INFLUENCE OF HIGH TEMPERATURE ON STIFFNESS OF R/C BEAMS

Experimental stiffness comparison of tensioned or compressed zone of the cross-section

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Abstract

The paper presents results of experimental research whose main topic was determination of stiffness reduction in bent reinforced concrete beams in two cases: when only tensioned or only compressed zone was exposed to high temperature. Twenty four reinforced concrete beams with rectangular cross-section were prepared for the experiment. Eight groups of beams were prepared in total: 2 reinforcement ratio - 0.44 and 1.13% x 2 levels of load - 50 or 70% of destructive force ensuring the constant value of bending moment in the centre part of heated beams x 2 diagrams. Three beams were used in each group. Significant cross-section stiffness reduction was observed in beams where the tensile zone was heated. This was due to considerable elongation of the bars where the steel load elongation summed up with the free thermal strain. In beams where the compressed zone was heated the stiffness reduction was observed only after the time where the tensile zone heated cross-sections were already destroyed.

Keywords: reinforced concrete beams, stiffness, fire, high temperature

INTRODUCTION

Both load capacity and stiffness of reinforced concrete elements exposed to fire conditions are reduced due to decrease of the mechanical characteristics of concrete and reinforced steel [1, 2]. Sufficiently long exposure of determinable static elements to high temperature resolves in their destruction. In case of indeterminable static structures – leads to a secondary static setup or redistribution of internal forces [3-7].

In bent multi-span elements which are subject to fire exposure in bottom parts it is the tensile zone heated in span cross sections and it is the compressed zone heated in supporting cross-sections. It is well known that as a result of exposure to high temperature the stiffness of span cross sections decreases significantly faster than in support cross-sections [3, 5-7] thus leading to redistribution of internal forces. Adequate quantitative description of stiffness reduction for each cross section has a principal significance for behaviour prediction calculations of the statically indeterminable reinforced concrete elements exposed to fire conditions.

This paper presents a description and results of an experimental program intended to determine the stiffness reduction in cross-sections of bent reinforced concrete beams subject to high temperature only in the tensile or only in the compressed zones.

1. EXPERIMENTAL PROGRAM

1.1. Elements

For this high temperature experiment, 24 reinforced concrete beams with rectangular cross-section 140×280 mm, 3500 mm. in length were used. All were made from C25/30 concrete with siliceous gravel aggregate. The main reinforcement was made of two B500SP class steel bars (f_{yk}=500 MPa), diameter 10 or 16 mm (reinforcement ratio ρ_l=0.44 or 1.13%).

Transverse reinforcement with 100 mm spacing made of 6 mm diameter St500b steel bars was applied only in supporting areas. In all beams the reinforcement cover was made in a way that the main reinforcement centre of gravity was 25 mm from the element's front. Dimensions and reinforcement methods are presented on Fig.1.

