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ON MECHANICAL PROPERTIES OF REINFORCING STEEL IN RC BEAMS SUBJECTED TO HIGH TEMPERATURE

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Abstract
This paper considers the reinforcement elongation of RC elements subjected to fire in conformity with Eurocode (EN 1992-1-2). The stress-strain relationships for bars tensioned in elevated temperatures given in Eurocode, refer to 100°C temperature intervals. These dependencies pertain to only a part of total reinforcement elongation – the part that occurs due to load action. The free steel thermal strain and creep elongations are not included. From the practical view point, when predicting the behaviour of RC elements once subjected to fire, it is important to estimate the total elongation of the reinforcement. It is the most convenient when these elongations are considered in correspondence with temperature, while the stress level is kept at constant. Such circumstances present the surroundings in which the reinforcement of structural elements is subjected during the real fire. In order to adequately predict the behaviour of heated reinforcement, free thermal strain should be added to the strain occurred due to load action. This paper presents appropriate relationships based on recommendations given in Eurocode, developed in the system of three coordinates: stress strain temperature.

Streszczenie
W artykule, bazując na wymaganiach Eurokodu (EN 1992-1-2), przeanalizowano odkształcalność zbrojenia elementów żelbetowych narażonych na działanie pożaru. Podane w Eurokodzie zależności naprężenie odkształcenie odnoszą się do rozciągania prętów w wysokich temperaturach, będących wielokrotnością 100°C. Zależności te uwzględniają jedynie część całkowitego odkształcenia zbrojenia powstającą na skutek działania obciążenia. Swobodne odkształcenia termiczne stali oraz odkształcenia pełzania są natomiast pominięte. Z praktycznego punktu widzenia prognozowania zachowania się elementów żelbetowych narażonych na działanie pożaru istotne jest oszacowanie całkowitych wydłużeń ogrzewanego zbrojenia. Wydłużenia te najwygodniej jest rozpatrywać w zależności od temperatury, przy ustalonych naprężeniach. W takich właśnie warunkach znajduje się zbrojenie elementów podczas rzeczywistego pożaru. W celu adekwatnego przewidywania zachowania się ogrzewanego zbrojenia, do odkształceń pochodzących od obciążenia należy dodać swobodne odkształcenia termiczne stali. W artykule przedstawiono stosowne zależności opracowane w układzie trzech współrzędnych naprężenie-odkształcenie-temperatura, na bazie zaleceń podanych w Eurokodzie.

Keywords: **High temperature; Reinforcing steel; Mechanical properties; Fire.**

1. INTRODUCTION

From the structural designer point of view, ensuring the fire safety of the building structures is to apply such solutions that would assure required fire resistance of all structural elements. While designing simple, ordinary RC structures, it is generally considered sufficient to use tabulated data [1], which, depending on the type of material and previously established fire resistance, describes the minimal dimensions of cross-section of given element as well as the minimal axis distance of reinforcement cross-section from the edge of the element's cross- section. In case of advanced, more complex designing, sophisticated structures with distinctive economic importance or those which may pose high risk to human safety, tabulated data [1] may prove not to be precise enough. In such cases, more accurate prediction may be obtained when fire is taken under consideration as an accidental design situation, where ultimate limit states of a structure are calculated [1-3]. In order to carry out this kind of analysis, one should be aware of diminishing mechanical properties of reinforcing steel once subjected to high temperature [4-6].

This paper presents basic information about the effects of elevated temperature on mechanical properties of reinforced steel; brings into focus using the Eurocode [1] model for fire design of RC structures. In fire conditions, the elongation of reinforcing bars can be much greater than in room temperature [7]. It may bring about vital consequences on internal forces and stress redistribution in the RC cross-section [8] as well as on high elongations of elements, which may, in some cases, evoke redistribution of internal forces within the structure [4, 5, 8]. More information about reinforced steel behavior in fire conditions can be found in [4, 9]. The results of experimental tests on the reaction of reinforcing bars in heigh temperatures are given in [11-15].

2. EUROCODE MODEL [1]

The Eurocode [1] model of stress-strain relationship as a consequence of tensioning the reinforcing steel at elevated temperatures is based on Anderberg research activities [16]. Let it be noted, that the same model is given in code [17] in regards to structural steel.

