weakened by openings

4. STRENGTENING OF WEAKENED BEAMS

Appearance of the damages described in Section 2 is a reason for repairing and, if necessary, also strengthening the weakened zone. Selection of repair method should be made after accurate analysis of the damage causes.

Required bearing capacity could be simply restored with the use of additional external transverse reinforcement, in the form of composite overlays (strips or fabrics) glued to the side surface of the beam. Researches of Havez et al. [10] showed that the use of FRP strengthening allows to restore the original load capacity of beam without openings and significantly reduces the propagation of cracks in the weakened zone. It is recommended to use two layers of fabrics arranged orthogonally (so that the fibers of the first layer are carried out in the vertical direction, and the fibers of the second layer in the horizontal direction [11]).

Unfortunately, the use of FRP strips or sheets for strengthening of prestressed beams with thinned webs is not always possible, due to the need of proper anchoring, which is usually covering the flanges (prestressing reinforcement precludes drilling of holes in flanges to fasten the tape end). Fabric requires shorter anchoring length, however, it should be noted, that it is unacceptable to wrap the anchoring end on the area of flanges.

With the lack of the anchoring capacity, mechanical fasteners can be used or, in extreme cases, external transverse compression with the use of steel or composite brackets.

With a close arrangement of openings, the easiest, but not always possible repairing method is to refill some openings (eg, every second opening). This allows the extension of area of compressive strut and proper transmission of inclined shear forces. To ensure cooperation between fill and the original concrete, cement mortar or concrete with low shrinkage properties should be used. When, for some reasons,

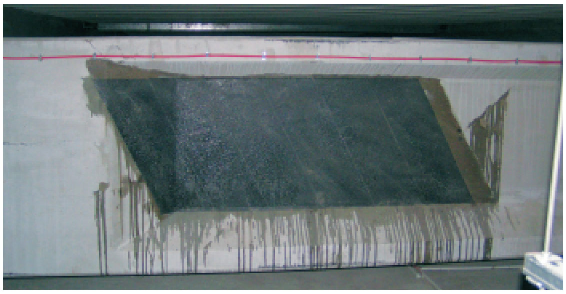

Figure 8.
Example of strengthening by filling the openings and side covering with two layers of orthogonally placed CFRP mat

it is necessary to leave the openings, it is possible to apply inside the opening the strut element in the form of rigid steel tube, respectively (Fig. 5c). Tube diameter must be at least 20 mm smaller than the diameter of the opening and the free space between tube and wall should be filled with low shrinkage cement or epoxy grout, to provide the appropriate cooperation with the surrounding concrete. In addition, this cooperation can be improved by using FRP sheets (carrying inclined tension). An example of such solution is shown in Figure 8.

Decision on the cracks injection should take into account the danger of cracking expansion caused by the drilling and filling pressure, which may unnecessarily weaken the beam.

5. SUMMARY

Implementation of the openings in the web near the support usually reduces bearing capacity of prestressed girder. This is due to the limited capacity of the web for the transfer of compression forces caused by shear and prestressing and difficulties in proper forming of transverse reinforcement. Zone weakened by openings is more susceptible to the occurrence of cracks and prestressing, which usually reduces the cracking effect, in this case causes the tensile stress concentration near the hole, thus increasing the risk of cracking.

Designing of openings near the support zones of prestressed beams should be limited to situations where their application is justified by the real necessity. Among the dozen of damaged prestressed concrete beams, met by the authors, just one opening served the pipeline.

REFERENCES

[1] *Kennedy J.B., El-Laithy A.M.*; Cracking at Openings in Prestressed Beams at Transfer, Journal of the Structural Division, Vol.108, No.6, June 1982; p.1250-1265

[2] *Godycki-Ćwirko T., Wesołowski M.*; Nośność na ścinanie belek żelbetowych osłabionych otworami, Materiały XLV Konferencji Naukowej KILiW i KN PZITB Krynica'99, T.2 Konstrukcje Betonowe; p.55-62

[3] *Schlaich J., Schafer K., Jennewein M.*; Toward a consistent design of structural concrete, PCI Journal, 05/06 1987; p.74-150

[4] *Wesołowski M.*; Wymiarowanie strefy przypodporowej belek żelbetowych z otworami, Politechnika Łódzka, Zeszyty Naukowe: Budownictwo Nr 60, Łódź 2009; p.115-122

[5] *Barney G.B., Corley W.G., Hanson J.M., Parmelee R.A.*; Behavior and Design of Pre-stressed Concrete Beams with Large Web Openings, PCI Journal, 11/12 1977; p.32-61

[6] *Ragan H.S., Warwaruk J.*; Tee Members with Large Web Openings, PCI Journal, 04 1967; p.52-65

[7] *Somes N.F., Corley W.G.*; Circular openings in webs of continuous beams, SP-42, American Concrete Institute, Detroit MI, 1974; p.359-398

[8] *Mansur M.A.*; Effect of openings on the behaviour and strength of R/C beams in shear, Cement and Concrete Composites 20, 1998; p.477-486

[9] *Savage, J. M., Tadros M. R., Arumugasaamy P., Fischer L.G.*; Behavior and Design of Double Tees with Web Openings, PCI Journal, V.41, 01/02 1996; p.46-62

[10] *Abdel Hafez L.M., Alaa Eldin Abou-Elezz Y.K.*; Static behavior of repaired RC beams having web circular openings in shear zone by using GFRP sheets, Proceedings of Eleventh International Colloquium on Structural and Geotechnical Engineering, Cairo – Egypt, paper code E05RC30, May 2005; p.17-19

[11] *Abdalla H.A., Torkey A.M., Haggag H.A., Abu-Amira A.F.*; Design against cracking at openings in reinforced concrete beams strengthened with composite sheets, Composite Structures 60, 2003; p.197-204