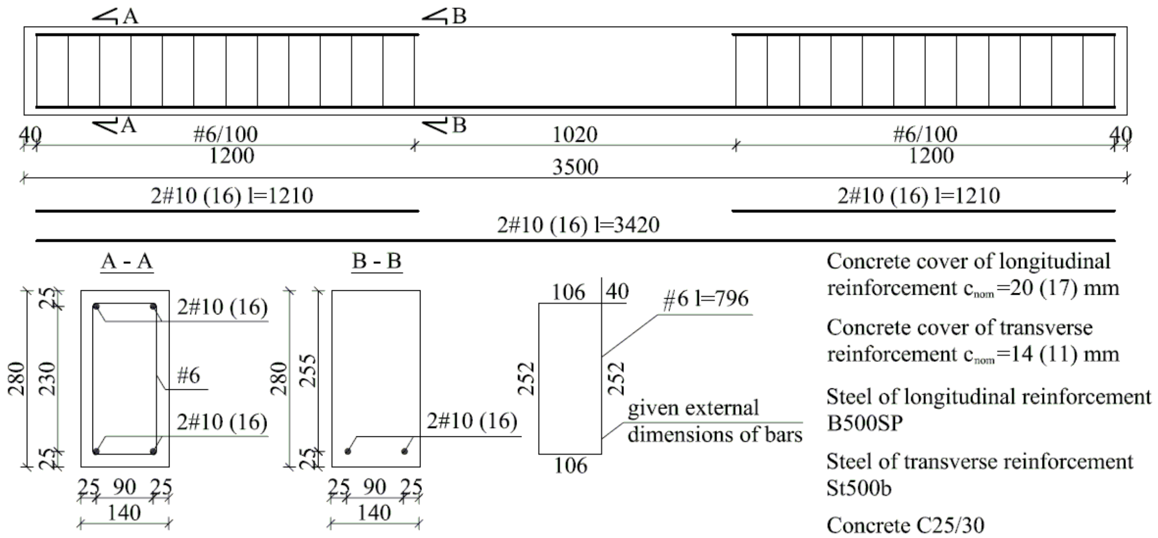
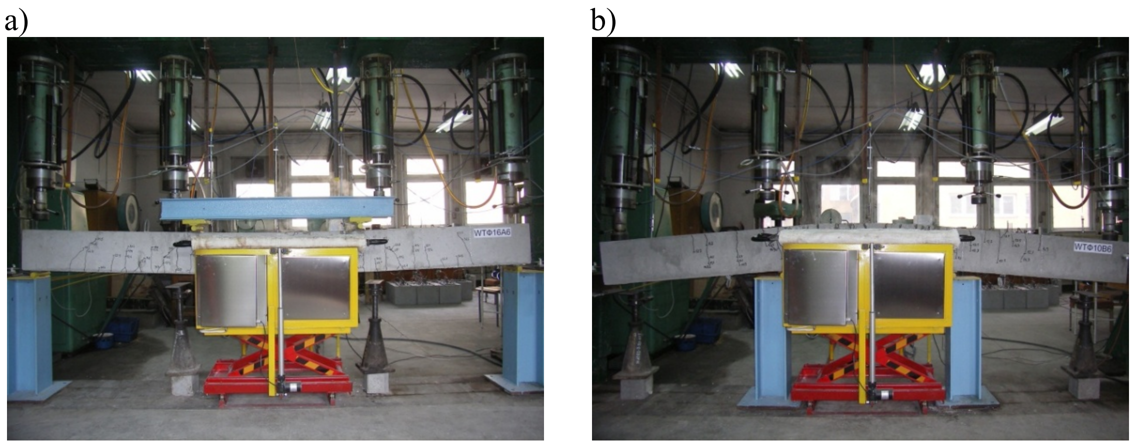


Fig.1. Dimensions and reinforcement of the tested beams

1.2. Experiment sequence

There were two static setups used ensuring a constant bending moment in the middle part of the beam heated from the bottom part in both cases. The first setup (Fig. 2a) simply supports the beam at its ends and is loaded with two forces located in 1/3 of the span (tensile zone heated). In the second one (Fig. 2b) the beam was inverted, supports were placed in 1/3 of the span and load applied at its ends (compressed zone heated).



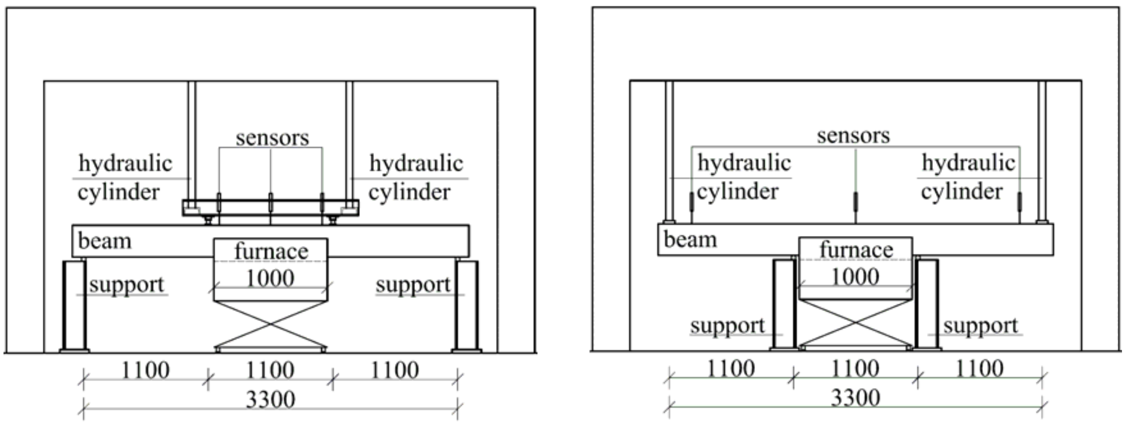


Fig. 2. Photographs and diagrams of the test-bed: a) tensile zone heated, b) compressed zone heated

Experiments in high temperature were executed under application of constant force amounting to 50 % and 70 % of load bearing capacity experimentally determined at room temperature. Overall there were eight series of beams consisting of three equal elements (2 diagrams x 2 reinforcement ratios x 2 load bearing capacity levels) used for the high temperature experiment.