The basic assumptions of Eurocode [1] model are presented in Fig. 1, as a general stress-strain relationship. This correlation consists of three linear segments and one part of ellipse inscribed in between two of them. Mathematical formulas of ellipse and coefficients that are necessary for the calculation of the value of mechanical properties of steel that occur on the vertical axis are given in [1]. Table 1 exhibits the coefficients used for determining values of mechanical properties placed on vertical axis, given in various temperatures.

For practical use of Eurocode [1] model, it is necessary to insert values, calculated according to the Tab. 1, into the relationship shown in the Fig. 1. However, while executing such steps, one can realize that the abscissa of point "2" in the Fig. 1 is given as

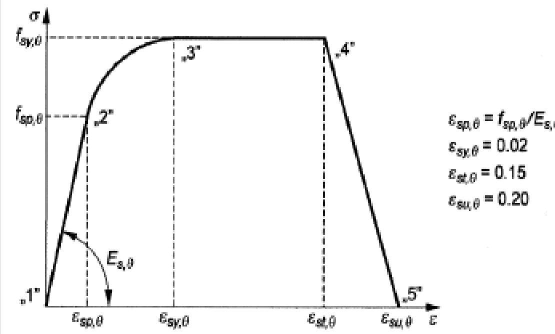

Figure 1.
General model of stress-strain relationship for reinforcing steel in elevated teperature [1]

Table 1.
Values for the parameters of the stress-strain relationship of hot rolled and cold worked reinforcing steel at elevated temperatures [1]

Steel Temperature	$f_{sy,\theta}/f_{yk}$		$f_{sp,\theta}/f_{yk}$		$E_{s,\theta}/E_{sk}$	
θ [ºC]	hot rolled	cold worked	hot rolled	cold worked	hot rolled	cold worked
1	2	3	4	5	6	7
20	1.00	1.00	1.00	1.00	1.00	1.00
100	1.00	1.00	1.00	0.96	1.00	1.00
200	1.00	1.00	0.81	0.92	0.90	0.87
300	1.00	1.00	0.61	0.81	0.80	0.72
400	1.00	0.94	0.42	0.63	0.70	0.56
500	0.78	0.67	0.36	0.44	0.60	0.40
600	0.47	0.40	0.18	0.26	0.31	0.24
700	0.23	0.12	0.07	0.08	0.13	0.08
800	0.11	0.11	0.05	0.06	0.09	0.06
900	0.06	0.08	0.04	0.05	0.07	0.05
1000	0.04	0.05	0.02	0.03	0.04	0.03
1100	0.02	0.03	0.01	0.02	0.02	0.02
1200	0.00	0.00	0.00	0.00	0.00	0.00

$\varepsilon_{sp,\theta} = f_{sp,\theta}/E_{s,\theta}$, the value of proportional limit $f_{sp,\theta}$, depends on f_{yk}, and $E_{s,\theta}$, depends on E_s = 200 GPa. As a result, the value of f_{yk} has to be previously established for calculation of the elongation $\varepsilon_{sp,\theta}$. It means that it is impossible to achieve the general relationship with relative values of reinforcing steel mechanical properties on vertical axis. In authors' opinion, precise prediction of proportional limits of reinforcing steel, based on the structural fire design point of

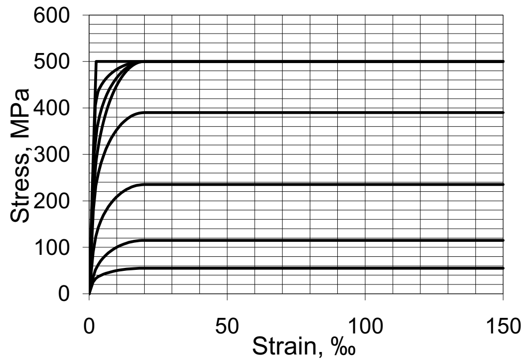

Figure 2.
The stress-strain relationship of hot rolled reinforcing steel (f_{yk} = 500 MPa) at high temperatures in the strain range of 0-150‰ [1]. Looking from the left side of the figure the successive lines refer to the temperature 100, 200, 300, 400, 500, 600, 700 and 800°C respectively

