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ESTIMATION OF STRESS STATE IN A STEEL CRANE RUNWAY COLUMN DAMAGED BY CORROSION

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Abstract

Influence of corrosion is very unfavourable, especially when the constructions are exposed to weather in open space. Problem can be observed in thinning of the elements which leads to lowering bearing capacity. That thinning can be significant if construction was exposed to atmospheric conditions in long period of time. In this paper of the column for support of a crane runway that has been built more than 50 years ago and was made of rejected railroad sleepers was analyzed. Long period of exploitation and inadequate maintenance has led to damage to the structure and demand for the capacity assessment. Analyses of the column capacity were performed for states before and after influence of the corrosion, and based on that investigation load reduction ratio was determined.

***Key words**: crane railroad, column, corrosion, load capacity.*

1 INTRODUCTION

The company KOPEX MIN OPREMA Niš is former part of the MACHINE INDUSTRY of NIŠ, established more than 100 years ago. It is a significant manufacturer of various steel structures. Within its production area an open storage for sheet metal and profiles is situated, serviced by two bridge cranes operating on a 200 m long runway (Fig. 1). On demand of the company, a thorough diagnostics of the crane runway structure was performed in order to determine the present condition of the structure, revealing series of interesting details.

***Fig. 1** Crane runway structure and cranes - general view*

The steel structure of the crane runway was, according to unconfirmed data [5], erected in the period 1958-1960. Top edge rail level is 5800 mm (from top surface of the concrete foundation footing).

According to Report [2] base elements for column and beam assembling were rejected railroad (RR) sleepers joined into compound sections by welding. Reason for such solution was strong industrial progress of the young post-war state and chronic lack of steel products. Marks on the structure elements (former RR sleepers) show the manufacturing years (1915-1931), thus estimating their age at the time of inspection (2001) at 80-96 years. Manufacturers were „UNION“, „KROL“, „BOCHUM“, „G. H. H.“, and „KRUPP“.

Chemical composition of the base material was examined within the Report [2], and determined to correspond to steel Č0246 (by Yugoslav standards). However, mechanical properties of the steel, a much more important fact, were not determined, neither its weldability. Details of the section of column are given in Fig. 2, revealing an impressive ingenuity of the former design engineers, having a task to make a real innovation on the spot.

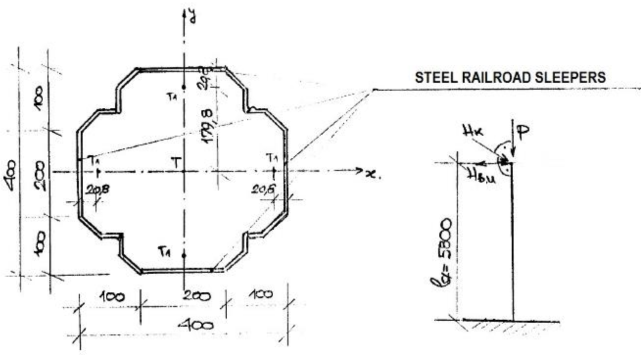

***Fig. 2** Cross sections and static scheme of the column assembled of 4 RR sleepers*

The crane runway and its bearing structure were reconstructed and enlarged several times. Reconstruction from 1978 encompassed removing three columns. Thereby a new, much longer span of the crane girder of 22.50 m was created. This new span was bridged using a new-built space truss, designed to accept vertical (self-weight and payload of the cranes) and horizontal loads (lateral force) from the cranes. Total length of the runway was also increased using I-sections.

The reconstruction from 1980 involved adding knee-braces on several columns to reduce pressure under footings. In addition, the runway was extended again, using I-sections. At early stage, the runway was used by one bridge crane (lifting capacity Q=5 t), but later another portal-bridge crane (Q=8 t) was added. Currently, both cranes are operating, separately or combined, depending of the production process needs.

Fig. 3 *Space truss over the transport platform*

Fig. 4 *Columns with added knee-braces*

2 THE STRUCTURE AT PRESENT

Visual inspection of the crane runway [3] revealed presence of corrosion, with different degrees from spot to spot. The lowest degree is on the runway beams (alteration of colour), slightly higher on lower parts of columns, (distinctive alteration of colour and occurrence of corrosion craters), and the highest on column base plates (peeling off and parting of layers).

Fig. 5 *Corrosion on structure elements*

Beside the visual inspection, an ultrasonic measuring of steel material thickness was done on some columns [4]. Here are presented three measured spots and results compared with nominal values (Table 1) [8].

