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CODE CALCULATIONS FOR LOCAL STABILITY OF SHAFT GUIDES

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Abstract: Steel structures for a conveyance guiding system are subjected to prolonged, intense corrosion during their operation leading to a considerable loss of material and structure capacity reduction. Shaft guides are made of closed profiles welded from hot-rolled channel sections. These profiles are categorized as class 1 cross-sections according to Eurocode 3, which means that they are resistant to local instability upon bending [1]. With an increase in the corrosion loss of the guides, the inertia moment of the cross-section is reduced. The resistance of profiles to local buckling is also reduced. However, calculations for local stability in guides upon bending are not required by the local Polish regulations on the operation of conveyance in shafts [2]. The question is whether this constitutes a shortcoming and risk for safe operation. Calculations according to steel construction standards [1] supported by numerical simulation were used to evaluate shaft steelwork guides resistance to buckling and their sensitivity to corrosion loss. It was shown that the guides of corrosion loss of 52–63%, depending on profile size, are prone to local buckling.

Key words: *shaft steelwork, corrosion loss, local buckling, steel profiles, FEM simulation*

1. INTRODUCTION

Currently, rigid guiding is the dominant shaft guiding system in Poland. The main elements of the shaft steelwork are buntons, built horizontally in the shaft and vertical guides fixed to them, which provide tracks for the conveyance [3]. A diagram of a shaft is shown in Fig. 1.

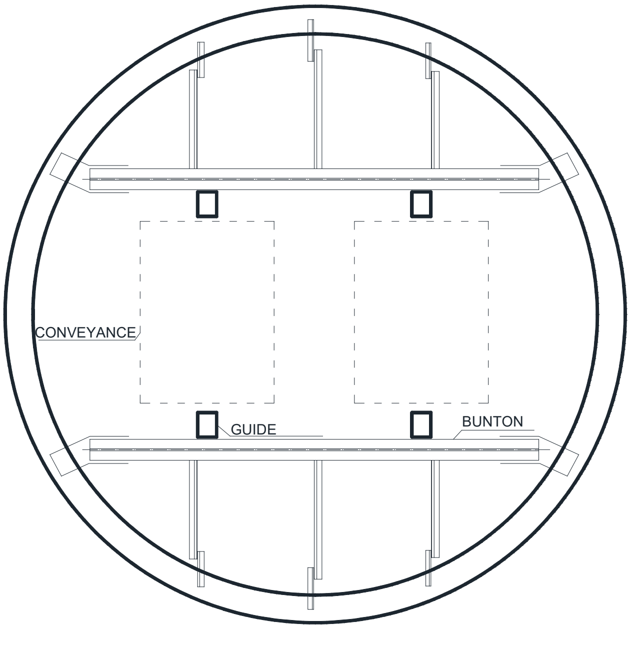

Fig. 1. Shaft steelwork

Shaft steelwork for conveyance equipped with grippers is designed for vertical forces. Currently, a substantial majority of all shafts use conveyance without grippers. The payload in these systems are the horizontal forces caused by the lateral movement of conveyances while driving along the shaft [4].

The earliest regulations for the design and inspection of shafts in Poland date back to 1963. The instruction [5] gives a formula for computing the horizontal force, global safety factors and permissible corrosion loss of profiles. The 1963 regulations were amended in 1995. The regulations [6] introduced new formulas for computing forces. Three directions were distinguished for forces driving the conveyance: horizontal-frontal, horizontal-lateral and vertical. A reduction with respect to the instruction [5] involved safety factors. The permissible corrosion loss factor was also maintained. Currently, the issues related to the operation of mine shafts steelwork are governed by the regulation [2]. In relation to the 1995 regulations, the formulas for computing forces were discarded in favor of actual forces, measured while driving the conveyance. Safety factors and corrosion loss limits have not changed in relation to the 1995 regulations.