Before high temperature testing a quasi-permanent load action was simulated by loading and discharging each beam eight times to the assumed load bearing capacity level.

Next, a furnace pre-heated to 400^{o}C was placed under the beam reaching about 850^{o}C in 60 minutes. The experiment relied on heating the bottom middle zone of the beam under constant load. The heating time, beam bending and temperature in assigned places were recorded. Fig. 3 presents location of the beam in the furnace cross-section and placement of temperature measurement points.

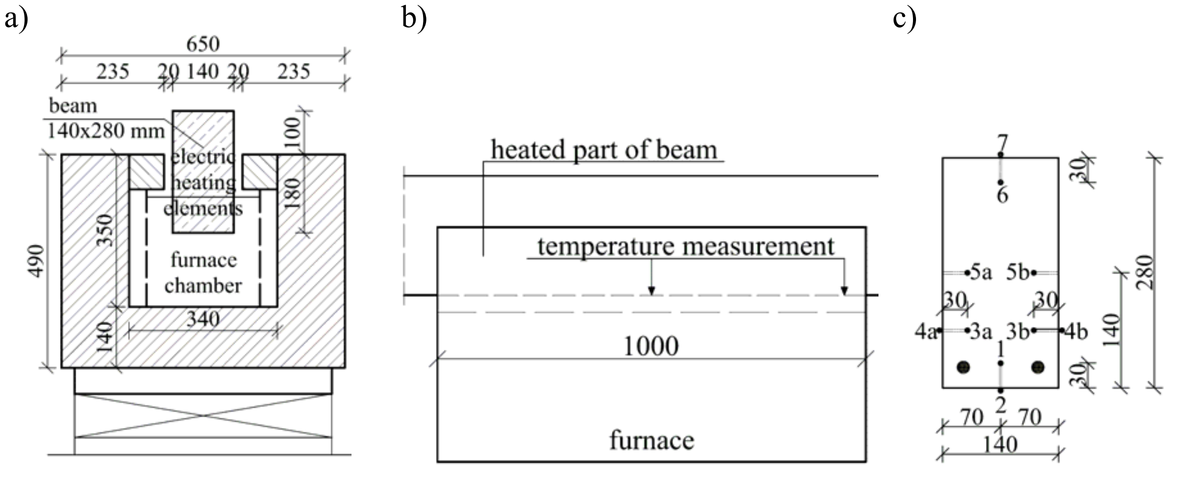


Fig. 3. a) Beam location in furnace cross-section, b) location of temperature measurement cross-sections, c) location of the thermocouples in beam cross-section

2. TEST RESULTS

Testing of the beams with tensile heated zone was performed until destruction which occurred after 40-50 minutes. Beams with heated compressed zone showed greater resistance to high temperature and finally were not destroyed during the assigned heating cycle lasting two hours.

Fig. 4, presents median temperature values in the beam's middle cross section in case of compressed zone heated against the standard fire curve.