Table 1 Ultrasonic measuring of steel material thickness

Column mark (local)	Nominal thickness (mm)	Min. measured thickness (mm)	Thickness reduction (%)
4D	10	9.3	7
5D	10	9.5	5
12D	10	9.3	7

3 STATIC ANALYSIS

Original static analysis of the structure was not available. However, Report [1] is treating bearing capacity of the crane runway, with some assumptions and limitations:

a) mechanical properties of the steel material were not determined;
b) static properties for beams and columns were taken as for new sections (RR sleepers), without corrosion loss;
c) static properties for beams were taken as for gross sections, (without rivet hole losses);
d) geotechnical properties of the soil were not determined.

Different load combinations and different positions of the two operating cranes were analysed. Resulting stresses and deformations, however, could not be compared with the allowable values since the steel material data were not disposable. As a summary of the Report [1], a new Report [2] was issued, giving strict limitations for crane operation, (allowable payload, and vicinity of two cranes).

Static analysis of the column shown in this paper is performed using finite element method and software FEMAP with NX NASTRAN. First, a model that corresponds to the structure before corrosion (after assembly) is analysed, and after that the model that corresponds to the structure after influence of the corrosion. Steel material used in model for analysis has properties shown below:

- type of material: *elasto-plastic, bi-linear*;
- Young's modulus: $E=210$ *GPa*;
- Poisson's ratio: $\nu=0.30$;
- yield criterion: *von Mises*;
- initial yield stress: $\sigma_y=235$ *MPa*;
- plasticity modulus: $E_p=0.01\ E=2.10$ *GPa*.

In the analysis surface finite elements of PLATE type with 4 nodes at corners [6] and with 6 degrees of freedom per node (Fig. 6) were used. Element size was ~20 mm. Welded connections were not included in model, so the refining of the mesh was not needed in connection areas. Thicknesses of the elements were equivalent to the profile thickness *(8 and 10 mm*). It was assumed that supporting of the column was throughout the gross area of the concrete base (Fig. 7), so in all the nodes of the base plate are applied PINNED NODAL CONSTRAINTS. Load was applied through a rigid plate that should conduct concentrated forces uniformly to the PLATE elements at the top of the column (Fig. 8).

Assumed forces at the top of the column [7] were:

- vertical force: F_z=-400 kN;
- lateral impact: F_y= F_z/10=40 kN;
- breaking force: F_x= F_z/7=57.143 kN.

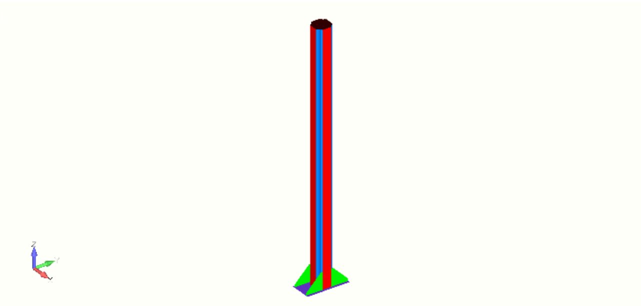

Fig. 6 *Model of the column – general view*

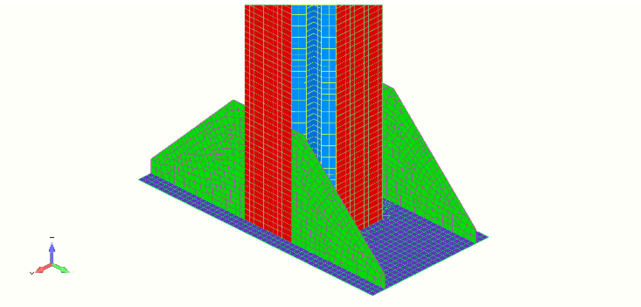

Fig. 7 *Detail of the base plate*

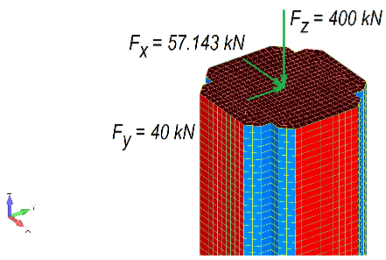

Fig. 8 *Detail of the rigid top plate with load*

Three types of analyses have been conducted: linear static analysis, buckling and nonlinear static analysis.

Linear static analysis is performed in order to validate the regularity of the model and to obtain results for further analyses. For application of the nonlinear static analysis load greater than the assumed ultimate value was adopted. In case of linear static analysis material and geometrical linearity was adopted, so the stresses obtained for such load are greater than the yield strength of the material, which should be prevented in reality.

