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Research paper

Post-fire behavior and residual capacity of high-strength grade 8.8 steel bolts

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Abstract: The paper presents results of experimental research involving assessment of the impact of temperature, fire exposure time, and the applied cooling method on the residual load-bearing capacity of high-strength construction steel bolts quenched and tempered (QT) in the production process, and their behavior under loading. The tests consisted in subjecting the bolts to simulated thermal impacts reflecting the environmental conditions of a real fire. During the experiment, a series of static tensile and shear tests were carried out on M20-8.8 construction bolts, exposed to the temperature of 100°C, 150°C, 200°C, 300°C, 400°C, 500°C, 600°C, 700°C, 800°C, 900°C, and 1000°C for the periods of 30′, 60′, 120′, and 240′, respectively. Moreover, the research took into account different cooling methods and analyzed their impact. After heating, the first batch of bolts was cooled in air, by allowing them to cool freely in ambient temperature conditions. In the case of the second batch, the bolts were cooled down rapidly by immersion in water, thus simulating the effect of a rescue and firefighting operation. In each series – for statistical reasons – 3 samples were tested in order to verify correctness and repeatability of the results obtained. Residual values of the post-fire tensile strength and the post-fire shear strength were determined. Values of reduction coefficients of the residual post-fire load-bearing capacity were determined as the ratio of the current load-bearing capacity of the bolt subjected to the conditions corresponding to a relevant fire situation to its reference load-bearing capacity in the initial condition. In addition, the article discusses changes in the plasticity and behavior of bolts subjected to the described environmental impacts and points out to the observed failure mechanisms. Attention was drawn to causes of the observed phenomena, the sources of which should be sought in microstructural changes of the bolt material that occur in the process of heating and cooling, depending on the temperature reached during the simulated fire exposure.

Keywords: elevated temperature, exposure time, high-strength steel bolts, load-bearing capacity, residual mechanical properties

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1. Introduction

Fire safety of civil engineering structures, in particular steel structures, for the last decades has become the subject of interest of scientists throughout the world. This was due to many spectacular building disasters caused by fire, among which the events of 11 September 2001 are probably the most embedded in the memory of generations of the modern times. Ensuring the structural stability and integrity in the situation of a fire is one of fundamental safety requirements that should be met through adequate design, proper construction, and skillful operation of a civil engineering structure. This obligation stems from, for example, the provisions of domestic legal acts [1, 2], which are a direct implementation of the provisions of the relevant European Union legislation, [3]. Documents intended to help in proper design of structures resistant to fire conditions include standards [4, 5], instructions and guidelines, the implementation of which is supposed to guarantee that the requirements mentioned earlier are complied with. In the case of steel structures, it is exactly the connections and joints that are the elements of the system directly involved in the transfer of loads from one structural element onto another and that ensure the integrity of the entire system. Therefore they play a key role, especially in an accidental situation of a fire, when the distribution of internal forces changes along with the development of the fire, causing changes in the stress level of connecting members – both in the temperature increase phase and the cooling phase. Experience derived from fires in actual building structures, as well as many fire experiments conducted in recognized scientific laboratories around the world show that in many cases a structural failure is the result of a connection failure – especially due to insufficient load-bearing capacity of bolts subjected to axial forces or combinations of axial forces and transverse forces. One may obviously also find examples where connections survived the fire, while structural members were irreversibly deformed, preventing the structure from further use. In both these cases, the structure can be brought back to use only through its complete reconstruction. Nevertheless, there are examples of buildings which structure has not suffered any visual damage for various reasons and the question arises whether they can continue to be safely used. The expert assessment process requires knowledge of the so-called post-fire residual strength parameters, the values of which – depending on the material – may be strictly dependent on such aspects, as the maximum temperature of the structure reached in the fire, the time of fire exposure, and the method of cooling of the heated structure. In principle, the residual properties often considerably differ from those applied at the design stage and provided for in the standards. In most cases, knowledge of residual properties is not well documented and not many people are aware of them. A substantial part of documented research shows permanent changes in the significant strength properties of steels heated to a temperature of 500°C and higher, explaining them by changes in the microstructural structure and grain dimensions, as well as reduction in the density of dislocations in the ferrite matrix [6]. Some of published research disregarded the impact of the cooling method (using only air cooling) and the time of fire exposure – elements were heated only for a period of no more than 10–20 minutes, the purpose of which was just to ensure that they are uniformly heated to the desired temperature throughout their entire volume. It was assumed that the impact of the structure soaking time is negligible, provided that it is long enough to ensure even distribution of the temperature field inside the sample, [6, 7], which in the light of later research turned out to be an incorrect assumption. Furthermore, the values of the tested parameters were usually assessed only during the heating phase of the samples, which led to design-reliable and substantially correct results only for the fire flashover (temperature increase) phase. These results were the basis for calibration of the reduction coefficients, which are currently provided in design standards in relation to such parameters as the yield point, tensile strength or Young's modulus. Tests conducted according to a similar model became the basis for calibration of the coefficients of the design tension and shear strength of bolts $k_{b,\theta}$ provided in Annex D to the standard [4]. Research carried out later on compared the values of parameters obtained also in the fire cooling phase, showing their quantitative difference in relation to the analogous values measured in the heating phase.