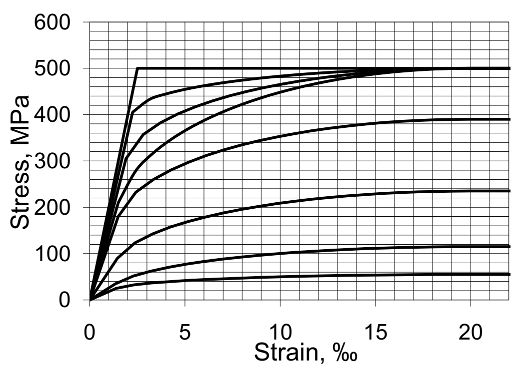

Figure 3.
The stress-strain relationship for hot-rolled reinforcing steel (f_{yk}=500 MPa) at high temperatures in the strain range of 0-22‰. Looking from the left side of the figure the successive lines refer to the temperature 100, 200, 300, 400, 500, 600, 700 and 800°C respectively

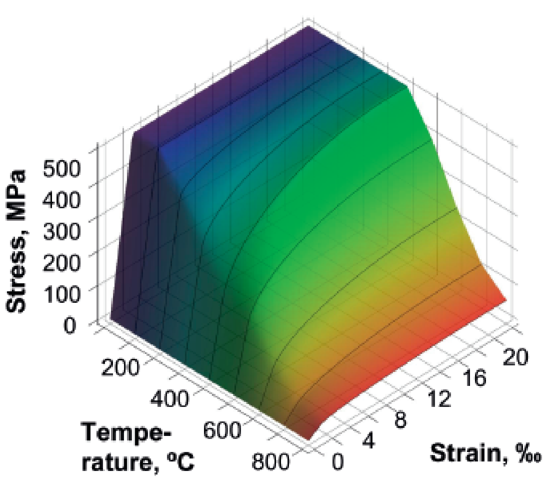

Figure 4.
The stress-strain-temperature relationship for hot-rolled reinforcing steel (f_{yk}=500 MPa), without thermal elongation

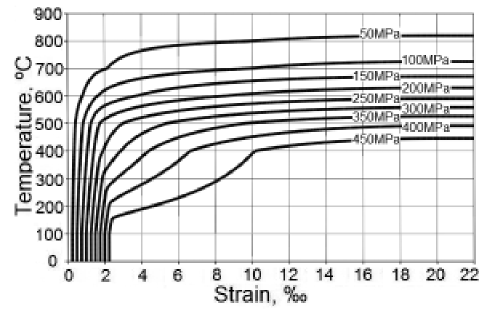

Figure 5.
The strain-temperature relationship for hot-rolled reinforcing steel (f_{yk}=500 MPa)

view, is not as crucial as one may have believed.

Figure 2 shows the examples of stress-strain relationships prepared by the authors, which presents the boundaries for hot rolled reinforcing steel yield strength of f_{yk} = 500 MPa. Comparing Figures 1 and 2, one can notice that the relationship shown in the Fig. 1 does not support the horizontal axis scale. Majority of the area of Fig. 2 is covered by the horizontal line situated between strain values of 0.02 and 0.15. However, most important data is contained within the narrow range from 0.00 to 0.02. The long horizontal lines can influence the calculation results only when advanced analysis is performed. When simplified calculation method is used for cross-section with one-layer of reinforcement (it might be resultant layer), the occurance of reinforcement elongation in point "3" in the Fig. 1 means that the cross-section ultimate limit state is reached. As a result in practical simplified analysis the cross-section ultimate limit state will always be reached when the steel elongation is equal to $\varepsilon_{sp,\theta}$ = 0.02 irrespectively of the temperature.

In the authors' opinion, introducing a constant, temperature-independent value of point "3", raises doubts. It should also be noted that in the Anderberg model [16] the line segment situated between points "3" and 4" was not horizontal but gradually achieved higher values as the strain increased. Horizontal segment "3-4" in Fig. 1 related to constant position of point "3" on horizontal axis seems not to be proper.