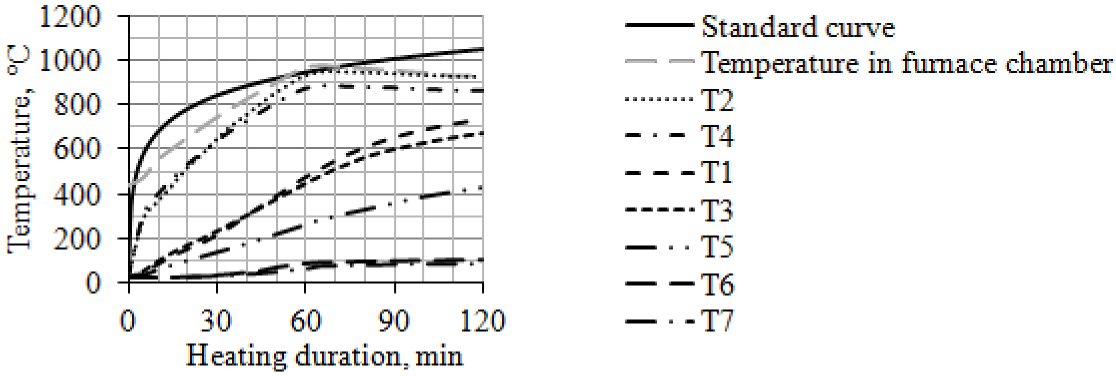


Fig. 4. Graphs for temperature increase in beam middle cross-section and furnace chamber

Fig. 5 presents median deflection graphs from all series of tested beams. In case of the beam's compressed zone heated the deflection value is as sum of results from sensor in the middle of the beam and arithmetic mean from sensors located under the forces.

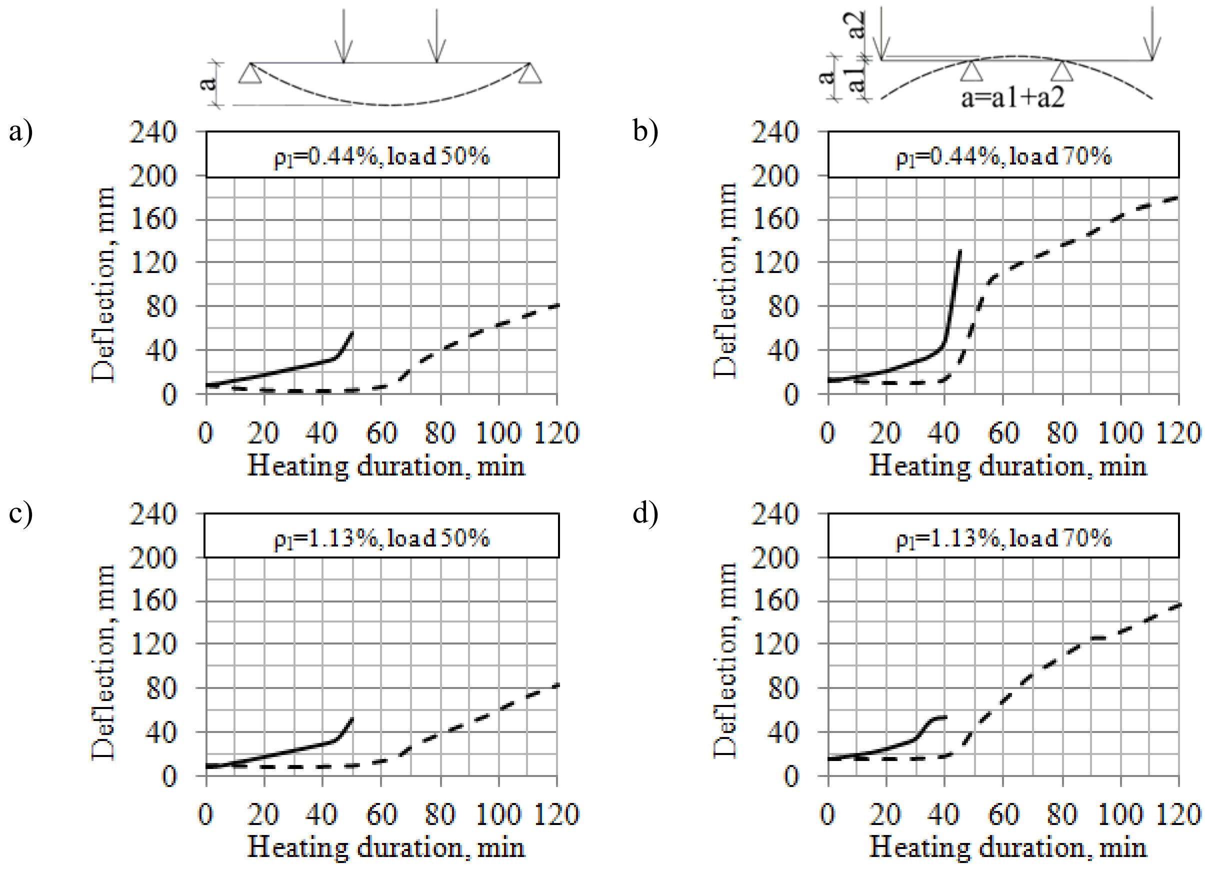


Fig 5. Test results: a) ρ_l=0.44%, load 50%, b) ρ_l=0.44%, load 70%, c) ρ_l=1.13%, load 50%, d) ρ_l=1.13%, load 70%; continuous line – tensile zone heated, dashed line – compressed