Kirby is commonly considered to be the precursor of post-fire bolt testing. In his works [8,9], he presented the results of the static tensile test and static shear test of M20-8.8 grade bolts, produced in the cold and hot forging process, subjected to soaking in the temperature of 20–800°C for 60 minutes, and then naturally cooled in air. He found that hot forged bolts were more sensitive to temperature changes than those produced in the cold forging process. He drew attention to the fact that if the fire temperature exceeds the tempering temperature in the production process, the bolt material gets noticeably softened and its plastic properties increase. The behavior of bolts in a fire was also analyzed by, among others, Lange et al. [10], however in their research, they limited themselves to tensile tests of 10.9 grade bolts. Strength tests consisting in a static tensile test and a static shear test of bolts in natural fire conditions (including in the cooling phase) were carried out, among others, by Hanus et al. [11]. They confirmed that the cooling phase of a structure after a fire may be crucial for the safety of connections. On the basis of tests of 10.9 grade bolts, Rezaeian et al. [12] proved that the degradation of load-bearing capacity in the cooling phase considerably differs from that in the heating phase. This is due to irreversible changes in the bolt steel that occur after the phase transition temperature is exceeded. A wider attention should be paid to a number of research works conducted by the team led by Kodur [13–16]. Works [13, 14] were based on M22 A325 and A490 bolts, available on the American market, on which static tensile and static shear steady-state tests were carried only in the heating phase, with 15-minute soaking of the bolts up to each of envisaged temperature thresholds. Work [15] presents results of tests of residual mechanical properties of M16, M18 and M22 8.8 grade bolts, heated to the test temperature at a speed of approx. 10°C/min. As in the previous case, the samples were heated for 15 minutes only, after which they were left to slow air-cooling inside a furnace chamber. An observation was made that, apart from the maximum temperature value to which the bolts were subjected in the soaking process, their residual properties were to the highest extent impacted by the percentage of carbon content and the tempering temperature in the production process. Yahyai et al. [16] carried out a set of tests similar to those described in [15], with the only difference that they worked on 10.9 grade bolts, reaching similar conclusions in the end. Comparative research, which was a natural continuation of that described in works [15,16], was undertaken by Daryan and Katebdari [17], who, using similar research procedures, conducted a series of experiments on both 8.8 and 10.9 grade bolts with various diameters – ranging from M12 to M30. Based on the obtained results, they found that in the case of bolts made of the same material and in an identical production process, the differences in bolt diameters does not significantly affect the differences in values of respective residual properties. Lou et al. [18] were among the first ones to indicate the significant influence of the cooling rate on the mechanical properties of high-strength bolts, after they subjected M20x120 8.8 and 10.9 grade bolts, heated for 60 minutes, to accelerated cooling in water and natural cooling in air, and then to breaking in a classic tensile test. The work was summarized with rather general conclusions, pointing out only to differences in the results obtained. What is also worth mentioning is the article by Gao et al. [19], which presents results of the static tensile test and Charpy impact tests on 8.8 grade bolt samples previously exposed to fire for 60 minutes and simulated firefighting action with water cooling. Another work deserving attention is paper by Wang et al. [20] devoted to post-fire assessment of properties of standardized high-strength steel samples, quenched and tempered in the production process, heated in a wide temperature range from 100 to 1200°C, for 0.5 to 4 h, and cooled at various rates (in water, air and in a furnace chamber).

This article presents the results of own research on the impact of various environmental conditions, occurring in an accidental situation of a real fire, on changes in the residual values of tensile and shear strength of high-strength bolts. The impact of temperature, soaking time and the cooling method used on the post-fire load-bearing capacity of the bolts were analyzed. The approach presented in the research, which involved comprehensive assessment of the impact of complex conditions of a real fire on the key post-fire residual strength properties of bolts, is not reflected in the available literature. In this context, the results of the research bring new value to the current state of knowledge and may contribute to progress in methods of assessing the safety and reliability of structures that survived a fire.

2. Experimental study

2.1. Test specimens and methods

M20-8.8 grade bolts were used in the tests, since they are commonly used – due to their extremely universal properties – both in pre-tensioned and non-tensioned butt joints and lap joints. The length of the bolt shank, namely 200 mm, was selected to fit the dimensions of the handles used in the tests. New unloaded bolts were subjected to thermal exposure corresponding to selected conditions of a simulated fire, by soaking them in batches in an electric furnace at the following temperatures, respectively: 100°C, 150°C, 200°C, 300°C, 400°C, 500°C, 600°C, 700°C, 800°C, 900°C, and 1000°C, for the time specified in the technical and construction regulations [1], corresponding to the classes of fire resistance of members of the main load-bearing structure of buildings, i.e. 30′, 60′, 120′, and 240′. Currently, there are no other guidelines or standards that would regulate the requirements and could provide reference for conducting post-fire experiments [21].

