Comparative analysis of laboratory methods of definition of characteristics of fire resistance and fire durability of steel elements of load-bearing construction and the actual conditions of thermomechanical influences in fire condition

Yuriy Gul

Cand.-Eng. Sc., A.P.
Heat Treatment of Metals Department
National Metallurgical Academy of Ukraine,
Dnipro, Ukraine

Aleksandr Ivchenko

Cand.-Eng. Sc., Sr. Staff Sc.
Heat Treatment of Metals Department
National Metallurgical Academy of Ukraine,
Dnipro, Ukraine

Pavel Kondratenko

Postgraduate
Heat Treatment of Metals Department
National Metallurgical Academy of Ukraine,
Dnipro, Ukraine

Valentina Chmeleva

Cand.-Eng. Sc., A.P.
Heat Treatment of Metals Department
National Metallurgical Academy of Ukraine,
Dnipro, Ukraine

Galina Perchun

Cand.-Eng. Sc., A.P.
Heat Treatment of Metals Department
National Metallurgical Academy of Ukraine,
Dnipro, Ukraine

Abstract
The Objective isto substantiate the need to improve the methods for determining the characteristics of fire resistance and fire durability of steel elements of load-bearing construction and to offer new schemes for these methods.Methodology isbased on a comparative analysis of existing methods for determining the characteristics of fire resistance and fire durability and the actual conditions of thermal influences on steel elements of load-bearing construction in fires, new schemes of the considered methods are developed and justified.New schemes of methods for determining fire resistance and fire durability characteristics under laboratory conditions are presented;these schemes take into account substantially the real conditions of thermal influences on steel elements of load-bearing construction in fires and the results of such influences. Scientific novelty consists in the fact thatfor the first time in the offered methods, the actual formation of a stressed state in the steel elements of load-bearing construction is taken into account in case of fires and under cooling conditions after them. There appears the need to use various loading schemes to determine the complex of properties; different heating and cooling rates; determination of not only the characteristics of the resistance to deformation, but also to fracture; the determination of the latter not only at ordinary but also at low temperatures; individual approach in determining the characteristics of fire resistance and fire durability, depending on the type of construction.The paper possesses the following practical significance. By definition, the offered methods for determining the characteristics of fire resistance and fire durability should ensure obtaining of substantially more adequate characteristics of the actual fire resistance and fire durability of steel elements of load-bearing construction and, consequently, of the load-bearing construction itself, when this information is included in the relevant regulatory documentation for calculating fire resistance and fire durability of construction and structures. The use of fire resistance and fire durability characteristics obtained with new methods in the development of new steel grades with an appropriate structural state – in conjunction with the above – will raise the level of fire resistance of various structures, which usesteel load-bearing construction.
Keywords: FIRE RESISTANCE, FIRE DURABILITY, ELEMENTS OF STEEL LOAD-BEARING CONSTRUCTION, ALGORITHM, LABORATORY TESTS

Introduction

Conducting mechanical tests of metal objects at elevated temperatures in relation to the room temperature has long been used in practice and is regulated by the relevant standards. But although the methods of these tests and determined at this characteristics of hot strength and thermal resistance – creep resistance and rupture strength – give information on the resistance to deformation and fracture of this object at elevated temperatures under given loading conditions, but they differ significantly from the conditions and characteristics of fire resistance. Therefore, the use of these methods and characteristics does not reveal adequate CFR and CFD.

At the same time, although a large number of works is devoted to the problem of fire resistance and CFR and CFD that are determined in this case (only a small number of them is presented in the list of references [1-15]), it can be justified to state that both the methods used for determining CFR and CFD and the characteristics themselves have a low correlation coefficient with the conditions of thermomechanical influences on theStEL-BC during fire and its quenching, and, accordingly, with the actual fire resistance indexes. It is quite obvious that such situation contributesneither to the development of reasonable standards for the calculation of load-bearing construction forFR and FD, nor to the development of the new lean alloyed steel grades for theStEL-BC with increased CFR and CFD.

Thus, the development of new methods for determining CFR and CFD, which are more correlated with the actual conditions of fire and its quenching, and also with the determination of the possibility of using the StEL-BC after a fire, is very relevant. In this work, we present general algorithms for new methods obtained at the analytical level.

