VERIFICATION AND VALIDATION OF CORBELS STRENGTHENED BY UNBONDED TENDONS AND BARS

Lukáš Bobek[1, a *], Lukáš Juříček[2,b], Michal Číhal[2,c], Jaromír Kabeláč[2,d] and Michael Konečný[2,e]

[1] Brno University of Technology, Faculty of Civil Engineering, Veveří 331/95, 602 00 Brno, Czech Republic

[2] IDEA StatiCa s.r.o., U Vodárny 2a, 616 00 Brno, Czech Republic

[a]lukas.bobek@vutbr.cz, [b]lukas.juricek@ideastatica.com, [c]michal.cihal@ideastatica.com, [d]jaromir.kabelac@ideastatica.com, [e]michael.konecny@ideastatica.com

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Abstract

Reinforced corbels are frequently used in industrial halls. A number of existing corbels are prestressed by unbonded tendons or bars in order to increase their load-bearing capacity, decrease the deflections and restrain cracks spreading. The goal of the project was experimental validation of the reinforced concrete corbel strengthened using unbonded tendons via CSFM (Compatible Stress Field Method). The method is based on materially nonlinear calculation considering the tension stiffening effect of rebars and compression softening of concrete. These effects and other assumptions implemented in CSFM capture real behavior of reinforced concrete members. Besides, CSFM is verified using an independent analysis, which is based on similar assumptions as those in Compatible Stress Field Method.

1 Description of the experiment

The research project was done in cooperation with the Faculty of Civil Engineering in Brno and the company PEEM, spol. ltd., Czech Republic. The goal of the experiment was to find the optimal way of strengthening the existing corbels in order to increase the load-bearing capacity and decrease the amount and width of cracks. The experimental models scaled at 1:1 were strengthened using several different layouts of unbonded tendons where the increase of load-bearing capacity was observed and compared to one corresponding to reinforced concrete corbels. Specimens were fabricated from concrete with 20 MPa cube strength and B500B reinforcement bars.

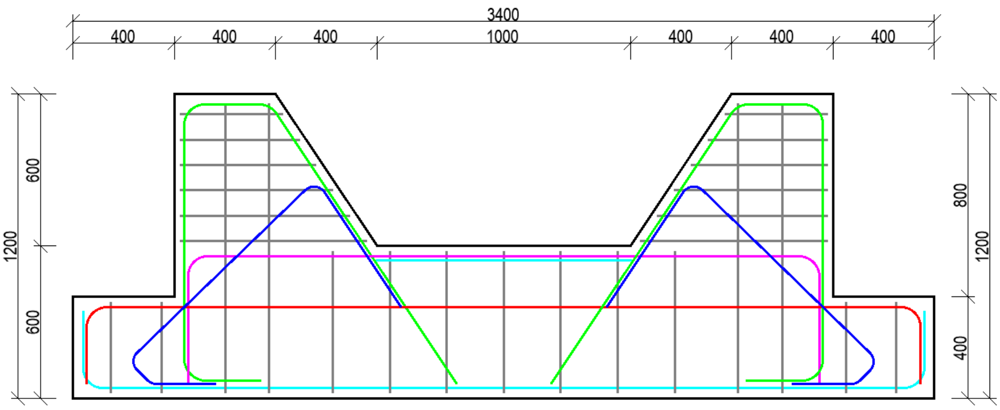

Fig. 1 Reinforcement of the sample

For the purpose of this article, the model where the corbels are strengthened using two unbonded tendons located in the drilled ducts with diameter of 42 mm was chosen. The experimental model consists of a pair of symmetrical corbels, which are connected by a beam representing the column. The shape of the reinforced structure is illustrated in (Fig. 1). Each tendon's (Fig. 2) anchoring force was 200 kN. Subsequently the corbels were loaded in the horizontal direction through the loading frame. The maximal force reached during the experiment was 1026 kN. For the purpose of validation of the finite element software the maximal considered horizontal load was 658 kN. After exceeding this load, crushing of concrete under the corbel occurred (location „i").

During loading, the vertical deformations of the model were controlled using a level device. Also, the strain in the concrete was monitored using inductive displacement transducers attached to the surface of the concrete. The stress on the main bending reinforcement bars was determined by resistance strain-gauges directly glued to the rebars (Fig. 2). All the collected data were used for the validation of the new computational method CSFM (Compatible Stress Field Method).

