Structural Mechanics

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FEM 3D analysis of RC frame foundations of rotary cement kiln

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Summary

Results of 3D finite element analysis of damaged foundations for cement tubular oven are presented in a paper. The foundation consists of four RC frames modeled for analysis using solid FE with 24 d.o.f. each. Serviceable and temperature loads, as well as loads from pre-stressing are taking into account. The frames, primary designed as 2D structures, are sensitive for out-off-plane and temperature loads. The additional effects of stresses from these loads should be taking into consideration during FEM analysis.

KEYWORDS: rotary cement kiln, RC foundation, spatial numerical model, FEM analysis

1. DESCRIPTION OF THE FOUNDATION

The support structure of rotary kiln under consideration was built in the early 1950s. It consists of four reinforced concrete solid frames spaced at equal intervals. The lowest frame is denoted by number 1 and the other by respectively 2, 3 and 4.

As part of rotary kiln retrofitting, frame 4 was to be torn down and an additional frame was to be placed next to frame 1 whereby the latter practically would not carry any loads. The other two frames: frame 2 and frame 3 were to continue to be in service and be subjected to additional loads. Because the two frames were considerably damaged it was necessary to determine their serviceability.

The foundation named frame 2 had been made as an RC frame embedded in the foundation plate. A static scheme with one column in the form of a rocker with both its ends articulated had been adopted. The other column had been rigidly fixed in the plate. The frame's spandrel beam had been thermally protected with an about 20 cm thick concrete overlay. In the course of its service considerable horizontal displacements of the kiln's foundation were observed. Therefore in the early 1980s the structure was strengthened by tensioning. The rigid-rigid column, the frame's spandrel beam and the joint connecting the members were subjected to tensioning.

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The bowstrings were made from ϕ5 mm strings combined into L1+6+12+18 ropes, with two ropes running on each side of the foundation and concreted.

The technical condition of frame 2 varied. The foundation plate was found to be in good condition. The foundation had not undergone settlement and was undamaged. The columns were in satisfactory condition. The concrete reinforcement cover was found not to have loosened or cracked. The frame’s spandrel beam was in bad condition. It was found to have sagged by 3-4 cm. The spandrel beam’s undersurface was cracked and its reinforcement cover was loose over a considerable area. When the loosened cover was removed, reinforcement in the form of superficially corroded #35 square bars was revealed. Also the spandrel beam’s entire top surface was found to be corroded.

The foundation named frame 3 had been built as a stiff frame, considerably long (8.6 m) along the kiln’s axis, embedded in the RC plate. There were two platforms: one for a motor and one for the kiln’s rotary bearing on the frame. The top surface of the frame was thermally protected with a 20 cm thick concrete overlay. The foundation plate was in good condition: no excessive settlements or damage were found. The columns were in satisfactory condition. They were uncracked and their reinforcement cover was found not to be loose. The frame’s spandrel beam was in bad condition since it had been subjected not only to considerable service loads and temperature impacts but also to the destructive action of grease escaping from the motor driving the rotary kiln. Lubricant leaks were visible on the spandrel beam plate’s undersurface.

2. FOUNDATION MATERIALS’ STRENGTH PROPERTIES AND EXPLOITATION CONDITIONS

2.1. Concrete

On the basis of the fragmentary documentation which survived in the cement plant’s archive it was found that the design strength of the foundation concrete had been assumed to be $R_w = 160$ kG/cm^2 which corresponds to current concrete grade B12.5-B15. According to non-destructive test results, the concrete in the frames could be classified as class B10 at the most. Therefore concrete parameters: $R_{bb} = 4.8$ MPa and $R_b = 5.8$ MPa were assumed for further calculations.

2.2. Reinforcing steel

In the surviving fragment of the design, smooth reinforcing steel ϕ20, ϕ30 and ϕ35 with allowable stress $\sigma_d = 1200$ kG/cm^2, corresponding to a design strength R_a of about 106 MPa, was specified. The lower steel strength had probably been adopted in view of the considerable diameters of the structural reinforcement.

