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ANALYSIS OF THE EFFECT OF FIRE CONDITIONS ON THE BEARING CAPACITY OF PRESTRESSED CONCRETE GIRDERS

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1. Effect of the fire temperatures on the bearing capacity of the prestressed structures

The performance of the prestressed structures under the fire conditions is of a very combined character, dependant upon numerous factors. The objections against application of these structures, under the circumstances of the increased fire danger, are connected especially with the properties of steel, applied to reinforce the prestressed concrete.

The high - quality steel, artificially hardened, changes its properties at the relatively low temperatures, ranging from 300 to 400 ° C and these temperatures shall be recognized as critical for the prestressing strings. Exceeding of these temperatures might cause the vanishing of the hardening effects, i.e. the significant plastic strains of steel, causing in consequence the fading of the initial stresses and the worse bearing conditions. The next objection concerns the effect of high temperatures on the development of the rheological phenomenon's, causing an acceleration of relaxation and of creep of the reinforcement steel.

As far as an application of high - strength concrete in the prestressed structures is concerned, concrete loses a part of its compressive and tensile strength under an influence of high temperatures and indicate a significant drop of the coefficient of elasticity, what encourages the appearance of high deflections.

The above objections, concerning the prestressed structures, discourage their application, however, exclusively under the conditions of an increased fire danger. On the other hand, under the conditions of an average, or even of a slightly increased fire danger, the above mentioned structures can be applied. An experience has proved that the performance of the prestressed structures, under the conditions of average fires, is good, in general. Within the known cases of the more serious fires, only a small percent of fires exist, during which a damage and a collapse of the structure has been caused by the defect of the prestressed concrete. Most frequently, these are the reasons connected with incorrect

elaboration of the structural details, examples: incorrect support of the items, lack of protection of the anchorages, improper filling of the post - tensioned prestressed concrete channels, incorrect performance of expansion joints, lack of perpendicular reinforcement etc.

The prestressed concrete indicates, however, certain advantage in comparison with the reinforced concrete, due to the tightness of covering, what has been caused by the lack of cracks in concrete. The Dutch tests of the prestressed floors, carried out in Heerlen, are very interesting in this respect.

The temperature at the bottom surface of the prestressed beams was 710 °C. After cooling, a cable has been uncovered in the middle of the beam, length 1.5 m and it has been found out that the cement injection has covered the wires very tightly. Few of the wires were tested parallelly with the wires which have not been subjected to the high temperature.

No significant changes in the properties of steel have been found out, which proves that the critical temperature of the reinforcement, ranging from 300 up to 400 °C, has not been exceeded.

A progress exists, as far as the manufacturing of steel, sensitive to high temperatures, is concerned. This steel indicates a reduced creep and relaxation, what encourages the broader application of prestressed concrete structures. From this point of view, monitoring and studying of an effect of fire conditions on the prestressed concrete structures seems very interesting.

A case to be presented concerns the post - fire tests of the post - tensioned prestressed concrete girders of the roofing of the machinery house in the power / heating plant.

The case is especially interesting due to the fact that the fire took place at the moment when the pipes, enclosing the strengthening cables of the structure, have still not been filled with the cement / water suspension. This fact created a possibility of the precise measuring of the effective prestressing force in these cables and of calculating its losses.

The purpose of the studies was to determine the range of decrease of the actual effective prestressing force from the side of the external cables, due to an accelerated steel relaxation, resulting from an increased temperature.

2. The reason and the development of fire

The blow - up of a gasket in a flange of an oil pipeline was a reason of a fire in the machinery house. The sprinkling turbine oil, ignition temperature: 204 °C, was ignited from the neighbouring unisolated devices, the temperature of which was about 400 °C.

The oil was on fire on the level of the floor of the machinery house in a tank below the turbine and on the devices. The fire covered an area of above 100 m².

The temperature of the fire on the level of the turbine was 1500 °C approximately. According to the opinion of the fire brigades the temperature on the level of the post-tensioned prestressed girders and of the roof was 300 °C approximately and was subjected to the continuous changes.