The samples were inserted into the furnace chamber previously heated to the desired temperature; after waiting for about 5-10 minutes so that the bolts could reach the relevant temperature, the measurement of the soaking time started. The furnace chamber temperature was controlled by 4 thermocouples, evenly spaced within the furnace chamber. Following the described thermal exposure, some of the bolts, after being taken out of the furnace, were left at ambient temperature to cool down in air (air-cooling/sample symbol: AC), Fig. 1. This was aimed at reflecting the situation of non-affected, natural fire termination, resulting either from shortage of oxygen or combustible substances. The second batch of bolts was shock-cooled by immersion in water until completely cool (water-cooling/sample symbol: WC), which was to simulate the conditions of a rescue and firefighting operation conducted by fire brigades.

(a) (b)

Fig. 1. Bolt soaking process: (a) inside the furnace chamber right after inserting the samples, (b) bolts of the same series: "bare" – for the shear test and provided with 2 washers and a nut – for the tensile test

In each series – for statistical reasons – 3 tensile samples and 3 shear samples were tested in order to verify correctness and repeatability of the results obtained, which led to a total of 534 samples, including 267 samples subjected to the static tensile test and 267 samples subjected to the static test shear. This number also includes samples in the initial state, used for reference. Apart from the reference samples in the initial state (IS-20), the remaining samples were marked according to the X/Y/Z scheme, where X indicates the cooling method, Y – the soaking temperature, and Z – the soaking time in the set thermal conditions (e.g. AC /500/120 means sample cooled in air, after soaking at 500°C for 120 minutes). The bolts intended for the static tensile test were provided with two washers and a nut already at the soaking stage.

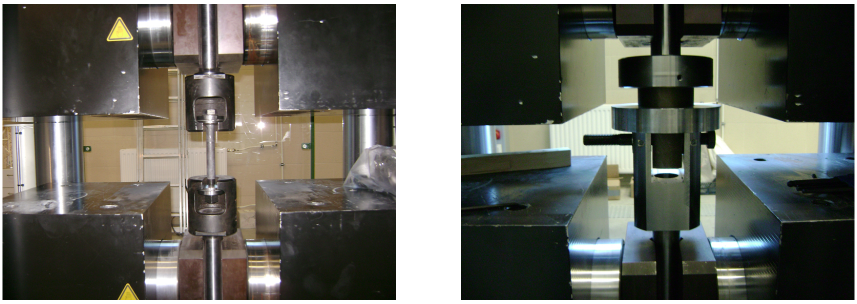
Bolts made of chromium alloy steel with an addition of boron, symbol 32CrB3, were used in the tests, the chemical composition of which is provided, according to the manufacturer's certificate, in Table 1. In the production process, the bolts were made of smooth wire rod in the hot forging process, and then, in order to obtain the mechanical properties expected of 8.8 grade bolts, they were subjected to thermal improvement by quenching them in oil at a temperature of approx. 850–860°C and tempering at a temperature of approx. 550°C.

Table 1. Chemical composition of the 32CrB3 bolt steel

Steel designation	**Chemical composition [%]**										
32CrB3	C	Mn	Si	P	S	Cr	Ni	Cu	Al	Mo	Sn
	0.31	0.84	0.13	0.012	0.013	0.74	0.08	0.15	0.025	0.018	0.010

2.2. Test setup and procedures

The bolt tests were carried out using the Instron 8806 universal testing machine, with a load range of up to 2500 kN, Figs. 2a– 2b, controlled by the Bluehill 2 program.



(a) (b)

Fig. 2. Test stand: (a) bolt in the tensioning handle, (b) bolt in the shearing handle

The tests were carried out using the displacement control method, assuming a constant strain rate (crossbeam displacements), with the tensile test carried out at a speed of 2 mm/min until the sample broke and the shear test at a speed of 1 mm/min. During both tests, the following parameters were recorded: the maximum loading force applied to a relevant sample during the test, the accompanying displacement of crossbeam of the testing machine, the value of the load at the moment of when the sample was destroyed, as well as the crossbeam displacement occurring at the moment of the destruction. In substantial terms, the most interesting results are the values of the residual strength of bolts to tension and shear, whereas the recorded displacements were only used to draw up load-strain diagrams and make qualitative assessment of the nature of behavior of the bolts subjected to the load. The values of failure stresses (bolt strength to tension and shear) were calculated using Eq. (2.1) and Eq. (2.2), respectively.

$$\sigma_{t,\mathrm{PT}} = f_{t,\mathrm{PT}} = \frac{F_{t,\max}}{A_s} \tag{2.1}$$

where: $\sigma_{t,\mathrm{PT}}$ – tensile failure stress of bolts subjected to prior thermal exposure (also known as post-fire tensile strength of a bolt), $F_{t,\max}$ – maximum tensile force obtained during the test, A_s – effective cross-sectional area of the bolt core (for M20 $A_s = 2.45$ cm^2).

$$\sigma_{v,\mathrm{PT}} = f_{v,\mathrm{PT}} = \frac{F_{v,\max}}{nA_v} \tag{2.2}$$