2.3. Foundation tensioning

The spandrel beam, the column and the joint of frame 2 had been tensioned using double steel ropes, made from $\phi5$ mm strings forming a steel rope of type L1+6+12+18, running on both sides of the foundations. The nominal rope breaking force of 1130 kN had been assumed. The ropes were tensioned with a force amounting to 60% of the nominal force. Thus the tensioning force had been S = 2700 kN. From the way in which the ropes were secured it one could be concluded that the spandrel beam had been tensioned above the neutral axis, as shown in Figures 1 & 2.

2.4. Exploitation temperature

Considering that the concrete overlay protecting the foundation against temperature effects was 20 cm thick the foundation had been assumed to be subjected at its surface to a temperature field of +40°C, decreasing at every 10°C/m towards the column’s base.

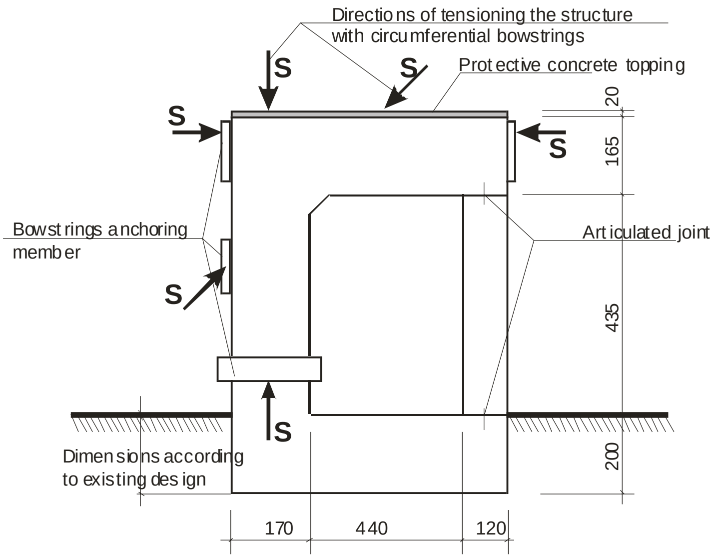

Figure 1. Frame 2. Structural and tensioning scheme

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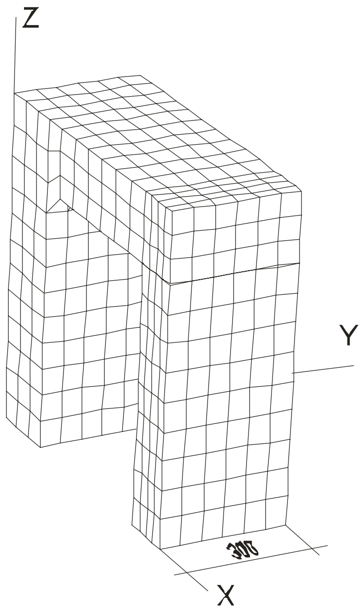

Figure 2. Frame 2. Division into finite elements

3. ANALYTICAL MODELS OF FOUNDATIONS

Program MES DIANA was used for the numerical analysis [4]. Linear physical and geometric relations were assumed for the material and the structure. Isoparametric 3-D finite elements HX24L, described by eight nodes, were used to build the models (Figure 3). In order to obtain more precise results a 3×3×3 Gaussian points integration scheme (triangles in Figure 3) was adopted.

In such finite elements stresses σ_{yy} and strains σ_{zz} are constant in direction x and they can linearly change in directions y and z. Stresses σ_{yy} and σ_{zz} and strains σ_{yy} and σ_{zz} respectively in directions x, y and z behave similarly. A uniformly distributed load or a load linearly variable along each edge can be applied to each wall of the finite element. The latter can also be loaded with temperature which may be different in each of its nodes. The displacements and deformations of the frames are given for the nodes while the stresses are given for the finite element's centre of gravity.