Shaft steelwork is exposed to corrosive environment. The main factors causing accelerated corrosion of steelwork elements include high air humidity and the presence of water in shafts, aggressive gases, stray currents and sulfur bacteria. The rapidity and location of outbreaks of corrosion loss are also influenced by mechanical factors associated with conveyances coming into contact with shaft steelwork [7]. Due to the low efficiency of anti-corrosion coatings that protect structures in shaft conditions [7], in practice, while designing shafts, a surplus for corrosion is assumed.

The degree of corrosion loss is defined as:

$$Z = \frac{g_{nom} - g}{g_{nom}} \cdot 100\% \qquad (1)$$

where:

g – wall thickness of the steelwork element

g_{nom} – nominal wall thickness of the profile used for the steelwork element

The measurements of wall thickness are checked during periodic revisions of the shaft [8], while the degree of corrosion loss is usually determined based on the thickness of webs [4].

2. SHAFT GUIDES AND CLASS OF GUIDE CROSS-SECTION

The shaft guides currently used in Poland are produced according to standard [9], by butt welding of two hot-rolled channel sections. A cross-section of the guide is shown in Fig. 2.

The standard [9] lists 5 sizes of guides divided based on the used UPN-profile (UPN 180-UPN 260) and gives their dimensions and main parameters. In addition, Polish mines use guides composed of two UPN 160 channel sections.

The design standard for steel structures Eurocode 3 introduces the concept of cross-section classes. The classification is to determine the section's resistance to local buckling. Cross-section classes are defined as follows [1]:

- Class 1 cross-sections are those which can form a plastic hinge with rotation capacity required from plastic analysis without resistance reduction.

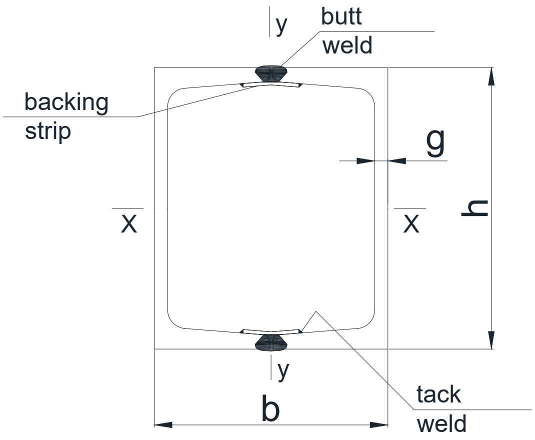

Fig. 2. Cross-section of a steel guide made of channel sections [9]

- Class 2 cross-sections are those which can develop their plastic moment resistance, but have limited rotation capacity because of local buckling.
- Class 3 cross-sections are those in which the stress in the extreme compression fiber of the steel member assuming the elastic distribution of stresses can reach the yield strength, but local buckling is liable to prevent development of the plastic moment resistance.
- Class 4 cross-sections are those in which local buckling will occur before the attainment of yield stress in one or more parts of the cross-section.

The classification is based on width-to-thickness ratio for the compression part [1] and the yield strength of steel f_y. The most unfavorable load-bearing state of the guide involves bending about the *y-y* axis and web compression (Fig. 2). The class of a guide cross-section should therefore be indicated by the width-to-thickness ratio for the web under compression.

Assuming a constant loss of material around the perimeter of the cross-section, new geometry characteristics were calculated and a classification of guide cross-sections was made. The calculations assumed the ε factor equal to 1.0 (as for steel St3S). The calculation results are shown in Table 1.

Table 1. Cross-section class by degree of corrosion loss

Degree of corrosion loss	Cross-section class for profiles					
[%]	160 × 130	180 × 140	200 × 150	220 × 160	240 × 170	260 × 180
35	1	1	1	1	1	1
40	1	1	1	1	1	2
45	1	1	1	2	2	2
50	1	2	2	2	3	3
55	2	2	3	3	4	4
60	3	3	4	4	4	4
65	4	4	4	4	4	4

3. RESISTANCE OF CROSS-SECTION

According to Eurocode 3 [1], depending on the cross-section class, the flexural modulus has the form of:

- plastic section modulus W_{pl} for classes 1 and 2,
- elastic section modulus W_{el} for class 3,
- effective section modulus W_{eff} for class 4.