A rapid increase of the temperature took place over the first 10 minutes of the fire. After the commencement of fire fighting action, the temperature was slowly decreasing. The maximum temperature, with certain changes, has been lasting for 30 minutes approximately. During the fire the flames reached the level of the girders structure.

3. Description of the bearing structure of the machinery house

The hall, in which the fire started, is a single - bay building, lay - out dimensions: 27.0 by 192.0 m.

The RF concrete columns constitute the bearing structure of the hall; the truss post-tensioned prestressed concrete girders with a curve bottom flange (Fig. 1), made of precast items, are supported by the columns. The height of the columns from the side of the windows is 2231 cm, and from the side facing the boiler house - 2380 cm (measured from the cantilevers by which the girders are supported). The distance between the columns is 6 m. The girders support the roof panel slabs, dimensions: 149 x 579 x 30 cm. The bottom flange of the girders is prestressed with five internal cables (Ø 12) and strengthened (due to the significant strains and cracks) with two additional external cables (Ø 24), located along both sides of the bottom flange of each girder. The external cables are enclosed in the water pipes dia 70/3 mm. A telescope connection is located in the middle of the length of the pipe (Fig. 2).

Just before the fire, the external cables have been prestressed and anchored in the steel anchorages (Fig. 3). During the fire, the prestressed cables were in order, enclosed within the steel pipes, without filling them with the anticorrosion material: cement / water suspension. Therefore, a direct contact of one or two wires of each cable with the pipes could take place.

4. Damages to the structure of the post-tensioned prestressed concrete girders, found out during the post-fire inspection

An inspection of the structure indicated the traces of fire on the enclosure pipes of the external cables of the girders. In the middle of the span of the girders the superficial