Maximum values of stresses occur at the corner of the cross section of the column, at the joint between the column and the stiffener plate. In buckling analysis an eigenvalue is obtained giving the multiplier needed to reach the Euler critical force.

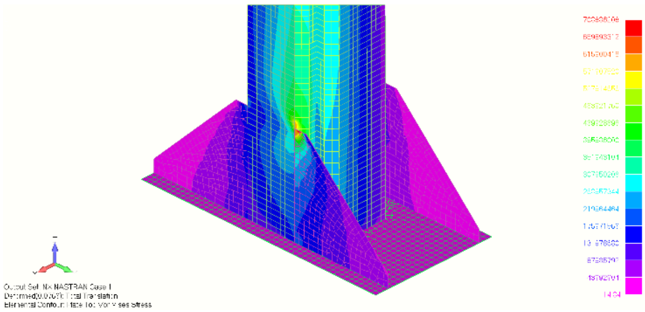

Fig. 9 *Linear static analysis,*
plate top von Mises stress; max value: 704 MPa

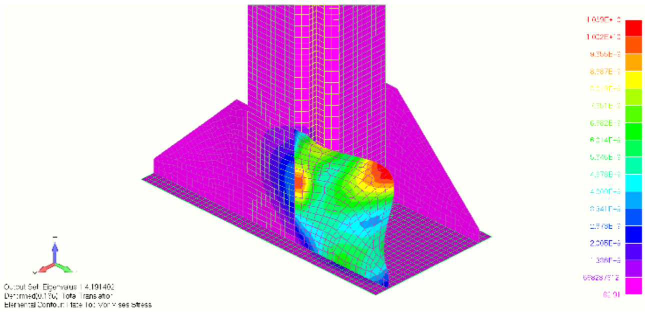

Fig. 10 *Buckling analysis, eigenvalue: 4.19*

From the contour presentation it can be observed that in case of reaching the critical force, buckling of the stiffener plate occurs, but the structure of the column itself remain stable. Critical force has value:

$$P_{kr,1}=4.19*400=1676\ kN \qquad (1)$$

Buckling analysis actually has only theoretical meaning, considering that it does not include great deflection effects and element imperfections. Its role is to provide starting values for possible stability limit state, and final results for behaviour of the structures subjected to load and its limit load capacity can be obtained only after geometrical and material nonlinear analysis.

For the conducting of the nonlinear analysis load was discretised in 20 increments (or Time steps). The convergence criterion was set displacement with tolerance of 10^{-5} m. Convergence path is shown in Fig. 11.

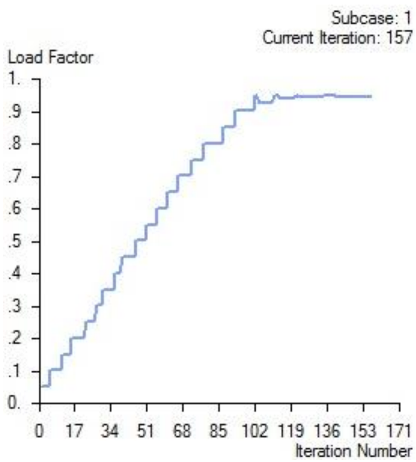

Fig. 11 *Convergence path*

The ultimate load factor obtained is 0.94375, which corresponds to the vertical load applied on column:

$$P_{f,1}=0.94375*400=377.5\ kN. \tag{2}$$

The following figures show stresses, deformations and zones of plasticization in case of critical load.

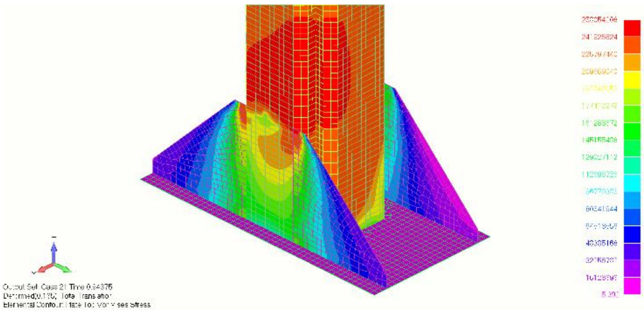

Fig. 12 *Nonlinear static analysis, plate top von Mises stress; max value: 258 MPa*