The load capacity of guides at corrosion loss degree, which allows to classify a cross-section in the first or second class, depends on the plastic section modulus. The plastic section modulus of the symmetrical cross-section, which is the guide profile, can be calculated using Equation 2:

$$W_{pl} = 2S_{pl} \tag{2}$$

where S_{pl} – first moment of area of the mid-section in relation to y-y axis

The load capacity of guides at corrosion loss degree that allows to classify the cross-section as the third class is dependent on the elastic section modulus calculated using Equation 3:

$$W_{el,\min} = \frac{J_y}{s} \tag{3}$$

where:

J_y – second moment of area with respect to y-y axis,

s – distance between the outermost fibers and the neutral axis.

The bearing capacity of the guide section at degree of corrosion loss classifying them as fourth-class is calculated based on the effective section modulus. The effective cross-section is established on the basis of determining the effective width of the compression section and leaving the non-reduced tension part.

The degree of cross-sectional reduction depends on stress distribution in the web and plate slenderness. It should be noted that the cross-sectional reduction of the compression part shifts the neutral axis. The modulus of the effective cross-section is calculated as follows:

$$W_{eff,\min} = \frac{J_{y'}}{s_{\max}} \tag{4}$$

where:

$J_{y'}$ – second moment of area of the effective cross-section,

$s_{\max}$ – maximum distance between the outermost fibers and the neutral axis.

With an increase in corrosion loss, the sectional area of the guide decreases, which leads to a reduction of strength and, as shown in Table 1, changes in the section class deriving from the increasing slenderness of the web. Figure 3 shows the dependence of flexural modulus on corrosion loss for 6 section sizes of guides. The continuous lines mark the modulus taking into account the section class (W_{pl} – for classes 1 and 2, W_{el} – for class 3 and W_{eff} – for class 4).

The first drop on the plot $W_{pl,el,eff}$ shows the change from class 2 to class 3 cross-section. The elastic sec-