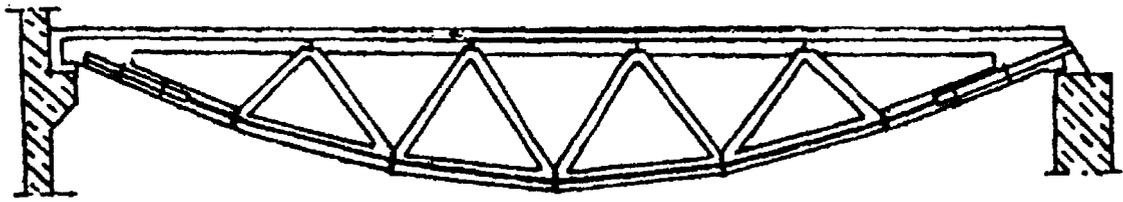


Fig. 1. Scheme of a girder

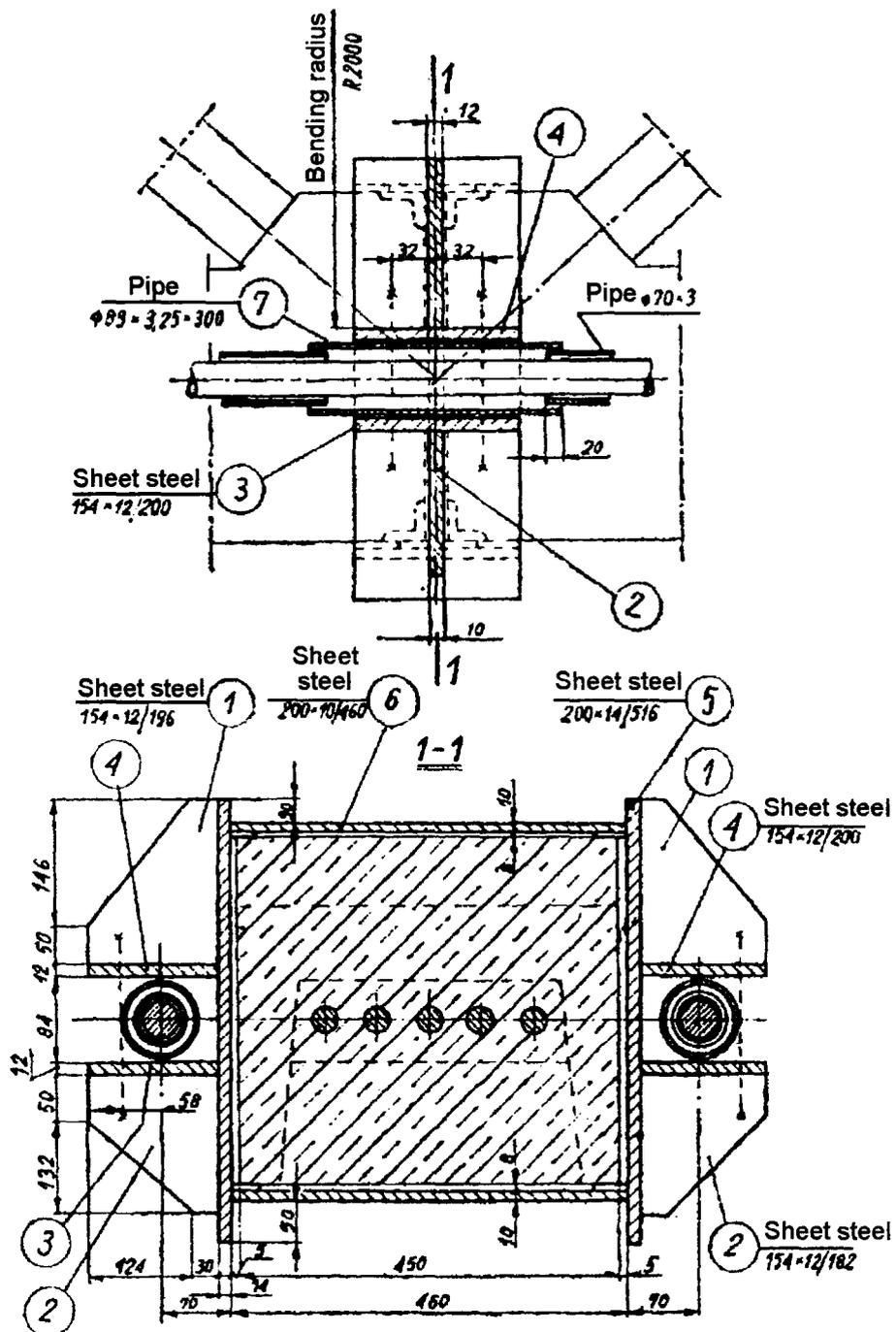


Fig. 2. Structure of suspension of external cables

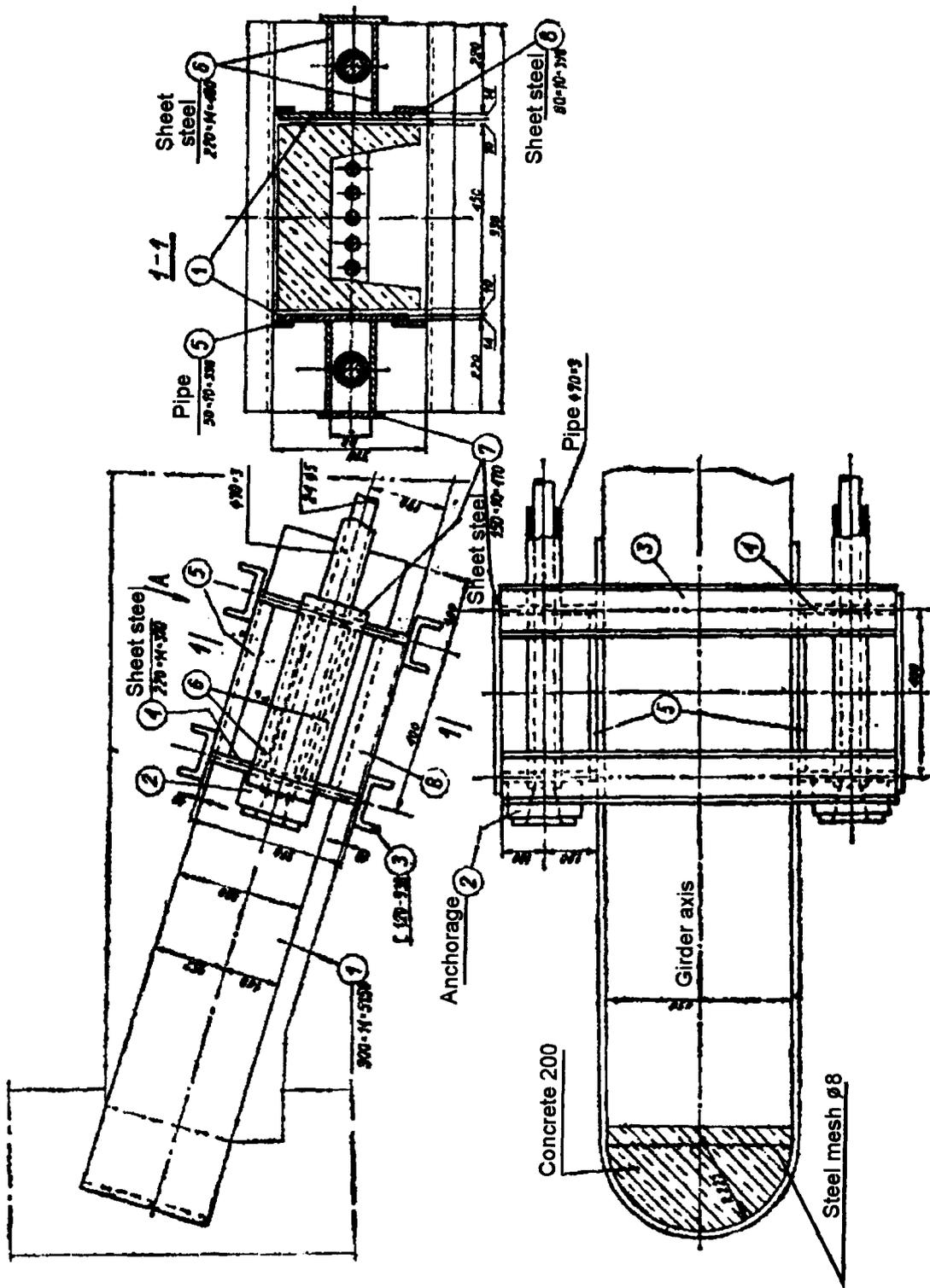


Fig. 3. Resistance structure of external cables

layer of paint was peeled and the primary layer of minium was damaged. At the ends of the girders only the local damages to the superficial layer of paint were visible (bubbles).

Under an influence of increase of the ambient temperature, the enclosure pipes were subjected to the thermal elongation. Due to the stable fixing of the pipes in the items of the anchorages, the above mentioned elongation could be exposed exclusively by the mutual displacement of the both branches of pipes within a telescope connection, located in the middle of the span of the girders.

After the fire has been extinguished, a shrinkage of pipes took place, which was exposed as a repeated mutual displacement of the branches within the telescope connection. The value of the thermal elongation of the pipes could be determined by measuring the smokeless section within the telescope connection. This elongation was always higher in the pipe from the side of the fire focal point and its value was following:

girder No. 14 - 40 mm and 28 mm

girder No. 13 - 20 mm and 13 mm

girder No. 12 - 16 mm and 11 mm

girder No. 8 - 10 mm and 6 mm

On the bottom flanges of the post - tensioned prestressed concrete girders, which were located within the fire zone, the signs of cracking were visible. The cracks appeared on the bottom parts of the vertical walls of the tray items and were caused by the nonuniform heating of the cross - section of the flanges (the walls of the down - oriented tray items were heated more intensively), and in further consequence, by arising of new additional reactions in the points of fixing of the cross braces and of the bending moments in the bottom flange. These cracks were formed during the heating of the items and were closed after the fire as a result of action of the prestressing force in the internal and external cables and as a result of disappearing of the bending moments. The damages to the concrete covering paint are the traces of these cracks, especially visible on the background of the smoked surfaces of concrete.