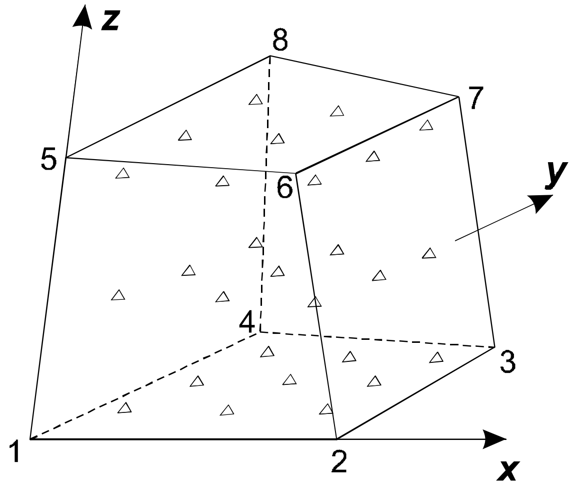

Figure 3. FEM element HX24L

The division of frame 2 model into finite elements is shown in Figure 2. 1022 nodes and 640 brick elements were used to create the model. The articulated joint between the spandrel beam and the rocker column was modelled using short articulated-articulated bars.

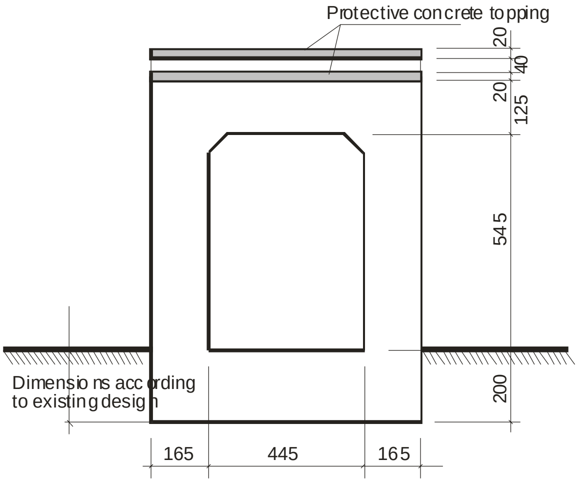

Figure 4. Frame 3. Structural scheme

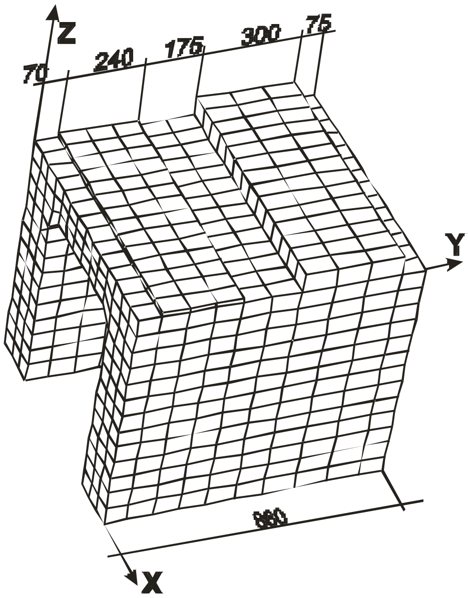

Figure 5. Frame 3. Division into finite elements

The model of frame 3 was created using 1660 nodes and 1104 brick finite elements.

The following load schemes were adopted for frame 2:

- the foundation dead load,
- the characteristic rotary kiln load,
- the design rotary kiln load,
- the frame tensioned with bowstrings,
- loading with a temperature field.

The following load schemes were adopted for frame 3:

- the foundation dead load,
- the characteristic rotary kiln load,
- the design rotary kiln load,
- loading with a temperature field.

The numerical 3-D model calculations were verified for a static flat bar scheme.