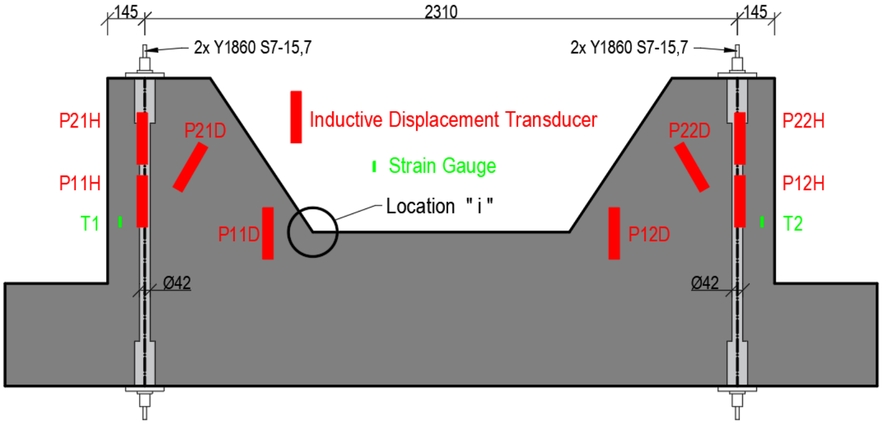

Fig. 2 Location of the prestressed tendons and sensors

2 Compatible Stress Field Method (CSFM)

The experimental sample was modelled in the application IDEA StatiCa Detail, where the CSFM method is implemented. The program uses a model with 2D finite elements representing the concrete part and the reinforcement bars are modelled as 1D elements. In terms of structural mechanics, the method considers plane stress only. The calculation is based on a materially nonlinear analysis. [1, 2, 3, 4]

The properties of the 2D model were set according to the experimentally found material characteristics of concrete and reinforcement. The computational model neglects the action of concrete in tension and replaces it by the tension stiffening effect.

The principal stress (Fig. 3) shows that the point with the maximal stress is located under the corbel (i), where all three compression struts merge. The principal stress in this area reaches the limit design stress 20 MPa and thus the concrete is being crushed.

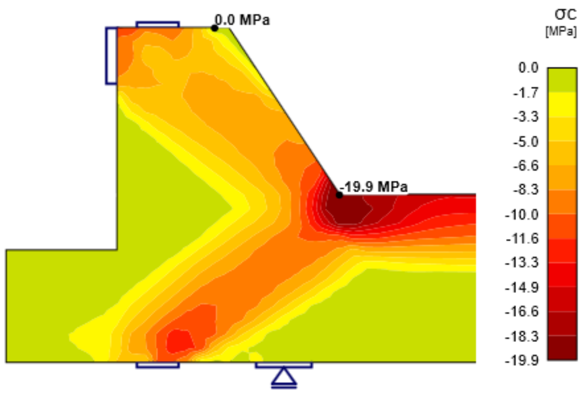

Fig. 3 Principal stress in concrete (CSFM)

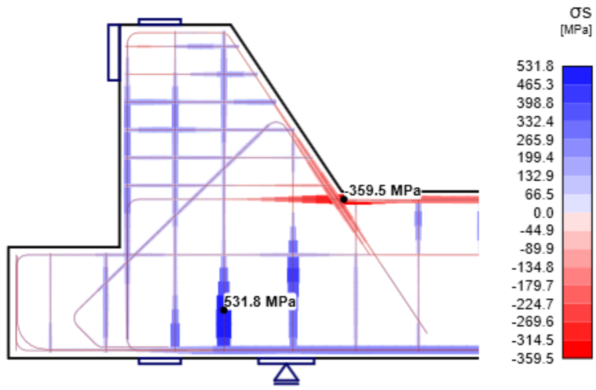

Fig. 1 Stress in reinforcements (CSFM)

The most utilized entities are the stirrups on the connecting line between the anchor of prestressing tendons and the location with maximal stress in concrete (Fig. 4). The stress in the reinforcement exceeded the design yield strength and plastifies further. This fact is in agreement with the occurrence of the biggest crack width (Fig. 5).

In the last step the vertical deformation of the structure was verified (Fig. 6). The biggest deformation was 4,6 mm on the left side of the corbel.