In the girders No. 14 and No. 15 the cracks appeared in the middle sections of the bottom flanges and crossed the total thickness of the walls of tray items, reaching the bottom of tray items. The distances between the cracks ranged from 20 to 40 cm. On the sections close to the middle sections of the bottom flanges of the girders, the cracks appeared exclusively in the vicinity of the stiffening ribs and especially on the walls from the side of the fire focal point. In the next girders (No. 13 and No. 16) the cracks appeared sporadically in the middle sections of the bottom flanges and exclusively in the walls of the tray items, from the side of the fire focal point.

On the basis the traces of the mutual displacement of the enclosure pipes in the middle of telescope connection and on the basis of the other accompaning phenomenons, as

well as on the basis of the estimation by the Fire Brigade it has been assumed that the temperature of the enclosure pipes reached 300 °C.

Taking into consideration an enclosing function of the pipes and of the trapped layer of air it seems possible that the temperature of cables has not exceeded 250 °C.

5. Testing of the effective prestressing forces in the cables after the fire

The tests were carried out on the girders No. 13 and No. 14, which were in the direct range of the fire and on the girders No. 29 and No. 30, which were the most remote from the fire focal point and were treated as a comparative test. The measurement of the actual prestressing forces in the external cables was possible thanks to a special structure of the anchorage blocks, on which an external thread has been performed. Since the cables have not been injected so far, a special prestressing / measuring apparatus was designed and constructed, by means of which the measurements were carried out (Fig. 4).

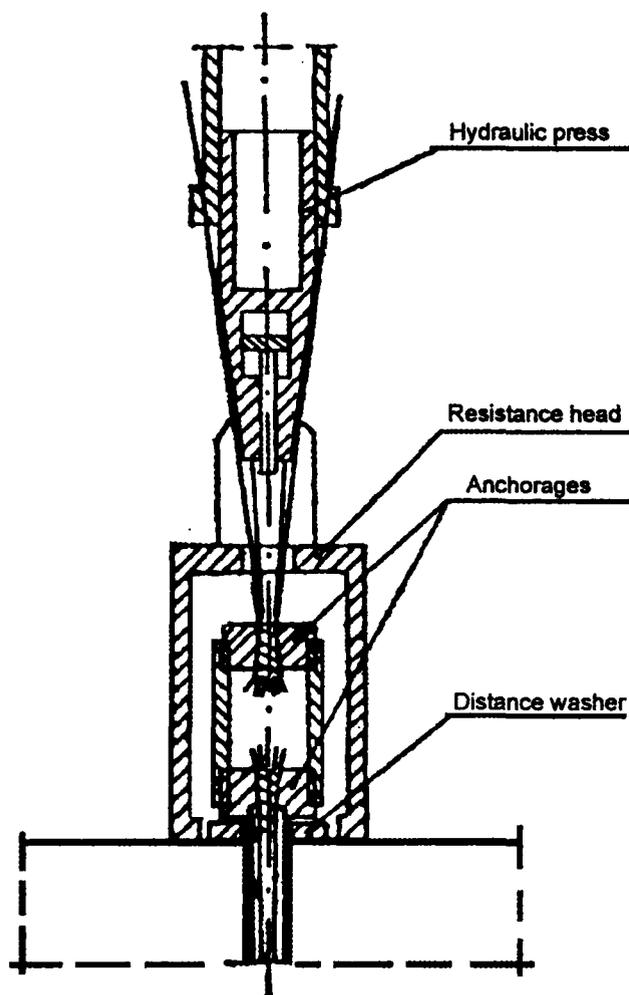


Fig. 4. Scheme of the apparatus for measuring forces in cables

The apparatus is composed of the resistance part, comprising: the external anchorage supported by a steel sheet of the cable fixing truss joint, the handling part wound on the thread of the block, the hydraulic servo. The displacements of the pipes in relation to the structure of the cable fixing truss joint were measured by means of the sensors fixed to the enclosure pipes.