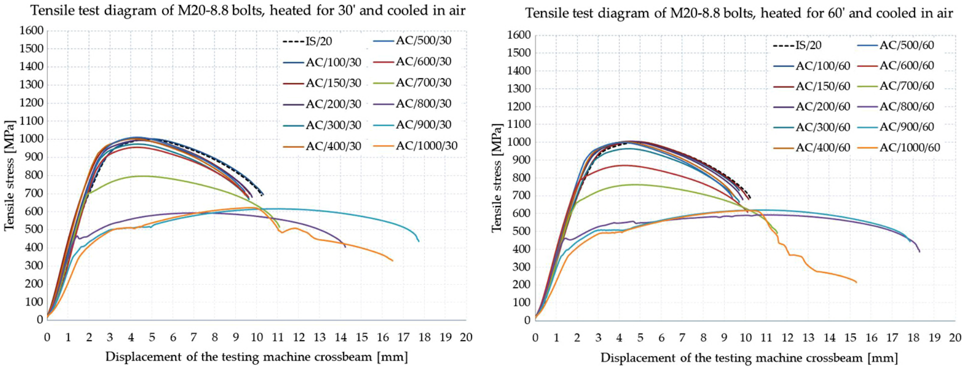
where: $\sigma_{v,\mathrm{PT}}$ – shear failure stress of bolts subjected to prior thermal exposure /referred to a single shear plane/ (also known as post-fire shear strength of a bolt), $F_{v,\max}$ – maximum shear force obtained during the test, n – number of shear planes (here $n = 2$), A_v – shear cross-sectional area of the bolt (for shearing of the non-threaded part $A_v = A = \pi d^2/4$, where d – nominal diameter of the bolt shank).

2.3. Experimental results and discussion

2.3.1. Stress-strain curves

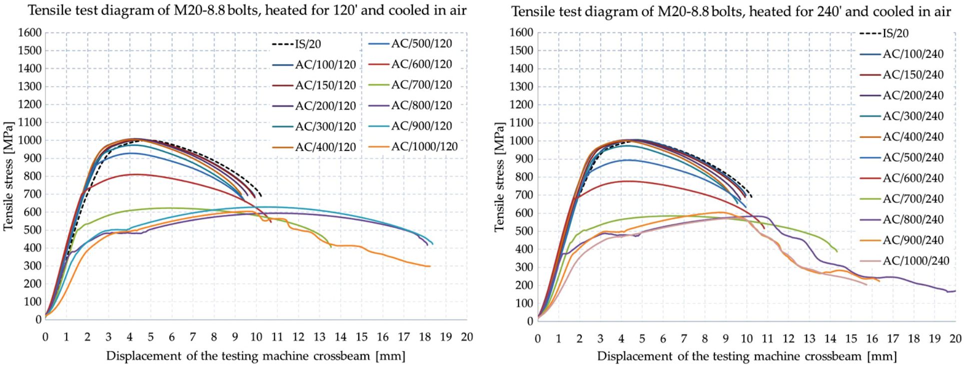
The recorded stress-strain curves presented in Figs. 3(a)–3(b) show how various factors influence the behavior of bolts under load and how the residual tensile strength degrades depending on the temperature reached, soaking time and cooling method. The diagrams were prepared for the average values of the results obtained for each of the 3 samples in a given series. Due to limitations in the size of the article, analogous curves obtained in the static shear test were not presented.

The analysis of the tensile curves presented in Fig. 3 shows that in the temperature range of 20–500°C (i.e. lower than the tempering temperature) and the soaking time of 30′ and 60′, the behavior of the bolts under load is almost identical, the curves practically coincide, the load-bearing capacity remains unchanged, regardless of the cooling method applied. Extension of the soaking time at 500°C (close to the tempering temperature) to 120′ and 240′ results in a decrease in the load-bearing capacity by approx. 7% and 11%, respectively, regardless of the cooling method applied (see Table 3). After exceeding the tempering temperature, reaching the level of 700°C (i.e. lower than the temperature of the beginning of the allotropic transformation



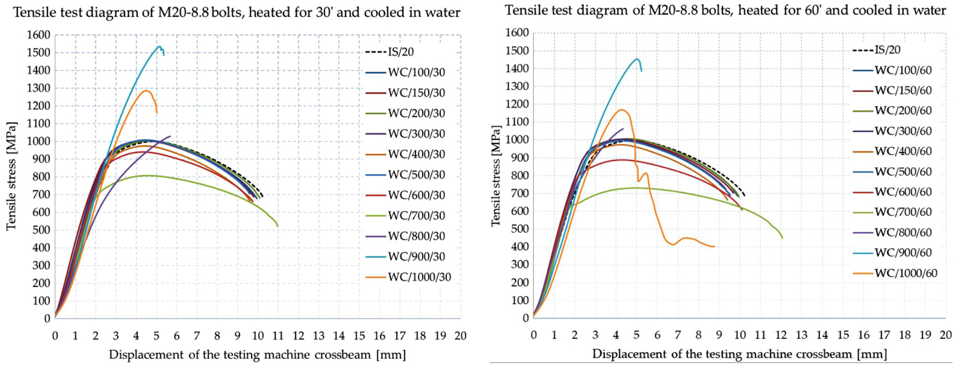
(a) 30′ of soaking time, air-cooled bolts