The objectiveis to offer new schemes of these methods and determined by them CFR and CFDon the basis of a system comparative analysis of the laboratory methods used to determine CFR and CFD of the StEL-BC and the actual conditions of thermal influences on theStEL-BCin case of fires and cooling during extinguishing.These systems are more adequate to the actual influences on theStEL-BC in case of fires and their extinguishing.

Methodology

The material of the study was available data sets, on the one hand, on the actual conditions and parameters of the influence on the StEL-BC in case of fires and their extinguishing, and, on the other hand, the currently used methods for determining CFR and CFD. By systemic comparison of these data sets, differences (inconsistencies) were revealed between the most important actual conditions, the parameters of the influence on the StEL-BC in case of fires and their extinguishing and the conditions, the parameters of the influence in determining CFR and CFD according to existing methods. Then, new schemes of methods were developed that should take into account, as much as possible, the actual influences and their conditions in case of fires and their extinguishing, with the possibility of implementing this account in the laboratory. The offered new procedures for the determination of CFR and CFD also made it possible to offer new types of such characteristics, as well as the desired sequence of determination of CFR and CFD, and the types of connections between these characteristics.

Results

1. Characteristics of fire resistance

The term «CFR» means the parameters determined using the given algorithm, used in the calculation of load-bearing construction for FR, i.e. that guarantees the preservation of load-bearing capacity under a given intensity of thermal influence in case of fire. It is assumed that this guaranty is met if the working strength(σ_w) upon heating of the StEL-BC to a given temperature does not lead to destruction or unacceptable deformation. Let us note that the values of σ_w>0 before the fire and, therefore, during the fire, already stressed StEL-BC are heated. In the known methods, steel elements or simple samples from given steel are first heated to different temperatures and after the temperature equalizing, they are subjected to loading, as a rule, according to the uniaxial stretching scheme till fracture.

Of course, the obtained information is important but:

a) it was obtained under other conditions of the loading and heating sequence in comparison with the real ones;

b) loss of load-bearing capacity of the construction occurs under conditions when the yield strength (σe) of theStEL-BC, decreasing as a result of heating, becomes lower σ_w: $\sigma_e<\sigma_w$;

c) during fire the heating rate can be different and no one, of course, is engaged in equalizing the temperature in the StEL-BCthat is why the presence in practice of a temperature gradient is more likelya rule than an exception, which must be taken into account when setting a heating mode in the laboratory;

d) for the different types of load-bearing construction more dangerous than uniaxial stretchingcould be other loading schemes, for example, compression with the risk of buckling failure in buckle, cross flexure, etc., therefore the loading scheme used before heating must be individualized.

The temperature value, at which the given value of σw leads only to the macro-elastic deformation (t_1), and the temperature at which σw leads to an allowable value of the residual deformation of theStEL-BC (t_2), is the value determined according to the offered methods of CFR of the StEL-BC for given values of σw and loading schemes and allowable types and deformation values (Fig.1).