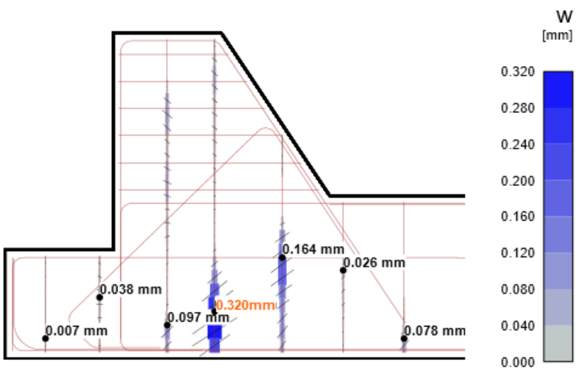

Fig. 5 Crack width (CSFM)

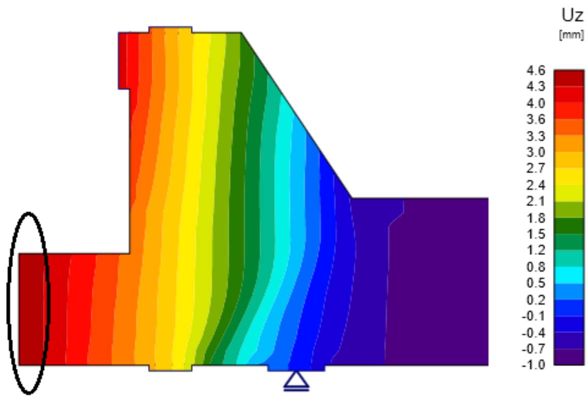

Fig. 6 Vertical deformation (CSFM)

3 Midas FEA

Using to the advanced application Midas FEA, the structure can be analyzed as a 3D model with the real layout of the reinforcement (smeared crack model). The corbel was modelled by 3D finite elements and the reinforcement by 1D elements. [5] Loads of the corbel and all the material characteristics were set in agreement with the inputs used in IDEA StatiCa Detail and also with the real properties of the used materials.

The figure (Fig. 7) displays the principal stress in concrete. The maximal principal stress of -22,07 MPa (Fig. 7) appeared in the same place as in the 2D model in IDEA StatiCa Detail. The stress in the reinforcement is illustrated in (Fig. 8). The results from the 3D model evidently correspond very well to the ones from the 2D solution using CSFM.

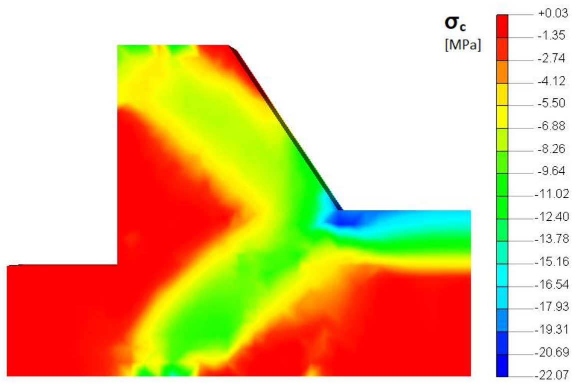

Fig. 7 Principal stress in concrete (Midas FEA)

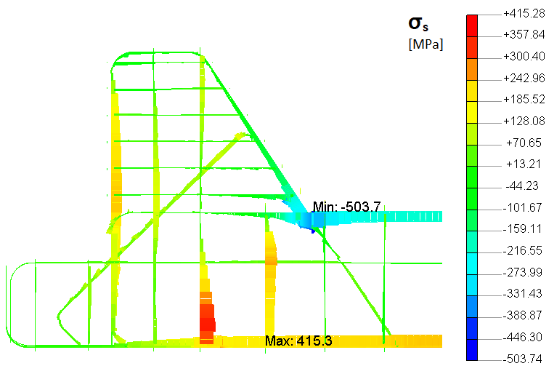

Fig. 8 Stress in reinforcements (Midas FEA)

Interpretation of the crack width in Midas FEA is relatively complicated (Fig. 9). The biggest crack width 0.57 mm is spread on the finite elements close to the area where the most utilized stirrups are located. Their position is in accordance with the CSFM method.

The vertical deformation (Fig. 10) on the observed left edge of the member reaches 5,03 mm. This deformation compares really well to the 2D solution.

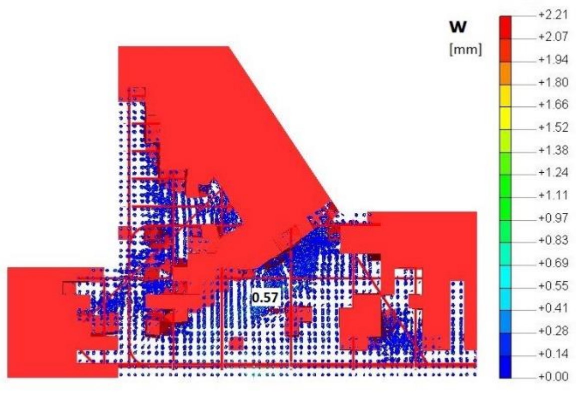

Fig. 9 Crack width propagation (Midas FEA)