(b) 60′ od soaking time, air-cooled bolts

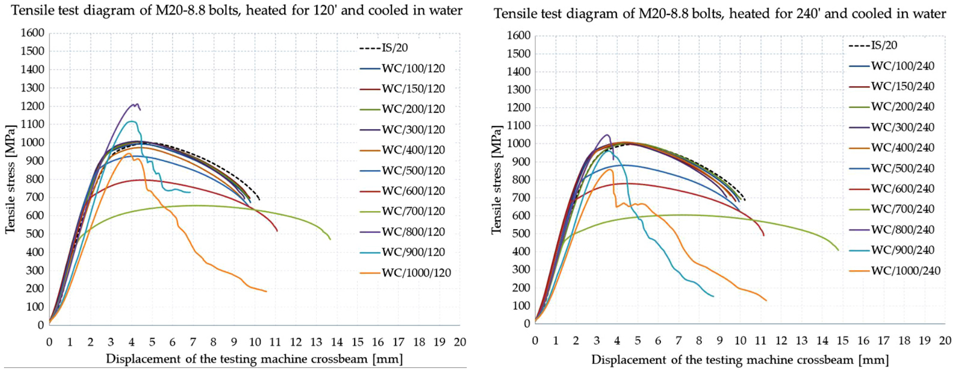


(c) 120′ of soaking time, air-cooled bolts

(d) 240′ od soaking time, air-cooled bolts



(e) 30′ of soaking time, air-cooled bolts (f) 60′ od soaking time, air-cooled bolts



(g) 120′ of soaking time, air-cooled bolts (h) 240′ od soaking time, air-cooled bolts

Fig. 3. Tensile test diagrams for varied soaking time, cooling methods, and temperature conditions

– Ac_1), the strength of the bolts gets successively reduced with a simultaneous increase in their ductility. When analyzing in detail the values of the reduction factors provided in Table 3, one may notice that this process is proportional to the applied time of the thermal exposure – the longer the time, the greater the strength reduction, regardless of the adopted cooling method. The situation changes at the temperature of 800°C, in which the steel of the sample is during the process of microstructural transformation associated with the phase change.

For the steel in question, this temperature is lower than Ac_3 – the temperature at which the austenitization process ends, therefore the time of exposure to fire conditions becomes a key factor. In the case of the samples subjected to tension, air-cooled and heated for no longer than 120′, their load-bearing capacity stabilizes at a similar level for all tested exposure times. Extension of the soaking time to 240′ results in a further decrease in the load-bearing capacity, which can be explained on the one hand by the effect of steel overheating, as a result of which the process of unnatural grain growth begins, and on the other hand by carbon burnout and oxidation of the surface layer of the bolt material. In physical terms, the form of damage to the tension samples changes – from the typical rupture in the threaded part to the shearing of the thread under the nut, and this form becomes the leading one for the temperature ≥ 800°C. This phenomenon can be seen in the form of an irregular end of the diagram shown, for example, in Fig. 3(d).

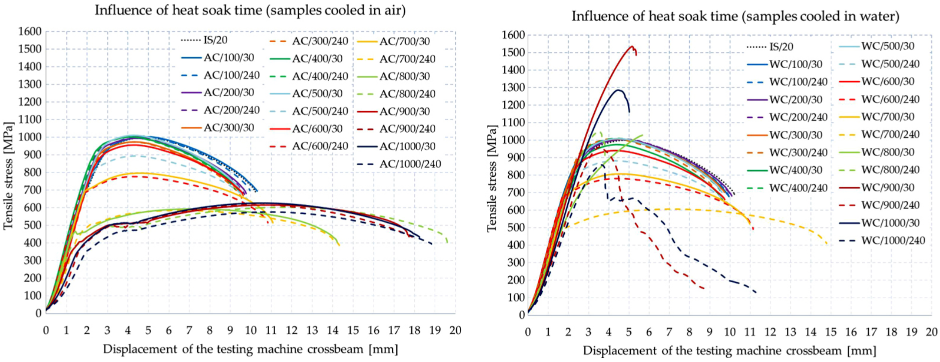
In the case of the shear samples cooled in air, the residual load-bearing capacity stabilizes at approximately 70% of the initial value, with slight fluctuations to one side or the other, which may be partially the result of wear of the cutting rings in the shearing handle.

This trend also exists at higher temperatures. In the case of the tension samples cooled in air, the residual load-bearing capacity stabilizes at a level close to 60% of the initial value, with slight fluctuations.