4. ANALYSIS OF RESULTS

The check of the deformations of frame 2 confirmed the latter’s susceptibility to horizontal loads. The total horizontal displacements of the spandrel beam, calculated in the elastic phase, exceeded 5 mm. Taking into account material plasticization, deformations about 2.5 cm were yield, i.e. above the permissible values.

The results of the numerical analysis, in the form of σ_{xx} and σ_{yy} graphs for frame 2 are shown in Figure 6 and for frame 3 in Figure 7. In both structures the stresses in the elements lying on the spandrel beam's edge and in its middle (along axis Y) were analyzed. In addition, stresses in the region of the elevated spandrel beam under the motor driving the kiln were taken into account in frame 3. The results are presented for the design service loads, the tension of frame 2 and the temperature increase load.

The total force tensioning the undersurface of the spandrel beam in frame 2 was 3326.4 kN. The load-bearing capacity of the reinforcement with a surface area as in the design was to 2259 kN, which means that it was insufficient to carry the loads. Similarly in frame 3, the total force tensioning the spandrel beam's undersurface was 3345 kN, which means that for the same assumed reinforcement it exceeded the spandrel beam's load-bearing capacity.

An analysis of stresses σ_{xx} in the spandrel beam of frame 2 shows only a slight influence of the temperature load on the degree of strain of the structure. The stresses due to an increase in temperature amount to merely 10% of the service loads, which confirms that lowly over-rigid structures are resistant to this kind of load.

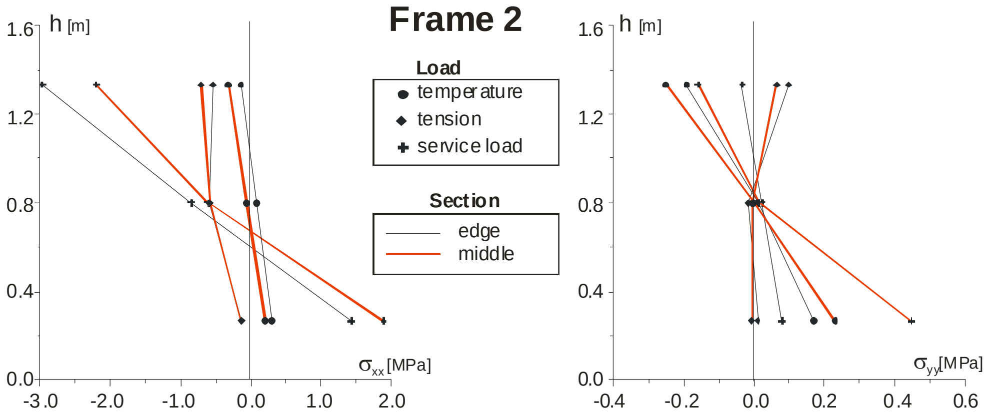

Figure 6. Frame 2. Stresses σ_{xx} and σ_{yy}

The effect of the stresses produced by tensioning was somewhat stronger. But due to the point of application of the steel ropes in the spandrel beam the expected reduction in tensile stress in the spandrel beam's bottom zone was slight (below 10%) while the deflection of the spandrel beam increased. The increase in tensile stress σ_{yy} in the middle of the spandrel beam thickness was significant: considering that the design tensile strength is 580 kPa it may explain the appearance of cracks propagating perpendicularly to the kiln's axis. This means that the spatial aspect of the behaviour of the spandrel beam should have been taken into account in the design.