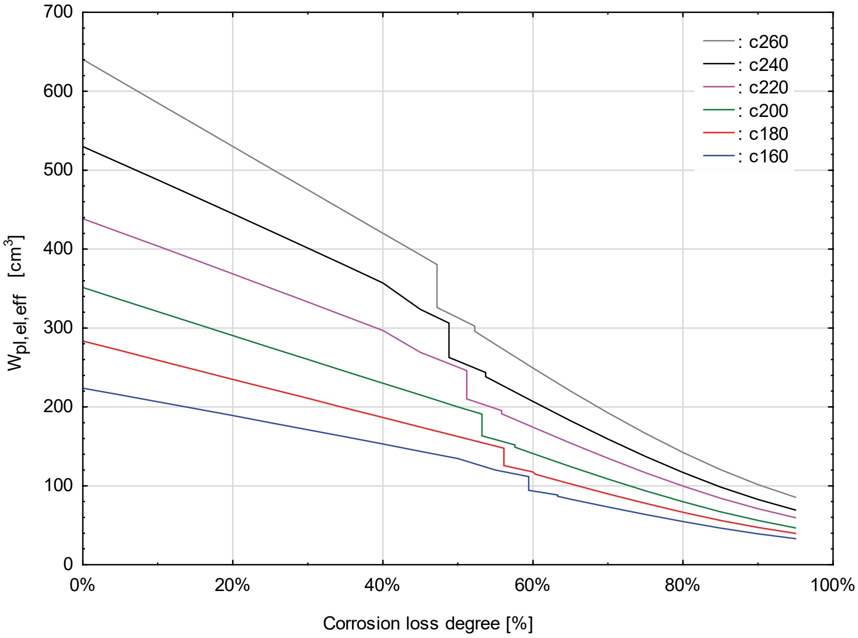

Fig. 3. The dependence of the section modulus as a function of corrosion loss

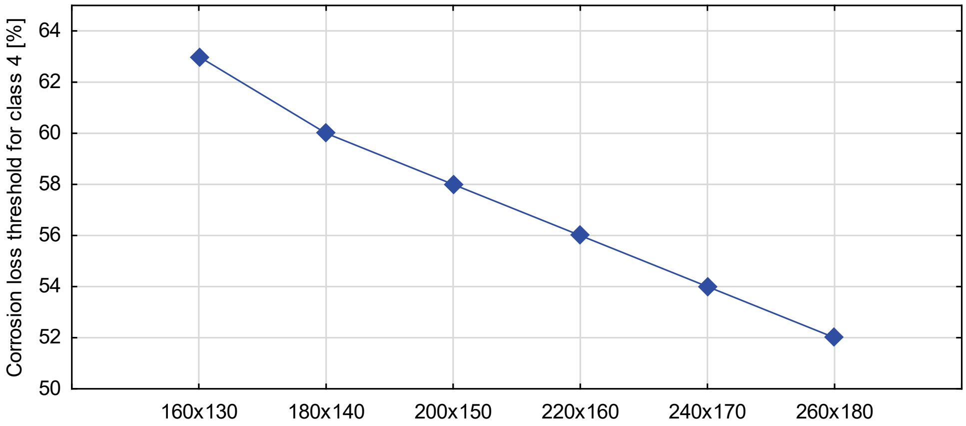

Fig. 4. The degree of corrosion loss at which the profile moves from the third to fourth class, depending on its size

tion modulus is much lower than the plastic section modulus. The second change of the plot $W_{pl,el,eff}$ demonstrates the change from class 3 to class 4. The difference between modulus W_{el} and the modulus of the effective cross-section W_{eff} is small. From this point, with corrosion loss the profile moves into class 4. Therefore, the instability of the web wall occurs in the range of the elastic work of the material. The profile transition into the fourth class occurs at varying degrees of corrosion loss for each profile. Figure 4 summarizes the degree of corrosion loss at which the profile moves into the fourth class cross-section, depending on its size.

4. FEM SIMULATION RESULTS

In order to verify the results and extend the conclusions, numerical simulations were performed using the finite element method in the ABAQUS system. The models of the guide made of two UPN 180 channel sections were analyzed for several different degrees of corrosion loss. The model mapped a 4-point bending of a 3-meter guide section. The static schema shown in Fig. 5, forms of a half-meter segment in the mid-section with a constant bending moment without the transverse force. The figure also presents the segment where displacements were monitored (red line).

The model was built with 30,000 cubic, eight-node elements with reduced integration (C3D8R). An elastic perfectly plastic material was adopted involving the HMH yield criterion and geometric non-linearity. Elastic constants and yield strengths were adopted in accordance with Eurocode 3: Young's modulus E = 210 GPa, Poisson's ratio v = 0.3, yield strength R_e = 235 MPa (steel St3S). The Riks method, particularly useful for non-linear, local instability analysis [10], [11], was applied. Simulations were performed for various degrees of corrosion loss modeled by the reduced thickness of profile cross section, with no imperfections. The linear, eigenvalue buckling analysis appeared inadequate for this problem.

Figure 6 shows the results of the simulations for 180 × 140 guide made of UPN 180 channels. The graphs of vertical displacements along the upper mid-section of the guide model, for maximum bending moments are presented. Characteristics were drawn for profiles at the corrosion loss degree of 50%, 60%, 65% and 70%. For the guide at 50% and 60% degree of corrosion loss, vertical displacement graphs show a single extreme value and no local buckling. Simulation results at 65% degree of corrosion loss show emerging local buckling and at 70% developed local buckling. These simulation results are consistent with local buckling code calculations [1] and cross-section class categorization (see Table 1).