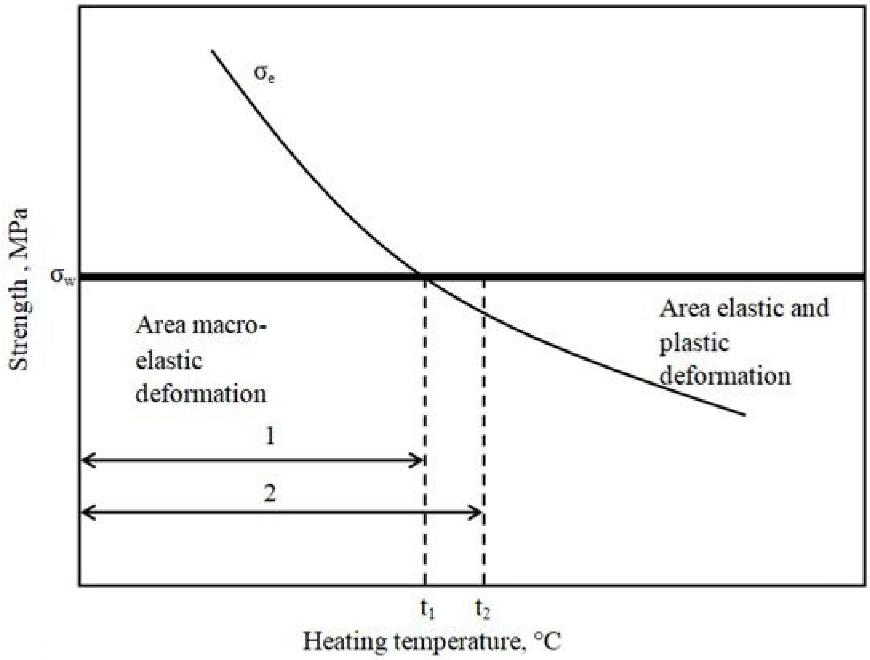

Figure 1. The ratio between values of the working strength(StEL-BC) and yield strength of the StEL-BC depending on the heating temperature.
1 and 2 – temperaturerange offireresistance

Taking into account the above, the general proposed algorithm for determining CFR is as follows:

1) choice of the type of the StEL-BC;

2) choice of loading scheme;

3) choice of value of σ_w;

4) choice of the overall temperature range of heating and the number of temperatures used in this range;

5) choice of heating modes;

6) loading of the StEL-BC to the selected value ofσw;

7) heating of the loaded StEL-BC to preset temperatures in the selected general heating temperature range according to a specified mode;

8) performing of the equalizing after reaching the heating temperature within a given time;

9) starting from point 6 until the performance of point 8 inclusive, a permanent record is made during the temperature test of the StEL-BC with simultaneous recording of a deformation and fracture diagram (if the latter occurs),in the coordinates the deformation of the StEL-BC is the heating time before reaching the preset temperature and the equalizing time after its achievement;

10) on the basis of the analysis of the diagrams obtained in accordance with point 9 the temperatures $t_1$and t_2 are determined.Comparison of the block diagrams of the CFR determination by the known and offered method is shown in Fig.2.

2. Characteristics of fire durability

The term “fire durability” generally refers to the preservation of the bearing capacity of a steel construction and, of course, its elements after a fire and its quenching, i.e. capability to further operation with the performance of relevant functions. In practice, FD testing under laboratory conditions is usually based on determining the degree of preservation of the working properties of the StEL-BC after heating and cooling.

CFR and CFD are closely connected. Firstly, the absence of destruction during the fire or inadmissible deformation of a load-bearing construction does not yet mean maintaining its load-bearing capacity for further “post-fire” operation for a predetermined warranty period of operation (before the fire). Therefore, it is necessary to determine CFD with the possibility of quantitative evaluation of the guaranteed further operation of the StEL-BC and its terms. Secondly, when determining CFD, it is necessary to simulate not only the actual heating conditions in a fire, as it is necessary in determining CFR, but also in cooling (extinguishing a fire). Here it is also necessary to take into account the possibility of phase changes during the cooling process depending on the cooling start temperature and the mode of this operation. Of course, a change in the structural state of steel under heating affects CFR, but taking into account the change in the structural state of steel has become fundamentally important for CFD, when the cooling mode forms the final structural state of steel and, accordingly, the set of the StEL-BC properties that determines the possibility of their further operation.