3. RESULT ANALYSIS

In beams with the tensile zone heated there is a significant increase in deflection. Initially it was close to linear then the destruction phase followed. The cross-section stiffness decreased significantly in result of reinforcement temperature increase. This was caused by considerable elongation of the bars where the deflection caused by the load elongation “summed up” with the free thermal steel strain.

In beams with the compressed zone heated there was no deflection increase recorded, in some cases it even decreased while in the same time beams with heated reinforcement were destroyed. This was due to elongation of the fibres in the compressed cross-section zone caused by concrete free thermal strain. The influence of concrete free thermal strain was thus greater than the concrete load induced thermal strain phenomenon [2-5]. This is not surprising as the stress occurring in the compressed zone of the concrete cross-section where not too big. In the initial heating stage median stress levels in the compressed zone can be estimated to: 6-14 MPa, depending on the examined case. The deflection in beams started to increase radically only after about 40-60 minutes, when the temperature of the compressed concrete zone was about 400-600°C.
Basing on the beam deflection one can estimate the cross-section stiffness. It is known that in case of a reinforced concrete element it is relative to the applicable bending moment and is significantly smaller if the cross-section is cracked.

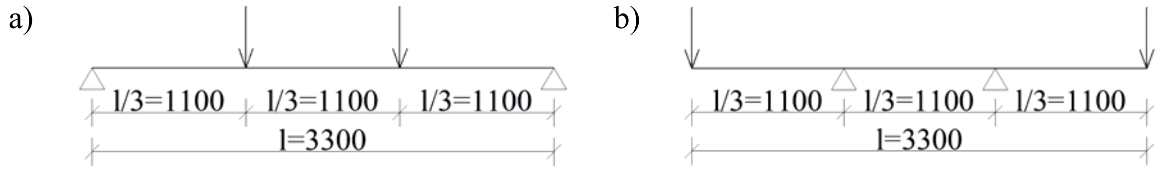


Fig. 6. Static diagram of examined element: a) tensile zone heated, b) compressed zone heated

In practice during calculation of deflections in reinforced concrete elements it is simplified (i.e. [8]) to constant cross-section stiffness in the whole length of the element equalling to a minimal value determined in the location of the maximum bending moment. Thus for further calculations the simplified constant stiffness distribution in the whole length of the examined element was taken. In the applied static setup (Fig. 6) the beam deflection at room temperature (before heating) can be calculated with formula *(1)*:

$$a_{t=0} = \int_0^l \frac{M\overline{M}}{B}dx = 2\int_0^{\frac{1}{3}l} \frac{M\overline{M}}{B_{t=0}}dx + \int_{\frac{1}{3}l}^{\frac{2}{3}l} \frac{M\overline{M}}{B_{t=0}}dx = \frac{1}{27}\frac{M_{max}}{B_{t=0}}l^2 + \frac{5}{72}\frac{M_{max}}{B_{t=0}}l^2 = \frac{23}{216}\frac{M_{max}}{B_{t=0}}l^2 \qquad (1)$$

where: M_{max} – maximal value of bending moment
$B_{t=0}$ – beam stiffness at room temperature, l – beam span.
In the examined beams only the middle section was heated thus it can be assumed that the first element *(1)* of the formula remained constant during the whole test, while the second one changed its values depending on the stiffness of the cross-section heated to high temperature (B_t). The deflection of the heated beam can be calculated for the formula:

$$a_t = 2\int_0^{\frac{1}{3}l} \frac{M\overline{M}}{B_{t=0}}dx + \int_{\frac{1}{3}l}^{\frac{2}{3}l} \frac{M\overline{M}}{B_t}dx = \frac{1}{27}\frac{M_{max}}{B_{t=0}}l^2 + \frac{5}{72}\frac{M_{max}}{B_t}l^2 . \qquad (2)$$

After transforming dependences *(1)* and *(2)* the relative stiffness decrease of the beam heated middle section can be determined from the formula:

$$\frac{B_t}{B_{t=0}} = \frac{15}{23\left(\dfrac{a_t}{a_{t=0}}\right) - 8} . \qquad (3)$$

Fig. 7 presents graphs of relative stiffness decrease in cross-section heated to high temperature depending on heating duration. Values for vertical axis were calculated from formula *(3)*, using experimental deflection values given on graphs at Fig. 5.