The value of the force existing in the cables was evaluated on the basis of oil pressure, measured on the manometer of the pump at the moment of desintegration of the anchorage from the resistance steel plate, i.e. at the moment when the total cable force has been taken over by the hydraulic servo. The moment was defined by three methods:

- a) taking into consideration the moment of the drop in velocity of pressure increase on the pump manometer,
- b) taking into consideration the moment of appearance of the crack between the anchorage block and the steel plate of the resistance structure, defined by the position of the clearance gauge, 0.3 mm thick,
- c) by the measurement of the displacements of the enclosure pipe in relation to the resistance structure of cables by means of the sensor.

6. Losses of the prestressing force in cables

The prestressing force in cables, called herewith the effective force, is not equal to the initial force due to the losses, resulting from numerous reasons. These losses have been called „the prestressing force losses”. The precise determination of its value is of decisive importance for the performance of the prestressed structure. The losses of the prestressing force can be divided into:

- a) immediate losses,
- b) rheological losses.

Both the immediate losses, as well as the rheological losses cause stable changes of the prestressing force. The immediate losses arise during execution of prestressing. The rheological losses depend upon the basic rheological properties of materials. The determination of the rheological properties depends upon establishing the physical limits of creep and relaxation, an impact of aging of a material, response to the stress corrosion and of the stable tensile strength. The rheological losses comprise, therefore, the changes of the prestressing force as an impact of shrinkage and creep of concrete, creep and relaxation of prestressing steel.

However, this is to emphasize that the difference between both the phenomenos concerned is not so clear, in fact, as it has been assumed by their definitions. Actually, both phenomenos take place simultaneously and are strictly combined between each other.

In case of prestressed structures the relaxation takes place, which is reduced by the retarded strains of concrete.

However, the process of steel relaxation takes place relatively quickly; therefore, the changes to the length of the structure can be omitted practically.

As we know from the field tests and from the laboratory tests, the prestressed reinforcement indicates the stabilization of the relaxation process within a limited period of time. For the hard steel this period ranges from few to several days.

An analytic formulation of the relation between the drop of stress in the prestressing reinforcement and the relaxation is rather difficult. For example, according to Ros, the drop of stress can be expressed by the following formula:

$$\Delta\sigma = E\varepsilon_p = E\left(-\frac{\sigma}{0.45\cdot Q_{r0.2}} - 1\right)^2 [\text{‰}], \quad (1)$$

where: ε_p - creep strain;

$Q_{r0.2}$ - yield point of reinforcement steel;

σ - initial stress in steel,

$\Delta\sigma$ - drop of stress in steel,

E - coefficient of elasticity of steel.

The logarithmic curves have been adopted for the purpose of describing the drop of stress resulting from relaxation. For the Polish steel $\varnothing 2.5$ mm S. Kajfasz introduced the following formula:

$$\Delta\sigma = C(\ln t - \ln t_0) + A, \quad (2)$$

where: C and A - constant parameters determined on the basis of tests concerning relaxation of steel at the given initial stresses;

t - time in days;

t_0 - 5 minutes (start of measuring the stress drops).

During the tests it has been found out that the yield point $Q_{r0.2}$, at which the rapid increase of relaxation takes place, is a critical point. The total losses of the prestressing force, resulting from relaxation and creep of steel, are calculated according to the following formula:

$$N_{V5} = \left(0.13 \frac{\sigma_w}{R_{vk}} - 0.05\right) N_w, \quad (3)$$

where: N_{V5} - losses of force resulting from creep and relaxation;

σ_w - stress in strings without taking losses into consideration;

R_{vk} - characteristic strength of prestressing steel. In case of high - quality steel, equal to the tensile strength, guaranteed by the manufacturer;
 N_w - prestressing force after taking the immediate losses into consideration.