With regards to the occurance of long horizontal lines in Fig. 2, situated between strain values of 0.02 and 0.15, it would be more useful and practical to focus only on the part or the segment of graph that ranges from 0.00 to 0.02. Limited graphs are shown in Fig. 3.

Mechanical steel properties used for structural fire design should be considered as depending on three variables: stress, strain and temperature. Fig. 4 shows the same relationship as it is shown in Fig. 3 (hot rolled steel, f_{yk}=500 MPa), but at three coordinate system: stress-strain-temperature. From the practical point of view it is important to be aware of changeability of reinforcement elongations, when steel is subjected to the constant value of stress and heated. Conditions described above could simulate the circumstances in which the real RC structural elements are subjected during the real fire.

Strain-temperature relationships with constant stress value, drawn by the authors, based on Fig. 4, (referred to stress values at 50 MPa intervals) are shown in Fig. 5. These graphs deem quite useful when predicting expected temperature, in which elongation of reinforcement would create a plastic hinge at the cross-section.

3. WAYS OF TESTING STEEL HEATED UP TO HIGH TEMPERATURE

In order to adequately utilize aforementioned model in practice, it is worth analyzing its assumptions and predictions along with the kind of reinforcement elongations it is referring to. It is desirable to first of all, point out ways of testing steel in elevated temperature.

In room temperature analyses of the mechanical properties of reinforcement are usually considered in two coordinate-system: stress and strain (σ-ε). In analysis concerning fire design situation, the third coordinate (temperature (θ)) occurs. However, testing samples in presence of three variable parameters (σ-ε-θ) could be difficult and would not lead to satisfying practical results. As a consequence, in practice two most important ways of testing reinforcing bars subjected to high temperature are usually used [16, 18]:

– at constant temperature (steady temperature state),
– at variable (increasing) temperature (non steady temperature state).

When the first type of testing is performed the samples are at first heated up to high temperature. This temperature takes various values but it is kept constant in each particular test. At constant high temperature, the stress-strain relationships are examined. The way of testing is usually more or less the same as the one used at room temperature. As a result, the tests performed at constant high temperatures are relatively easy to implement in practice, and the results can be compared with the results obtained in room temperature tests.

When the second type of testing is performed, the samples are loaded at first. The level of stress is various however, it is kept constant in each particular test. During the test the samples are heated up and the elongation (in practice displacement) is measured. The temperature strain correlation for various stress values are obtained in such a manner.

The results of testing mechanical properties of reinforced steel obtained by the use of these two methods cannot be compared together uncritically.

The total elongation of reinforcing bar heated up to high temperature ($\varepsilon_{s,tot}$) can be expressed as the sum of three components as follows [16, 18]:

$$\varepsilon_{s,tot} = \varepsilon_{s,0} + \varepsilon_{s,\sigma} + \varepsilon_{s,cr} \quad (1)$$

In formula (1):

$\varepsilon_{s,0}$ – is the free thermal steel strain (occuring without any load action),

$\varepsilon_{s,\sigma}$ – is the elongation occuring due to load action; sometimes the ε_σ elongation can be divided in two parts: the elastic and the ductile part,

$\varepsilon_{s,cr}$ – is the creep elongations; it occurs due to long term simultaneous action of load and high temperature.

In the tests performed at constant temperature the free thermal steel strain ($\varepsilon_{s,0}$) and creep elongations ($\varepsilon_{s,cr}$) are usually not taken under consideration in the test results. Based on the assumption that the measurement of the elongation begins after stabilization of the elevated temperature, and the load action is quite short, it can be noticed that during the test performed at constant temperature the elongation occuring due to load action ($\varepsilon_{s,\sigma}$) is measured. The test performed at constant high temperature does not simulate the real conditions to which the structural elements are subjected during the real fire.