As regards the bolts heated at 800°C and cooled in water, the effect of re-quenching begins to be visible, demonstrated by a significant increase in the load-bearing capacity along with a noticeable decrease in material ductility. As the phase transformation of steel has not yet been fully accomplished, the effect of re-quenching for this temperature is still incomplete. Soaking at 900°C and cooling in water leads to full quenching of the samples and the related increase in strength and decrease in ductility, resulting from the full martensitic transformation in steel, [22]. Both the increase in time and soaking temperature to 1000°C result in a decrease in the load-bearing capacity, which is due to the overheating of the steel, excessive growth of austenite grains and, as a result, a coarse-grained structure of the formed martensite and significant structural stresses in the steel.

In order to better illustrate the impact of each of the analyzed factors on how the bolts behave under loading, Figs. 4a– 4b show, respectively, the stress-strain curves showing the effect of the soaking time, while Figs. 5a– 5b – the effect of the cooling method, as a function of the temperature to which the samples were subjected before testing.

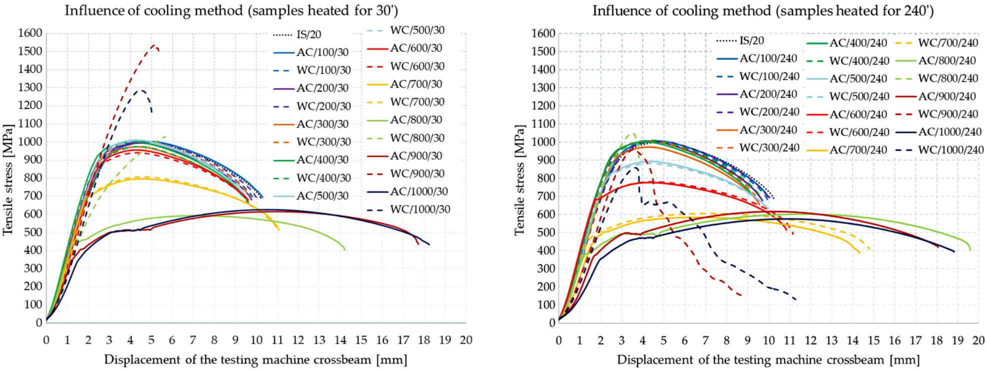
Figure 4 compares the effect of the soaking time on the stress-strain curves, both for bolts cooled in air and in water. The continuous line shows the curves for bolts heated for 30′, whereas the dashed line for bolts subjected to thermal exposure for 240′. This effect is visible from the soaking temperature of 500°C (close to the bolt tempering temperature in the production process) upwards, but it is different for varied temperature thresholds and not obvious.



(a) (b)

Fig. 4. Influence of heat soaking time on stress-strain curves; (a) air-cooled bolts: continuous line – 30′ of heat soaking time, dashed line – 240′ of heat soaking time, (b) water-cooled bolts: continuous line – 30′ of heat soaking time, dashed line – 240′ of heat soaking time

Figure 5 shows a comparison of the influence of the cooling method on the tensile stress of the bolts subjected to prior thermal exposure for 30′ and 240′, respectively.



(a) (b)

Fig. 5. Influence of cooling method on stress-strain curves; (a) bolts heat-soaked for 30′: continuous line – air-cooled bolts, dashed line – water-cooled bolts, (b) bolts heat-soaked for 240′: continuous line – air-cooled bolts, dashed line – water-cooled bolts

The continuous line shows the curves for samples cooled in air, whereas the dashed line – for bolts cooled in water. In the case of temperatures of 700°C and lower, the influence of the cooling method on the post-fire behavior of bolts is small, even negligible. As regards temperatures of 800°C and higher, a significant increase in load-bearing capacity is observed, accompanied by a decrease in ductility, for bolts cooled in water in comparison to samples subjected to the same temperatures, but cooled in air.

2.3.2. Post-fire residual strength factors

Tables 2 and 3 show the obtained values of the reduction factors of the post-fire residual strength, which are the ratio of the actual load-bearing capacity of the bolt subjected to the conditions corresponding to a given fire situation, to its design load-bearing capacity.

The values of the reduction factors of the post-fire residual strength to tension and shear were determined on the basis of Eq. (2.3) and Eq. (2.4)

$$k_{b,t,\mathrm{PT}} = \frac{f_{t,\mathrm{PT}}}{f_{t,\mathrm{Is}}} \tag{2.3}$$

where: $f_{t,\mathrm{PT}}$ – post-fire tensile strength of a bolt, determined in tests, $f_{t,\mathrm{Is}}$ – initial-state tensile strength of a bolt, determined in tests,

$$k_{b,v,\mathrm{PT}} = \frac{f_{v,\mathrm{PT}}}{f_{v,\mathrm{Is}}} \tag{2.4}$$

where: $f_{v,\mathrm{PT}}$ – post-fire shear strength of a bolt, determined in tests, $f_{v,\mathrm{Is}}$ – initial-state shear strength of a bolt, determined in tests.