The technical limit of relaxation is of essential importance for designing the prestresses structures. The technical limit of relaxation means the stress at which a defined drop of stress (0.5 - 3.0 %) takes place within a given period of time. The technical limit of relaxation is indicated by testing relaxation under a normal temperature (20 ° C). The strength properties of steel change together with the changes of temperature.

A higher temperature, increasing the thermal vibrations of the atoms, enables arising of the stable strain for such a state of stress and such a time, for which this state would have not been achieved in normal temperature.

It means that together with an increase of temperature the technical limit of relaxation decreases; on the other hand, together with the plasticity of steel, the velocity of relaxation increases proportionally to the increase of the velocity of creep:

$$V_r = -EV_p \quad (4)$$

where: V_r - and V_p - velocities of relaxation and creep.

In this case, we can speak about an accelerated relaxation.

At the moment of measuring of the effective prestressing force in the external cables of the girders, the losses resulting from the relaxation of steel have already taken place to large extend. In the girders located in the focal point of the fire one could expect the increased losses resulting from the acceleration of steel relaxation. On the contrary, it has been found out that the total losses of the prestressing force in the girders subjected to the fire were the same as the losses in the girders remote from the fire focal point.

The table below shows the values of forces calculated on the basis of the obtained parameters of the prestress force of the cables and the values of forces established on the basis of measurements, carried out on the girders after the fire has been set off.

Girder and cable No.	Prestressing force before fire	Force measured N	Difference in forces N	Loss %
30/1	346 000	290 000	56 000	16,2
29/2	346 000	290 000	56 000	16,2
13/1	376 000	343 000	33 000	8,8
13/2	376 000	336 000	40 000	10,6
14/1	356 000	301 000	55 000	15,4
14/2	356 000	301 000	55 000	15,4

7. Conclusions

1. The above studies indicate that at the temperature up to 250 °C the increased relaxation of steel and the combined decrease of the prestressing stress do not take place. As a result, the total rheological losses in cables subjected to the impact of fire were similar to the losses in cables of girders remote from the fire focal point. At the above mentioned temperature both the structural changes as well as the changes of the strength properties of steel do not take place. Therefore, there is no danger of reduction of safety coefficient as far as a damage of cables is concerned.
2. The temperature achieved by the prestressing cables is dependant upon the protection of these cables in the cable channels. In our case, the cables enclosed in the steel pipes reached the temperature lower than the enclosing protection pipes. One may assume that a tight (without cracks) concrete covering, together with the careful injection of the cable channels will constitute a proper cable protection and that the difference of temperature between the external surface of the girder and of the cables will be much higher. This might be supported by the increased cable enclosures (2 - 2.5 times bigger than the section of strings), the mixtures applied to injection, improving the enclosure of strings, example: resin concrete.

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TEMPERATŪROS SĄLYGŲ ĮTAKOS IŠ ANKSTO ĮTEMPŲ GELŽBETONINIŲ SANTVARŲ LAIKOMAJAI GALIAI ANALIZĖ

Z.Bednarek

S a n t r a u k a

Analizuojama temperatūros įtaka iš anksto įtempimų gelžbetoninių konstrukcijų darbui. Parodyta, kad temperatūra iki 250°C padidina armatūros įtempimų relaksaciją, tačiau bendri įtempimų nuostoliai nežymūs. Tyrimai parodė, kad bendri reologiniai įtempimų nuostoliai vijose, tiesiogiai paveiktose ugnies, buvo beveik tokie patys, kaip vijose, kurios buvo nutolusios nuo ugnies židinio. Temperatūros įtaka armatūros įtempimų pokyčiams priklauso nuo jos betono apsauginio sluoksnio ir armatūros kanalo. Armatūros vijos, išdėstytos kanaluose su metaliniu apvalkalu, buvo veikiamos žemesnės temperatūros negu be jų. Parodyta, kad įtakos turi ir kanalų užpildymas.