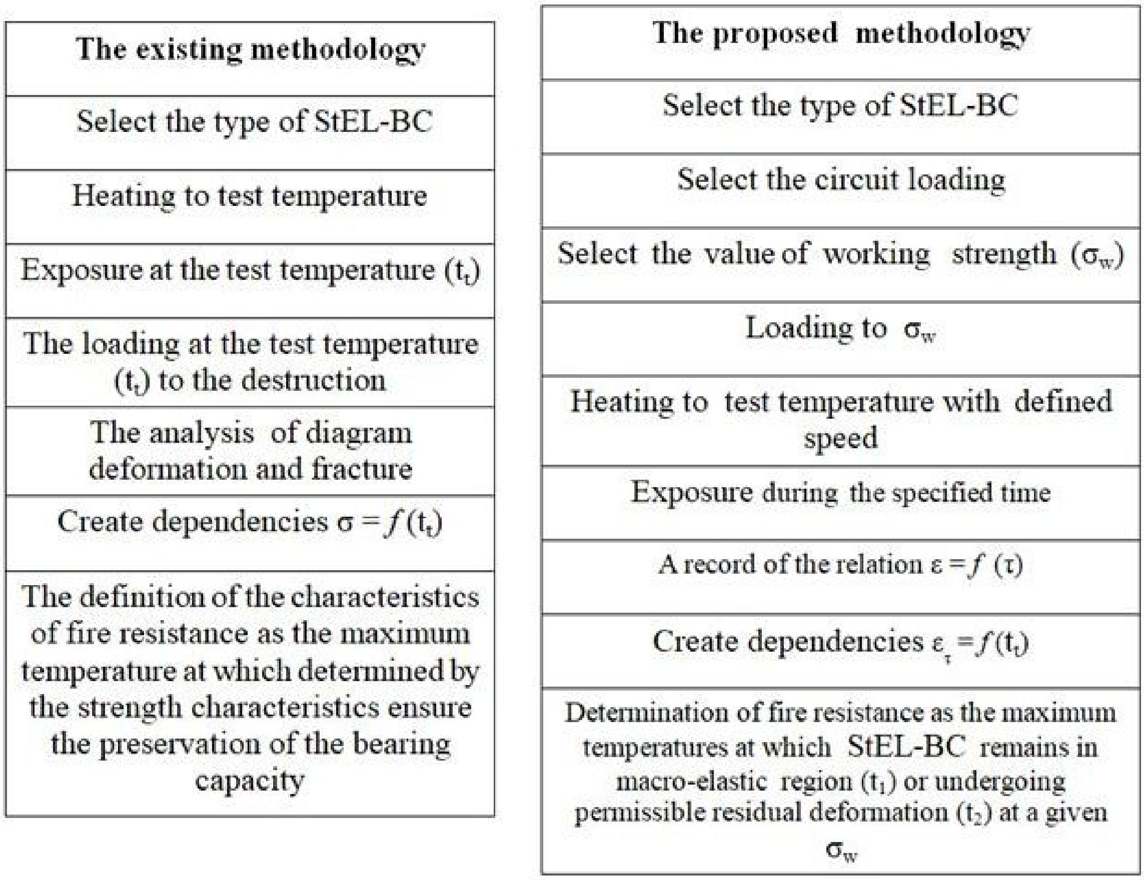

Figure 2. The block diagram of the existing and proposed methods of determining the characteristics of fire resistance

The methods used to determine CFD do not take into account the actual conditions of either heating in the event of a fire or when it is extinguished.

As the properties defined as CFD, the values of resistance of the plastic deformation (yield strength and breaking point for the uniaxial stretching scheme) are usually used. At the same time, the characteristics of the fracture resistance of various types, which can be significantly reduced as a result of heating and cooling in comparison with the «pre-fire» values, are not determined.

In view of the foregoing, the following algorithm is offered for the determination of CFD of the StEL-BC:

1) the determination of CFD is performed after determining CFR for a given StEL-BC;

2) the chosen StEL-BC was subjected to heating in the overall temperature range of its fire resistance, previously determined by the methods analyzed above;

3) several StEL-BC should be subjected to heating to each temperature from range referred to in point 2;

4) under each heating temperature the StEL-BC are cooled with different rates: from cooling in air to cooling in water;

5) the StEL-BC cooled according to point 4 are subjected to complex tests with determination of the properties of the resistance to deformation and fracture in accordance with the operating conditions of this bearing construction;

6) by comparing the results of the tests in accordance with point 5 with the initial properties of the StEL-BC before the simulated effects of the fire factors and its quenching, the degree of fire durability according to this property is determined by the coefficientKFD≤ 1 with the indication of the heating temperature (th) and the subsequent cooling rate (type of the cooling medium); with that,the value th

$$\sigma_T^{600} = 500/\text{Air}$$

is assumed asthe highest temperature at which KFD is still equal to unity. For example, the formula means that CFD at a yield strength with a value of 500 MParemains to a temperature of 600 °C inclusive, followed by cooling to room temperature in air and KFD = 1. In other cases, the value of KFD is showed as less than unity;