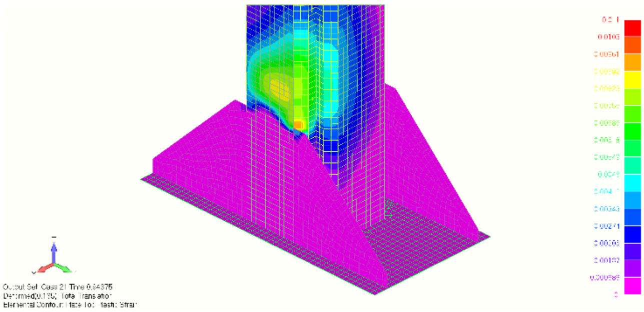

Fig. 13 *Nonlinear static analysis, plate top plastic strain; max value: 0.0110 m/m*

In case of a structure damaged by corrosion, element thicknesses of the structure are lower than nominal. In the previous section tests conducted for determination of the thicknesses of the elements forming the columns are described, and they revealed loss of the material of ~7%. Tests were performed on limited number of sample spots, and for the calculations are adopted average values of material loss. Visual inspection also showed appearance of corrosion crates on elements that were not taken in consideration. For calculation of the damaged construction, values given in Table 2 are adopted.

Table 2 Thickness of steel plates

Nominal thickness (mm)	Thickness reduction (%)	Thickness (mm)
8	7	7.4
10		9.3

The analysis was conducted for the corrosion damaged structure, as well as for the undamaged one. Results of the linear static analysis are presented as contour representation (Fig. 14). As in previous case, the stresses obtained by linear analysis are higher than the yield strength of the steel material. The highest stress value occurs at the edge of the cross section, at the joint of the column and the stiffener plate. In buckling analysis an eigenvalue is obtained, too, giving the multiplier needed to reach the Euler critical force.

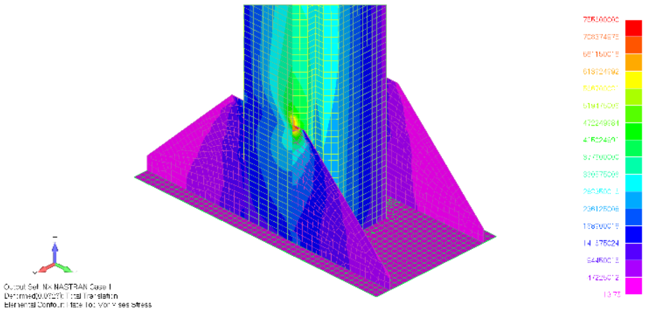

Fig. 14 *Linear static analysis, plate top von Mises stress; max value: 756 MPa*

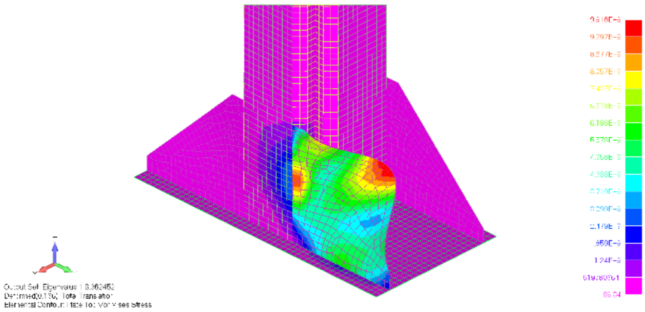

Fig. 15 *Buckling analysis, eigenvalue: 3.36*

From Fig. 15 one can see that reaching of the critical force, buckling of the stiffener plate occurs, again leaving the global structure of the column stable. Critical force has value:

$$P_{kr,2}=3.36*400=1344\ kN \tag{3}$$

Previous analyses show that the model with lower element thickness behaves as expected. Final results about the behaviour of the structure under the load and its ultimate load capacity can be estimated applying geometric and material nonlinear analysis. Parameters adopted for the nonlinear analysis of the corrosion damaged structure were equivalent as in the previous nonlinear analysis. Convergence path is shown in Fig. 16.

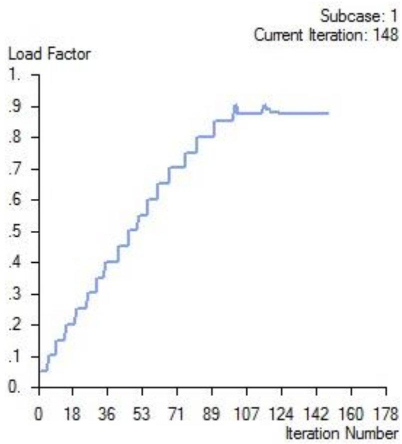

Fig. 16 *Convergence path*

The ultimate load factor obtained is 0.94375, which corresponds to the vertical load applied on column:

$$P_{f,2}=0.875*400=350.0\ kN. \tag{4}$$

The following figures show stresses, deformations and zones of plasticization in case of critical load.