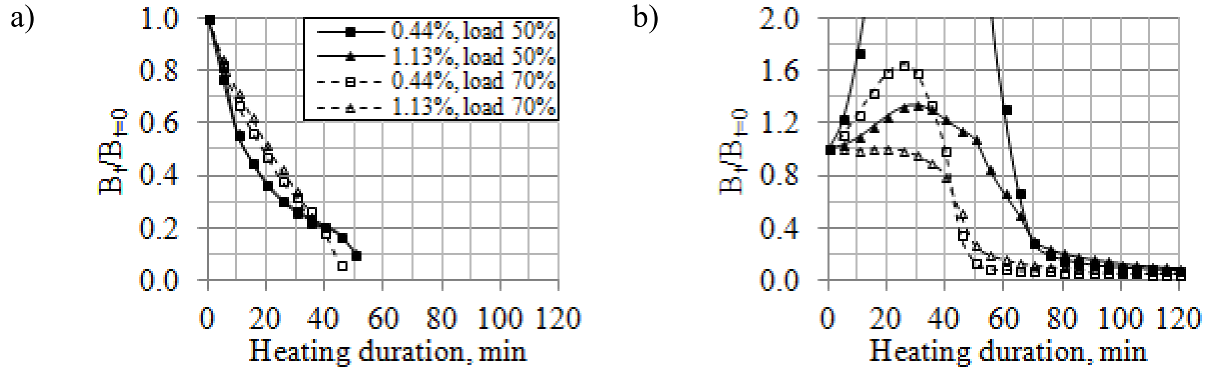


Fig. 7. Graphs of relative stiffness decrease in cross-section: a) tensile zone heated, b) compressed zone heated (descriptions apply to both graphs a & b)

In cases of all beams with heated tensile zone significant stiffness reduction was observed. The relative value decrease was not relative to the beam reinforcement ratio but was relative to their load. In less loaded beams (50% load bearing capacity) already after 12 minutes of heating there was a twofold stiffness reduction. In more loaded beams (70% load bearing capacity) the twofold relative stiffness reduction occurred a little later, after about 20 minutes of heating. This regularity is a consequence of greater deflection values of more loaded beams occurring at room temperature. As it was mentioned before the deflection values in beams with heated tensile zone at initial heating stages decreased a little (or remained roughly constant). Thus values calculated from formula *(3)* increased. The relatively estimated cross-section stiffness value was increasing more with the decrease of the stress level in the concrete compressed cross-section. This confirms the regularity that concrete in the heated compressed zone expanded freely due to its free thermal strain at the same time contracting due to the load induced thermal strain, [2-5].

Following, after 40 minutes of heating time – in case of bigger load or 60 minutes – in case of smaller load, there was a systematic increase of deflection in the examined beams. This was due to the significant concrete deflection increase (shortening) in the compressed zone heated to about 400-600^{o}C. As a consequence the graphs on Fig. 7b show violent relative reduction of cross-section stiffness, which till the end of the experiment remained on roughly constant low level. However it should be noted that the radical decrease in cross-section stiffness of the heated compressed zone happened only after the cross-sections with tensile zone heated were already destroyed.

4. FINAL REMARKS

In beams with tensile zone exposed to high temperature a significant reduction of cross-section stiffness was observed. This was caused by significant elongation of bars where the deformation due to load action "summed up" with the free thermal strain of steel.

In beams where the compressed zone was heated at initial stages the "fibres" of the compressed cross-section zone elongated. This was caused by the free thermal concrete strain which was greater than concrete deformation due to load (load induced thermal strain).

Results of the performed experiments can be a proof for the regularity that in multi-span reinforced concrete elements exposed to fire conditions at their bottom part one should expect redistribution of bending moments manifested in decrease of sagging moments and increase of hogging moments.

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