Table 2. Post-fire residual tensile strength factors of bolts after the thermal exposure – $k_{b,t,\mathrm{PT}}$

Temp. [°C]	**Post-fire residual tensile strength factor after the thermal exposure lasting**							
	30 minutes		**60 minutes**		**120 minutes**		**240 minutes**	
	Cooled in air (AC)	**Cooled in water (WC)**	**Cooled in air (AC)**	**Cooled in water (WC)**	**Cooled in air (AC)**	**Cooled in water (WC)**	**Cooled in air (AC)**	**Cooled in water (WC)**
20	1	1	1	1	1	1	1	1
100	1.004	1.004	1.005	1.008	1.003	0.995	1.006	1.006
150	1.008	1.007	1.006	1.005	1.005	1.006	1.003	1.009
200	0.994	1.005	1.007	1.009	1.009	1.007	1.006	1.009
300	0.974	1.007	0.967	1.006	0.974	1.011	0.973	1.008
400	1.003	0.975	1.003	0.974	1.005	0.975	1.001	1.010
500	1.012	1.009	1.000	0.998	0.928	0.928	0.893	0.882
600	0.956	0.941	0.872	0.889	0.810	0.797	0.777	0.780
700	0.796	0.807	0.764	0.732	0.623	0.657	0.585	0.606
800	0.593	1.029	0.594	1.063	0.594	1.236	0.585	1.063
900	0.616	1.543	0.621	1.460	0.629	1.145	0.609	0.966
1000	0.624	1.288	0.618	1.177	0.605	0.979	0.575	0.868

Table 3. Post-fire residual shear strength factors of bolts after the thermal exposure – $k_{b,v,\mathrm{PT}}$

Temp. [°C]	**Post-fire residual shear strength factor after the thermal exposure lasting**							
	30 minutes		**60 minutes**		**120 minutes**		**240 minutes**	
	Cooled in air (AC)	**Cooled in water (WC)**	**Cooled in air (AC)**	**Cooled in water (WC)**	**Cooled in air (AC)**	**Cooled in water (WC)**	**Cooled in air (AC)**	**Cooled in water (WC)**
20	1	1	1	1	1	1	1	1
100	0.965	1.009	0.955	1.023	0.980	1.006	0.984	0.999
150	1.009	1.018	1.012	1.032	1.026	1.041	1.027	1.042
200	0.971	0.966	0.961	0.966	0.933	0.964	0.960	0.982
300	1.033	1.021	1.017	1.018	1.034	1.033	1.035	1.055
400	1.032	1.019	1.031	1.044	1.006	1.028	0.984	1.036
500	1.027	1.070	1.031	1.065	1.006	1.009	0.984	0.974
600	1.009	1.001	0.941	0.964	0.893	0.905	0.881	0.883
700	0.913	0.880	0.866	0.848	0.739	0.748	0.710	0.726
800	0.743	1.068	0.704	1.266	0.682	1.678	0.691	1.691
900	0.679	1.695	0.701	1.703	0.718	1.659	0.719	1.648
1000	0.696	1.649	0.715	1.613	0.690	1.611	0.686	1.560

2.3.3. Observed forms of damage

Figure 6 shows examples of damage to the tension bolts. The bolts cooled in the air retain a plastic, ductile nature of the shank rupture, whereas the bolts cooled in water, heated at 800°C and higher – a brittle, violent form. Due to the oxidation of the surface layer of the material in this temperature range, the bolt can also be damaged by cutting off the thread (nut slip). The image of the bolt rupture at the failure point indicates differences in the microstructural structure resulting from a different cooling method. A brittle fracture occurs without any macroscopic plastic deformation and is caused by a load that exceeds the cohesion of the material. The surface of the fracture is flat, shiny, crystalline, hence the name "crystalline fracture" or "grainy fracture" is sometimes used. The brittle fracture runs along strictly defined specific crystallographic planes of the grain, also referred to as cleavage planes or grain boundaries. Plastic or ductile fracture is preceded by macroscopic plastic deformation. Due to its appearance, it is also called a "fibrous fracture", [22]. More detailed information on the changes observed in the microstructure of tested bolts can be found in [23].

(a) (b)

(c) (d)

Fig. 6. Examples of damage to tension bolts: (a) – (b) damage by plastic rupture in the threaded part of the shank (bolts cooled in air) or by the thread shearing/nut slip, (c) – (d) damage by brittle fracture (bolts cooled in water)

3. Conclusions

The article presents the results of experimental tests of the residual tensile and shear strength of M20-8.8 bolts previously subjected to the environmental conditions of a simulated fire. The aim of the research was to determine the effect of the soaking temperature, the time of exposure to set thermal conditions, and the cooling method on the post-fire load-bearing capacity and behavior of the bolts subjected to axial and transverse forces. Based on the results obtained and the observations made, the following conclusions can be formulated:

- The soaking temperature has a significant effect on the value of the residual tensile and shear strength and the behavior of the tested bolts under the load. The impact of thermal conditions becomes visible when the soaking temperature is close to or higher than the tempering temperature applied in the production process.
- The time of exposure of the bolts to thermal conditions noticeably affects the values of the residual load-bearing capacity of the bolts: in general, in the temperature range up to Ac_1 (beginning of the phase transformation) and above Ac_3 (end of the austenitization process) the extension of the soaking time reduces the residual load-bearing capacity of the bolts. In the intermediate temperatures, this rule is somewhat disturbed, which is associated with the transformation of pearlite into austenite, accompanied by the allotropic transformation $\mathrm{Fe}(\alpha) \rightarrow \mathrm{Fe}(\gamma)$, which are processes involving energy absorption.
- The cooling method has less impact when the soaking temperature is lower than the Ac_1 austenitization temperature (on average approx. 727°C). After this value is exceeded, the influence of the cooling method begins to play a significant role, both from the point of view of the bolt behavior under load and the value of the bolt residual load-bearing capacity. Cooling in water leads to the re-quenching of the bolts, which results in an increased strength of the bolts combined with their reduced plasticity/ductility, due to the formation of a brittle martensitic structure of the steel. In view of the foregoing, the method of carrying out a firefighting operation may have a crucial effect on the safety of building in fire. Rapid cooling increases susceptibility of the bolts to brittle fracture, which can lead to a sudden construction disaster without the occurrence of the so-called intermediate phase, which is usually a natural warning sign for rescue teams and other people in a fire-engulfed building.
- It is important to realize that the environmental conditions included in the research constitute a kind of limited set, relating to certain adopted limit parameters. This applies in particular to accelerated cooling conditions by immersing hot bolts in water until their temperature across the shank diameter equalized. In real fire conditions, the likelihood of applying a continuous stream of water to the connections and joints until they are completely cooled is unlikely, unless the facility is equipped with an efficient sprinklers' or the water-mist system. A more likely scenario in the case of traditional fire-fighting is a relatively short exposure of the structural components to a water jet. Then, in the case of a structure heated above the austenitization temperature Ac_1, incomplete secondary quenching of the screws may occur (unless the temperature reaches the Ac_3 level) or complete quenching only in the near-surface layer (in case the temperature of the bolts exceeds Ac_3), while the shank core may still retain some plasticity. In either cases, both

the behavior of the bolts and their actual residual strength will differ from those presented in this work. It is expected that these properties will be intermediate in terms of strength. Referring to the behavior of the bolts (the nature of stress-strain curves) - it is difficult to be predicted, due to the non-uniform nature of the material across the thickness of the shank. In this case, the behavior of bolts under load can be strongly dependent on the shank diameter. The phenomena accompanying microstructural changes in steel in fire are extremely complex and require further research.

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Po-pożarowa nośność i sposób zachowania się pod obciążeniem śrub budowlanych o podwyższonej wytrzymałości klasy 8.8

Słowa kluczowe: czas ekspozycji, metoda chłodzenia, nośność, podwyższona temperatura, rezydualne właściwości mechaniczne, śruby o podwyższonej wytrzymałości

Streszczenie:

W artykule zaprezentowano wyniki badań polegających na ocenie wpływu temperatury, czasu ekspozycji pożarowej i metody chłodzenia na rezydualną nośność łączników wykonanych ze stali śrubowej, uprzednio ulepszanej termicznie w procesie produkcyjnym, oraz sposób ich zachowania pod obciążeniem. W ramach przeprowadzonych badań śruby poddano symulowanym wpływom termicznym, mającym odzwierciedlać warunki środowiskowe realnego pożaru. W trakcie eksperymentu przeprowadzono serię prób statycznego rozciągania i ścinania śrub jakościowych M20-8.8, wygrzewanych w temperaturze 100°C, 150°C, 200°C, 300°C, 400°C, 500°C, 600°C, 700°C, 800°C, 900°C i 1000°C przez okres odpowiednio 30′, 60′, 120′ i 240′. W badaniach uwzględniono zróżnicowany sposób chłodzenia i przeanalizowano jego wpływ. Pierwszą partię śrub, po wygrzaniu, chłodzono w sposób naturalny, pozwalając im ostygnąć swobodnie w warunkach temperatury otoczenia. W przypadku drugiej partii, śruby wystudzono w sposób gwałtowny, przez zanurzenie w wodzie, symulując tym samym efekt akcji ratunkowo-gaśniczej. W każdej z serii przebadano po 3 próbki, celem weryfikacji poprawności i powtarzalności uzyskanych wyników. Określono wartości rezydualne po-pożarowej nośności na zrywanie oraz po-pożarowej nośności na ścinanie. Wyznaczono wartości współczynników redukcyjnych rezydualnej nośności po-pożarowej, będące stosunkiem aktualnej nośności śruby poddanej warunkom danej sytuacji pożarowej do jej nośności w stanie wyjściowym. Omówiono zmiany w zakresie sposobu zachowania śrub poddanych zadanym oddziaływaniom środowiskowym, jak również wskazano na obserwowane mechanizmy zniszczenia. Zwrócono uwagę na przyczyny obserwowanych zjawisk, których źródeł należy upatrywać w zmianach mikrostrukturalnych materiału śrub, zachodzących w procesie wygrzewania i chłodzenia, w zależności od wysokości temperatury osiągniętej w trakcie ekspozycji pożarowej.

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