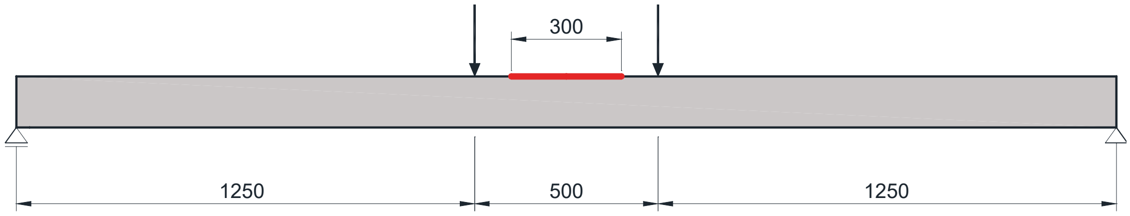

Fig. 5. Diagram of support and load of the 180 × 140 guide model

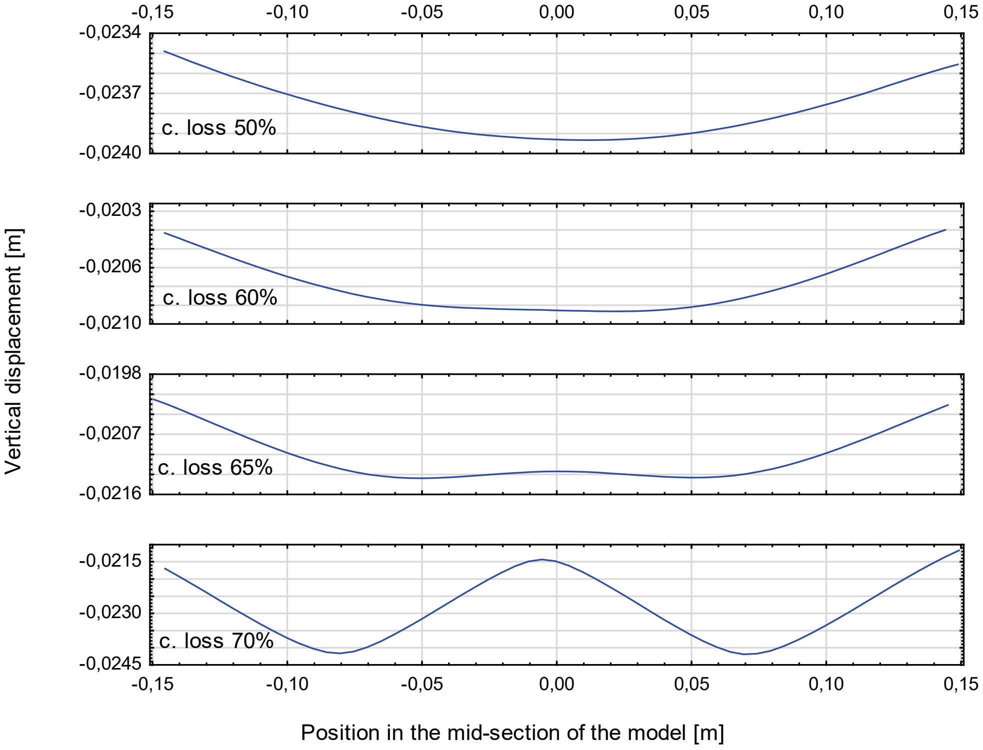

Fig. 6. FEM simulation results. Vertical displacements in the upper mid-section of the guide model for maximum bending moments

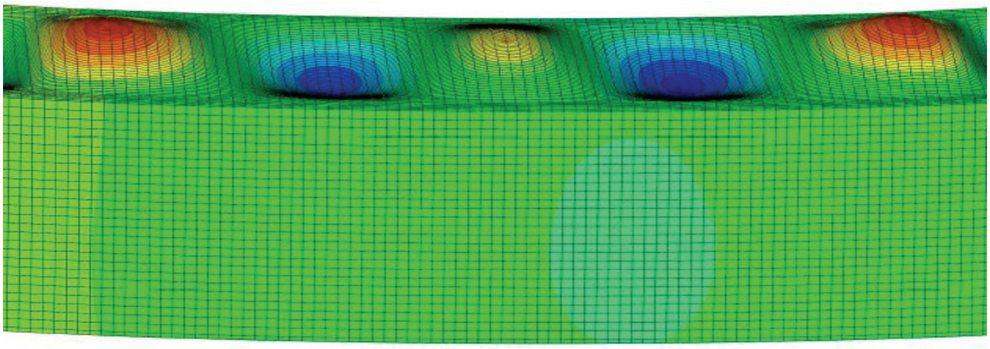

Fig. 7. FEM simulation results for guide at 70% corrosion loss degree.
Vertical displacement distribution shows local buckling in the upper mid-section of the guide.
Visualization shape shows vertical displacements enlarged 10 fold