The real fire conditions can be simulated during the tests performed at variable (increasing) temperature. The reinforcing bars of real structural elements are stressed before the fire starts. During the fire the bars are heated up while stressed. In the tests performed at variable (increasing) temperature it is possible to measure the total bar elongation ($\varepsilon_{s,tot}$). However, it should be noted, that part of the total bar elongation ($\varepsilon_{s,tot}$) is the creep elongation (ε_{cr}) and the signifi-

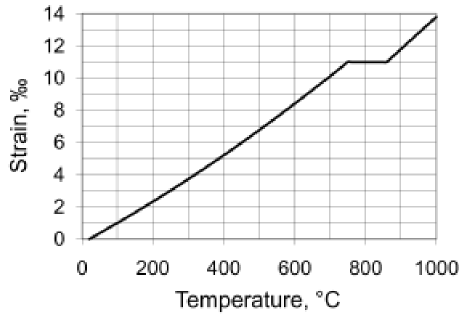

Figure 6.
Free thermal elongation of reinforcing steel [1]

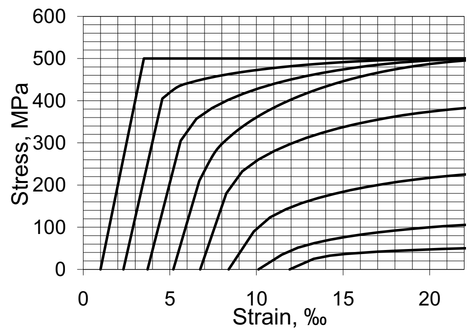

Figure 7.
The stress-strain relationship (included steel free thermal elongation) for hot-rolled reinforcing steel (f_{yk}=500 MPa) at high temperatures in the strain range of 0-22‰. Looking from the left side of the figure the successive lines refer to the temperature 100, 200, 300, 400, 500, 600, 700 and 800°C respectively

cance of it depends on the time interval of simultaneous heating and stressing. The heating rate during the test should be similar to increase of the temperature of reinforcement in RC element subjected to real fire. At the temperature range of 400-500°C the creep elongation ($\varepsilon_{s,cr}$) is too small to be considered significant [11]. If temperature is above that range, creep elongation strongly depends on heating rate. During the real fire heating rate could be between 5°C/min to 50°C/min [11]. According to [10] in such conditions the influence of creep elongation is not significant either.

4. USING OF EUROCODE MODEL IN PRACTICE

The Eurocode model [1] is based on tests performed in conditions of variable temperature [16]. In accordance with this model fundamentals and one's ability to apply aforementioned model in practice, free thermal steel strain should be added to elongations pre-

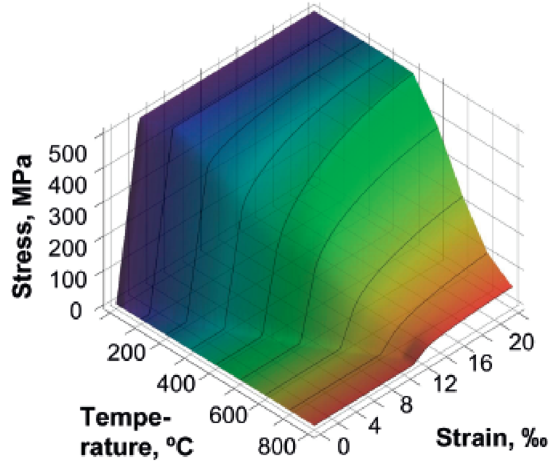

Figure 8.
The stress-strain-temperature relationship (included steel free thermal elongation) for hot-rolled steel (f_{yk}=500 MPa)

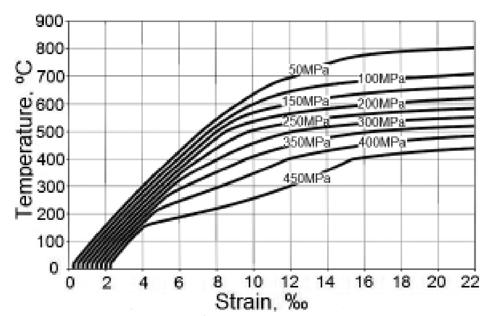

Figure 9.
The strain-temperature relationship (included steel free thermal elongation) for hot-rolled steel (f_{yk}=500 MPa)