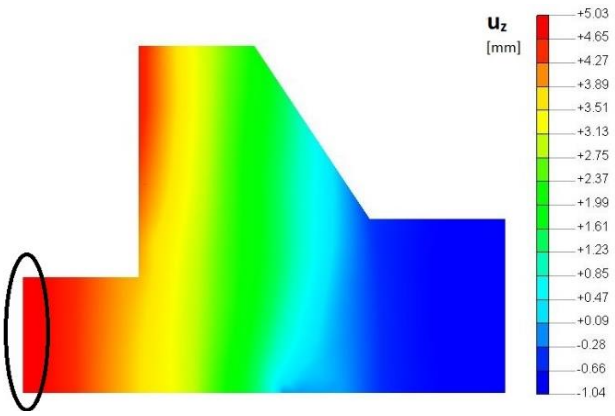

Fig. 10 Vertical deformation (Midas FEA)

4 2D model vs. 3D model vs. experiment

For an easy comparison, the stresses in concrete obtained from the experiment and from the two softwares were plotted into two graphs.

The structure was loaded in two stages. In the first stage the prestressing of the corbel was simulated in the vertical direction using two unbonded tendons with a total force 400 kN on one corbel. Subsequently the corbel was loaded in the horizontal direction with the maximal force 658kN.

Two places were chosen for the purpose of comparison of the stress in concrete. The first analyzed position is close to inductive displacement transducer P11H (Fig. 2), where it is possible to use the values of strain from the experiment. Given the fact that the concrete is cracked at this place, it was necessary to reduce this effect, that could lead to distortion of the results. For the 3D model (Midas FEA) there is also a significant difference between the results on the finite elements which are located on the surface of the structure, and on those that are inside of it. Since the inductive displacement transducer was fixed to the surface of the corbel, the finite element in the same position was considered to obtain relevant results. CSFM considers a plane 2D model, which averages the stress within the thickness of the wall. This averaging could cause slight deviations of principal stress in concrete (Fig. 11).

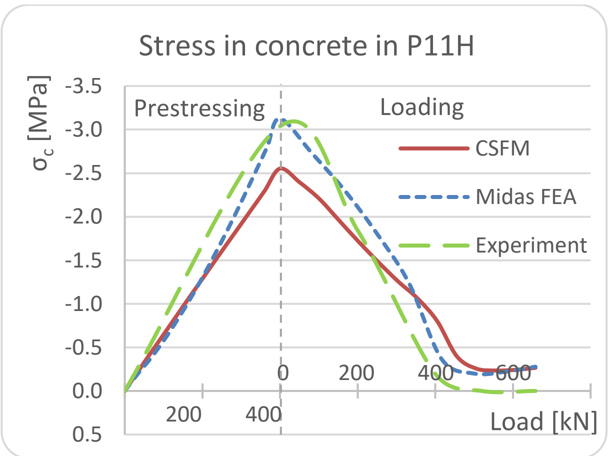

Fig. 11 Stress in the concrete - sensor P11H

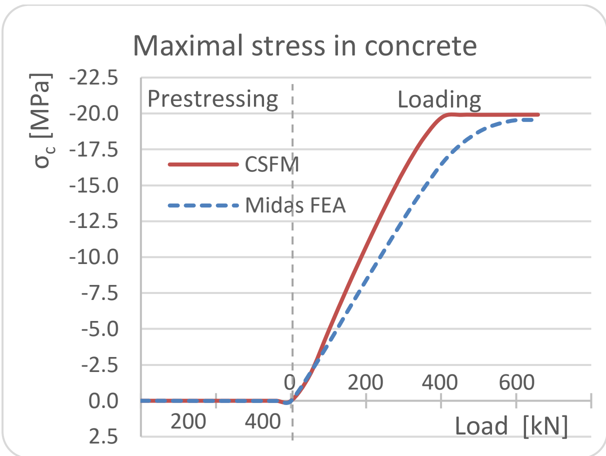

Fig. 12 Stress in the location „i“ under corbel

Figure 12 shows changes in stress in concrete during the loading in the most utilized part of the member (location „i“). The evaluated range of stresses for each software is very similar. The deviations are caused by irregular stress distribution by the thickness of the 3D model. The final parts of curves show that the concrete reaches strength in compression by the load of 600 kN. During the experiment there was no inductive displacement transducer placed into that spot, so it is not possible to compare real values of stress with the software results. It can be confirmed that crushing of concrete has occurred as the horizontal load in experiment exceeded 600 kN.