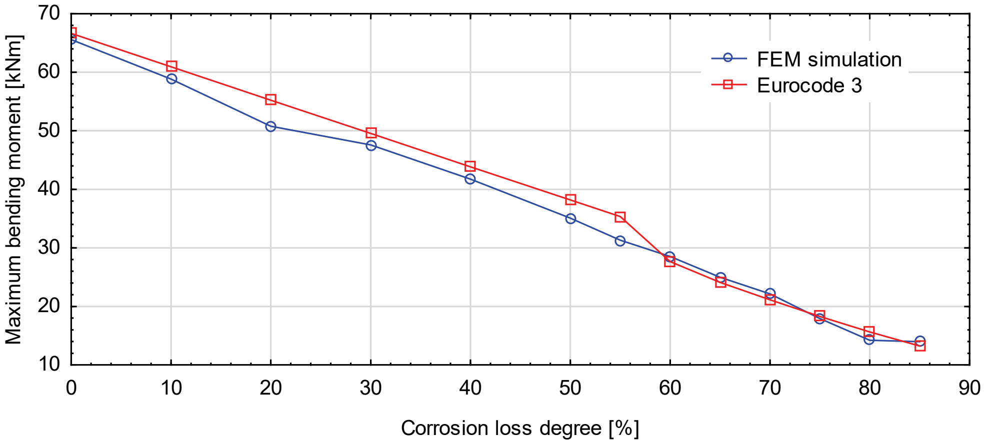

Fig. 8. Maximum bending moment from FEM simulation and Eurocode analysis by degree of corrosion loss 180 × 140 profile

Figure 7 shows the buckling shape of a guide at 70% corrosion loss degree. Figure 8 presents the maximum bending moments for various corrosion loss degrees as resulted from the FEM simulation and the characteristic critical moments calculated according to Eurocode 3. The difference between the results is less than 10% and the results are consistent.

5. CONCLUSIONS

The corrosion of steelwork is one of the major technical problems in the operation of shafts. The current Polish regulations on shaft steelwork operation specify detailed instructions for steelwork guide design and maintenance [2]. They do not refer to steel construction standards [1], specifically, they do not require local buckling calculations. These calculations are usually not required for steel constructions made of closed profiles welded from a hot-rolled channel, since they are resistant to the local instability upon bending. Shaft steelwork guides are made of such profiles, but as shown in the paper, the local buckling of shaft steelwork can be observed as a result of the significant reduction of the effective guide cross-section, due to intensive, long-lasting corrosion.

In the course of calculations according to steel structures standards [1], the classes of guide cross-sections were identified as a function of corrosion loss. Based on the cross-section class, section moduli were determined for various sizes of guides. The results of the analysis indicate that local instability is expected in guides at more than 50% corrosion loss. The degree of corrosion loss, at which the section's carrying capacity becomes less than the resistance of cross-section defined by the elastic section modulus, depends on the size of the guide. For the smallest guides (160 × 130) sensitivity to local buckling is present at 63% corrosion loss degree. For the largest profiles (260 × 180) the threshold is at 52%.

The results of the local stability code calculations were verified by FEM simulations for the 180 × 140 guide profile. Local bucking was indicated for profiles of 65% corrosion loss degree.

According to the former and current Polish regulations [2], if the maximum permissible degree of shaft steelwork corrosion was not decided on by other means, it should be equal to 50%. The rationale for setting a limit at this value was not given in the regulations or publications. Whether by coincidence or not, this is consistent with the presented analysis results, which show sufficient resistance to local buckling of guides profiles of the corrosion loss degree of 50%. For any higher limit value, a local buckling design criterion must be checked, in addition to the procedures specified in the regulations.

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