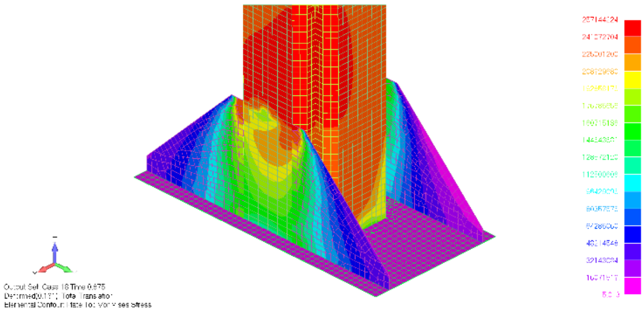

Fig. 17 *Nonlinear static analysis, plate top von Mises stress; max value: 257 MPa*

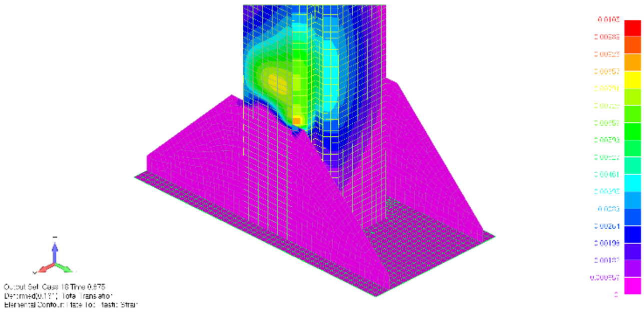

Fig. 18 *Nonlinear static analysis, plate top plastic strain; max value: 0.0105 m/m*

The obtained results are shown in Table 3. According to them one can observe that failure load for the column is lower for thinner walls, which is expected. Also, the stresses in the corrosion damaged column have higher values than for the undamaged column, in case of the same load.

Table 3 Results

Analysis	Value	Before damage by corrosion (analysis 1)	After damage by corrosion (analysis 2)
Linear	max von Mises stress [MPa]	704	756
	Euler's critical force [kN]	1676	1344
Nonlinear	max force [kN]	377.5	350.0
	max von Mises stress [MPa]	258	257
	max plastic strain [m/m]	0.0110	0.0105

The ratio between the stress values before and after the action of corrosion in case of linear static analysis is:

$$\sigma_{c,1}/\sigma_{c,2}=704/756=93.1\ \%, \qquad (5)$$

which represents the ratio of the load capacities calculated using linear elastic theory, too. The ratio of the maximal forces acting on column according to nonlinear theory is:

$$P_{f,2}/P_{f,1}=350.0/377.5=92.7\ \%. \qquad (6)$$

Critical Euler's forces are not the fact of importance when comparing the load capacity, because the critical force causes buckling of the stiffener plate only (Fig. 10 and Fig. 15). Values of stresses and plastic dilatations for the ultimate load in case of nonlinear analyses are approximately equal, so they are not governing for general conclusions of load capacity reduction. Based on the relations (5) and (6) one can observe that the ratios of the maximum forces according to linear and nonlinear static theory are very similar. That indicates the possibility to conduct evaluation of the structure stress state by determination of the force until value reaches the allowed stress level or yield point. Although such analysis is performed using linear static theory, sufficient accuracy for practical use can be reached.

4 CONCLUSION

This paper reveals real life cycle of one steel structure, and it is typical for our region. At the time of its creation, owing to shortage in material resources, design engineers had to find non-standard technical solutions that could be easily called an innovation [8]. Further theoretical researches could be conducted on models with SOLID elements that would better describe the structure, and introduce normal stresses with direction perpendicular to the elements of the plate. Modelling of the welded connections is generally difficult with plate finite elements. In this paper the welded connections are modelled using common nodes between adjacent elements. When for modelling solid elements are used, that deficiency could be eliminated with appropriate refining of the finite element mesh in the connection zones.
The diagnostic process done for this concrete structure puts on an unavoidable conclusion: with such number of unknowns, one could not guarantee further safe exploitation of the structure. Nevertheless, the ultimate curiosity is that the cranes and runway structure are still operating. Obviously, in this case the material denies engineering logic, but for how long, stands as an open question [8].

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