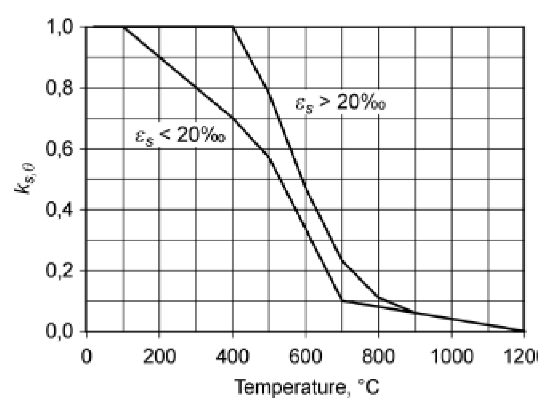

Figure 10.
The reducing factor of the yield strength of reinforcing steel [1]

sented in Fig. 3, in order to keep conformity. It is often assumed in practice that the value of total thermal elongation coefficient is 10^{-5}. However, there is a relationship between thermal elongation coefficient and temperature given in [1]. According to that fact, free thermal strain is a bit greater than 10^{-5}. This relationship is shown in Fig. 6.

Figures 7, 8 and 9 show, prepared by the authors, relationships of mechanical properties of reinforced steel. In these graphs free thermal strain, shown in Fig. 6 is added to strain taken from model shown in Fig. 1. The graphs pertain to hot rolled steel with yield strength f_{yk} = 500 MPa.

Fig. 7 shows stress-strain relationships for tensioned steel at elevated temperatures, which refer to the temperature values established at 100°C intervals. Fig. 8 shows similar relationship; however, at three coordinate system: stress-strain-temperature. The strain-temperature relationships with constant stress value (referred to stress values at 50 MPa intervals) are shown in Fig. 9. The relationships given in Figs. 7-9 might be used for predicting the behaviour of RC elements during fire.

It is absolutely necessary to be familiar with the strain process while tensioning the reinforced steel, in order to carry out advanced analysis. In the simple practical cases, to determine the load bearing capacity of RC cross-section, knowledge of yield strength reduction in correspondence to the temperature is considered sufficient enough. Fig. 10, prepared by the authors on the basis of [1], shows reduction factor $k_{s,\theta}$ corresponding to the temperature. The reduction factor is a quotient of yield strength at elevated temperature and characteristic yield strength at room temperature. Eurocode [1] recommends to use this relationship when performing analysis while utilizing simplified method of structural fire design.

The upper line in Fig. 10 pertains to decreased yield strength when the strain is greater than or equals to 20‰. Coordinates of that line comply with the values given in basic model (vide Table 1, col. 2). According to the description given in [1], the line situated on the bottom demonstrates the decrease of the yield strength when the strain is less than 20‰. However, there is no information in [1] as to what values of the strain were taken into consideration while creating this line.

In the author's opinion, calling the values in the lower part of relationship graph, shown in Fig. 10, by the name of yield strength, occuring in limited strain, has its genesis in analogy to the stipulated yield strength in room temperature. This analogy should not take place in case of taking into consideration RC elements exposed to high temperature. In the fire conditions substantial deformations occur (big elongations of reinforcement); therefore, it is important to estimate critical stress level in reinforcing bars when those are undergoing the process of destruction (stress labelled by line on the top of Fig. 10). It may be simply assumed that the difference between yield strenght of steel and its tensile strength disoccurs in high temperature conditions. To estimate the strength of steel bars in RC elements upper line of the Fig. 10 should be applied.

5. CONCLUSIONS

The stress-strain relationship for tensioned reinforcing steel recommended in the Eurocode [1] is based on the test results performed at steady temperature state conditions. The relationship based on this type of test describes only elongation occuring due to load action. It does not include free thermal elongation of steel.

The reinforcing bars of real bent RC structural elements are stressed before the fire starts and during the fire bars are heated up while stressed. It is desired to combine the strain determined according to the basic stress-strain relationship with the free thermal strain of steel to resemble and satisfy the real fire conditions.

The paper presents graphs (Figs. 7-9) based on data taken from the Eurocode [1], which might be used for estimating the total elongation of reinforcement (hot rolled steel, f_{yk} = 500 MPa) in RC elements exposed to fire.

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