7) the highest temperature values obtained for CFD forKFD = 1 are compared with the values of CFR: $t_1$and t_2. If the values $t_{FD} \geq t1$, then the values of CFR provide not only the retaining of the bearing capacity in the event of a fire, but also its operability after extinguishing the fire. If $t_{FD}$is much lower thant1, then for fire resistance of load-bearing construction should be taken the value of t_{FD};

8) the methodology of quantitative prediction of the warranty period for the operation of the StEL-BC according to the obtained CFD requires further discussion and development, including the degradation characteristics of the structural state of the StEL-BC steel due to a fire and its quenching, as well as optimization of the forced extinguishing conditions. A comparison of the block diagrams for determining CFD using the known and offered methods is given in Fig. 3. Fig. 4 illustrates the need to use methods for determining CFR and CFD in the complexity and sequence described above, which is not provided for by known methods.

Steps for further improving the development and use of the methods for determining CFR and CFD are shown in Fig. 5.

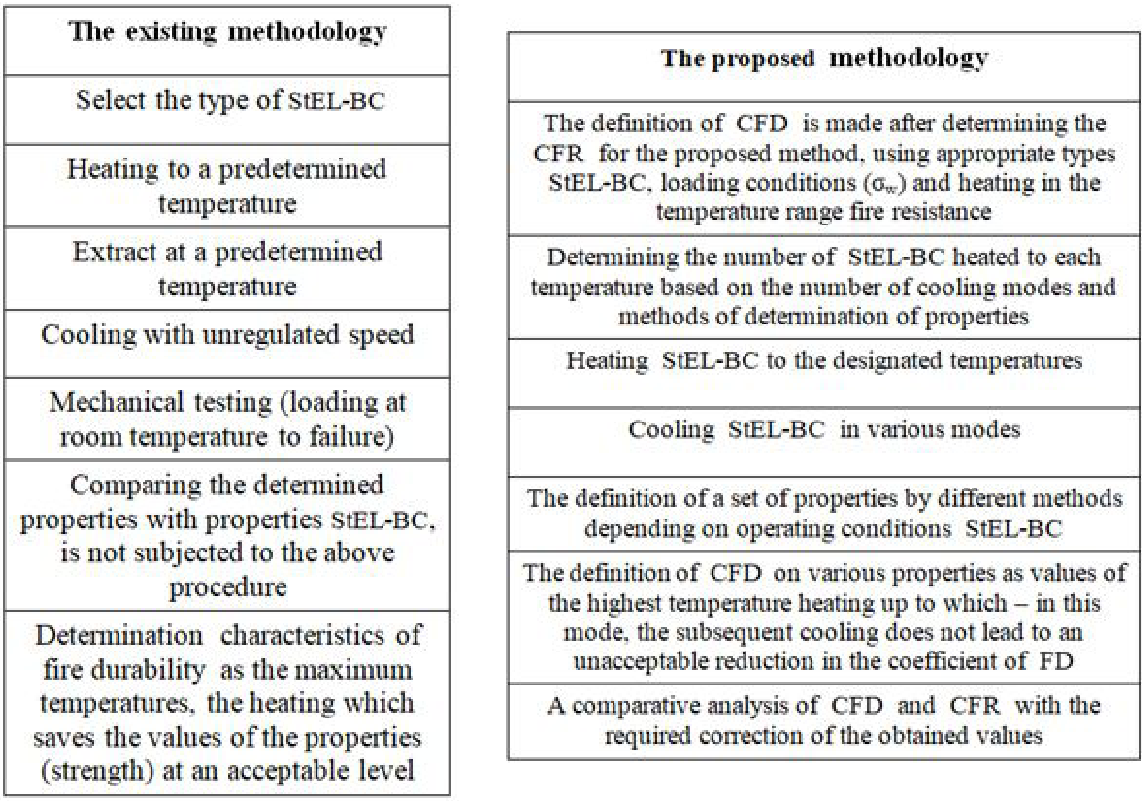

Figure 3. The block diagram of the existing and offered methods of determining the characteristics of fire durability