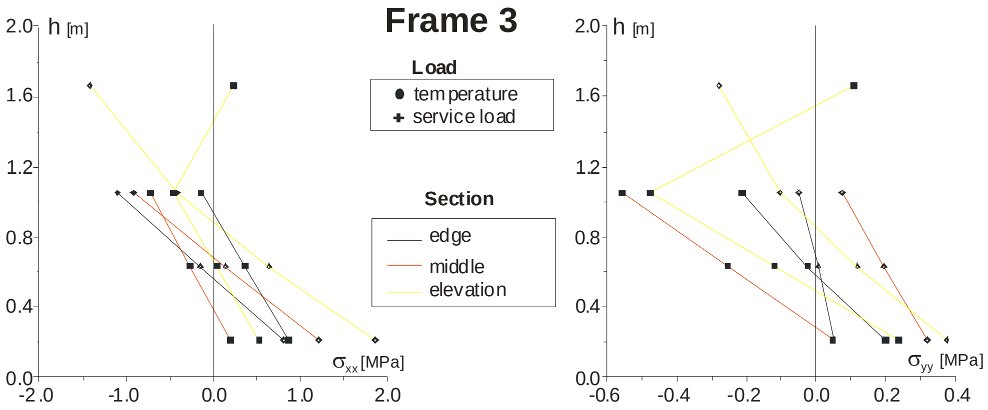

Figure 7. Frame 3. Stresses σ_{xx} and σ_{yy}

In frame 3 the temperature load impact was much greater. Stresses σ_{xx} produced by temperature were nearly as high as the ones due to the design service load whereas stresses σ_{yy} exceeded them significantly. Interesting was the appearance of tensile stresses in the spandrel beam's top zone thickened in order to mount the motor. The stresses did not exceed the concrete's tensile strength but as a result of the long-lasting action of temperature they might cause cracking in and damage to the spandrel beam's top surface.

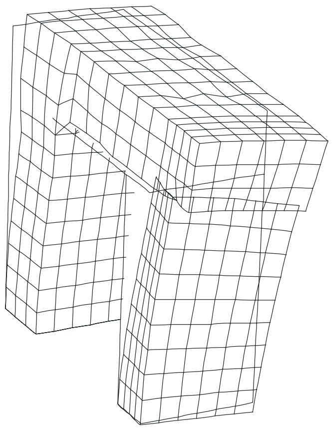

Figure 8. Deformation of frame 2

Similarly as in frame 2, the share of tensile stresses σ_{yy} (acting along the kiln's axis) produced by the service loads was found to be considerable. The stresses were responsible for the appearance of cracks perpendicular to the rotary kiln's axis.

Figure 8 shows the deformations of frame 2 under the service load, the tension and the temperature field. The deformations of frame 3 under the service load and the temperature field are shown in Figure 9.

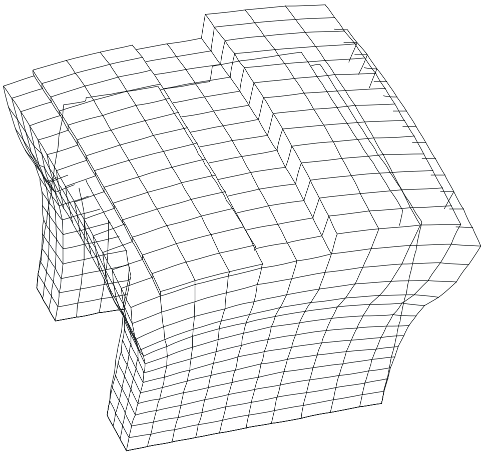

Figure 9. Deformation of frame 3

5. CONCLUSIONS

From the numerical analyses the following conclusions were drawn:

The load-bearing capacity of the spandrel beams in the investigated rotary kiln support frames was insufficient to carry the design loads.

The originally adopted static scheme in the form of a frame with one rocker column was susceptible to horizontal displacements which might increase if disturbances in the operation of the kiln occur or if the kiln components would be nonaxially assembled.

The cracks in the spandrel beam of frame 3, running perpendicularly to the kiln's axis, were the result of the spandrel beam's spatial work neglected in the original design.

When designing rotary kiln support frames it should be taken into account the increase in stress, due the thermal field, particularly when the static scheme should be changed for one with two rigid columns.

The 3-D frame model calculations have confirmed the fact that tensile stresses in the column and in the spandrel beam were concentrated closer to their axes and not at their outer surfaces. Therefore additional reinforcement should be provided to carry these stresses.

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