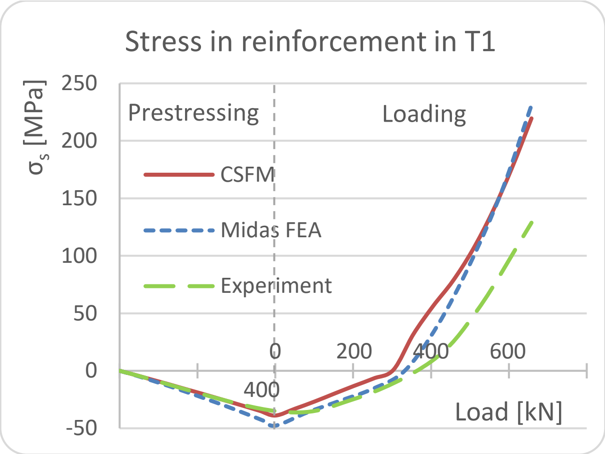

Fig. 11 Stress in reinforcement - sensor T1

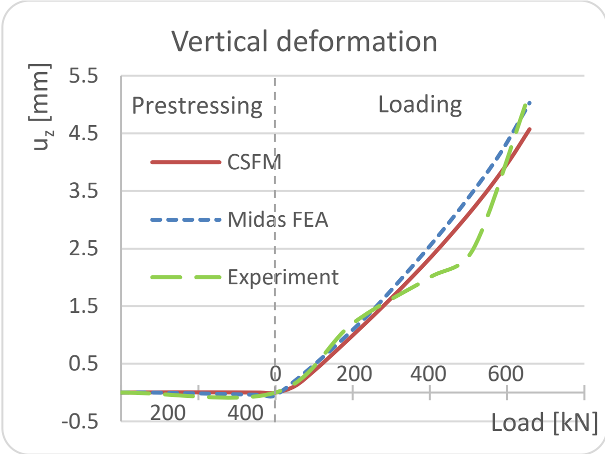

Fig. 14 Vertical deformation of the left edge

The next tracked parameter is the stress in the main tensile reinforcement of the corbel, where the strain-gauge T1 was placed (Fig. 13). The stress from both software and experiment follow a similar curve. In the software, results were displayed along the whole length of the main tensile reinforcement of the corbel and show the place with extreme normal stress. Due to the fact that the strain-gauge T1 was placed in the middle of the occurred cracks, values of tension stress in reinforcement in experiment are lower than in the softwares. This is partially caused by the interaction of concrete in tension. The location of the strain-gauge proves uneven distribution of the stress on the bar length.

The deformation gives a really good overview about the behavior of the structure. During the experiment, the level device was used to track the vertical movement of the structure in 3 different places. The comparison of the deformation can be seen on the (Fig. 14), where the deformation of the real structure and the deformations from the softwares can be compared.

Fig. 15 Experimental structure with sensors

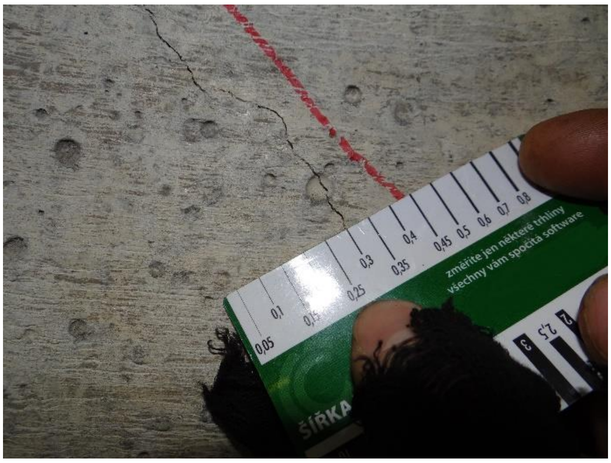

Fig. 16 Crack width by the load 658 kN

Thanks to the nonlinear analysis of both applications, crack width can be determined for the structure. The maximal crack width using the CSFM solution reached 0,32 mm (Fig. 5). The 3D model in Midas FEA gives a higher crack width in the same place, 0,57 mm (Fig. 9). The real crack width in the experiment was 0,3 mm (Fig. 12), what corresponds very well to the result from the 2D model with the implemented CSFM method.

5 Conclusion

A wide variety of tools for the design of details of reinforced concrete structures is currently available on the market. Some of them are simple (such as CSFM), while others are more sophisticated (Midas FEA, Ansys). The CSFM solution uses a simplified design model to reach better numerical convergence and to reduce the time consumption of the calculation in comparison with general methods. Despite this simplification, CSFM proves really good accordance with the experiment and provides precise and safe design of reinforced concrete structural details. Moreover, this solution is much less time consuming in comparison with a 3D simulation in more sophisticated applications, which are overly complicated for the use the common engineering practice.

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