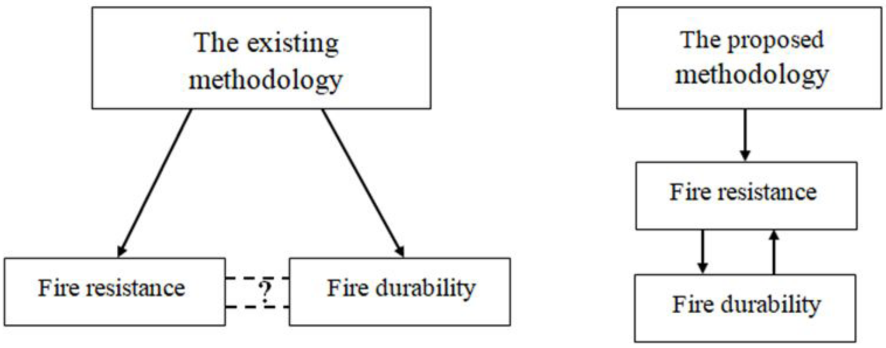

Figure 4. The offered sequence and relationship techniques to determine the characteristics of fire resistance and fire durability of the StEL-BC

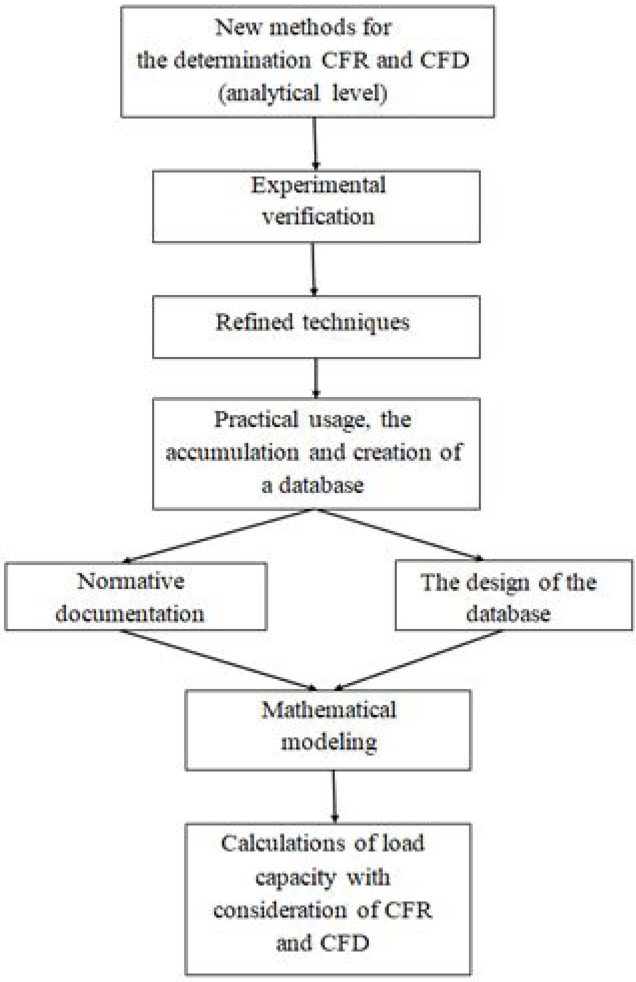

Figure 5. Development direction, improvement and use of new methods of determination of the characteristics of FR and FD

Conclusions

1. It is shown that the existing methods for determining CFR and CFD of the StEL-BC practically do not take into account a number of important actual conditions of thermomechanical influences due to fire (heating) and its quenching (cooling), the most dangerous loading schemes for specific types of bearing construction and the necessary level of all mechanical properties, that provides the possibility of post-fire operation of the StEL-BC.

2. General algorithms of new methods for determining CFR and CFD are offered with a much greater consideration of the factors listed above, which should ensure a greater approximation of CFR and CFD to their actual values for theStEL-BC.

3. It is established that CFR and CFD are closely connected and in large measuredetermine each other, which was not previously analyzed. For instance, the determined temperature range of fire resistance completely determines the corresponding range in the tests for fire durability. Therefore, the determination of CFR must always precede the determination of CFD. On the other hand, it is quite possible that the values of CFD will determine the temperature range of fire resistance.

4. The next stage in the development and refinement of the new methods for determining CFR and CFD in comparison with the existing ones is their experimental verification.

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