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Structural integrity of butt welded connection after fire exposure

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Abstract

The paper presents a study for fire behavior of the butt-welded joints subjected to low cycle fatigue loading, taken into account the post fire conditions and the possibility of welding strengthening. The need of in service life of a steel structure after being exposed to fire raises the problem of strengthening or replacement of some structural elements. There is presented a case study – a building structural element subjected to dynamic loading after fire exposure [1]. For the in case study, post fire investigations revealed several welding flaws including crack type flaws. An assessment was needed in order to determine the structural integrity and life assessment of some structural elements. From the fracture mechanics point of view, a Failure Assessment Diagrams level 2 – FAD 2 procedure was applied in order to determine the in service safety of the structure. Several flaws types were assessed and conclusions were taken. The results can be used for damage assessment and strengthening technique of post fire steel structures.

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Keywords: Type your keywords here, separated by semicolons ;

1. Introduction

Under fire exposure, steel structures are easy to lose strength but post fire assessment reports indicate that in most cases fire exposed steel structures retain much of their load bearing capacity after cooling [2]. Therefore, in many cases, after structural safety assessment fire exposed, steel structures can be reused. Establishing the post-fire residual capacity of steel structures has a major importance in overall assessment process.

When having a dynamic low cycling fatigue loaded steel structure, the procedure for assessment of the capacity of the structure, must include also the fracture mechanic approach. Numerous studies on the behavior of fire exposed

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bolted and welded connections are reported in the literature [3-7]. However, only few studies are undertaken on the post-fire behavior of dynamic loaded welded joints.

In the case of welded joints, chemical composition of base metal and weldment are different, and the effects of heating and cooling are similar to tempering and hardening, thus different transformations may occur in the base metal and the weld region. Therefore data on the mechanical properties of the weld is required for assessment in order to assess the whole capacity of fire-exposed steel structure.

In many cases, the parts affected by the fire are presenting visible deformations thus having an indicator of the tensions' redistribution generated by increased temperature, so much in the assessed element as in the adjacent elements.

The evaluation of the general stability of a steel construction affected by the fire is made on the basis of the inspection of building component elements and on the damage degree. According to ASTM E119 [8], carbon steels have to satisfy certain acceptance criteria, depending on the structural element's type.

The European norms [9] present recommendations and design rules for connections exposed to different temperatures. For example, the design strength of a full penetration butt weld, for temperatures up to 700°C, should be taken as equal to the strength of the weaker part of the connection using the appropriate reduction factors for structural steel.

Nevertheless, rules or recommendations regarding the post fire behavior of these connections do not exist, and therefore the structures and associated joint are evaluated based on similar experiences and the published literature. The problem arises when trying to choose the solutions of consolidation for some steel structures after a fire exposed.

The paper is presenting the results from tests on welded joints specimens made of S355JR after exposed to temperatures up to 650 °C high temperatures [1] and furthermore, an assessment of the structure from the fracture mechanics point of view in order to determine the structural integrity of the post fire structure, considering the discovered flaws.

In case of steel structures, existing of flaws in critical parts of structural elements may lead to failures of the element and in case of lack of redundancy, even to the collapse of the entire structure. An Engineering Critical Assessment (ECA) is an analysis, based on fracture mechanics principles, of whether or not a given flaw is safe from brittle fracture, fatigue, creep or plastic collapse under specified loading conditions. An ECA can therefore be used: during design, to assist in the choice of welding procedure and/or inspection techniques; during fabrication, to assess the significance of known defects which are unacceptable to a given code, or during operation, to assess flaws found in service and to make decisions as to whether they can safely remain, or whether down-rating/repair are necessary.

The analysis is carried out in accordance with the British Standard procedure BS 7910 ('Guide to methods for assessing the acceptability of flaws in metallic structures') [10].

The ECA concept (also termed 'fitness-for-purpose analysis') is widely accepted by a range of engineering industries.

For an analysis of a known flaw, the following information is needed:

- size, position and orientation of flaw,
- stresses acting on the region containing the flaw,
- toughness and tensile properties of the region containing the flaw,

The fact that knowledge of all these three aspects are necessary, implies a multidisciplinary approach, involving stress analysis, NDT expertise and materials engineering.

2. Case study – low cycle fatigue fire exposed element

In order to study the behavior of welded joints and the mode of their subsidence, there has been suggested an experimental program based on testing butt welded parts specimens extracted from a steel structure subject to the fire. The construction represented a wood industry manufacturing hall with steel columns, truss beams and longitudinal 10 to overhead crane steel beams (figure 1).

Fire action on the structure has been accidental. The time of exposure to heat was estimated at 60-90 minutes, with a random propagation of fire. Usually, the materials inside the building on fire provide accurate information related to temperature regime, by identifying the status and knowledge of their post-fire occurs melting temperature at which these materials. It has been estimated an average temperature of 600ºC.

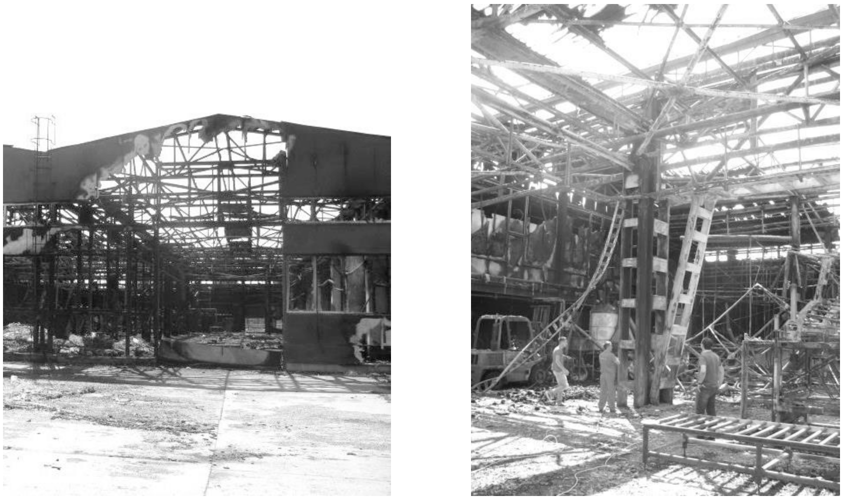
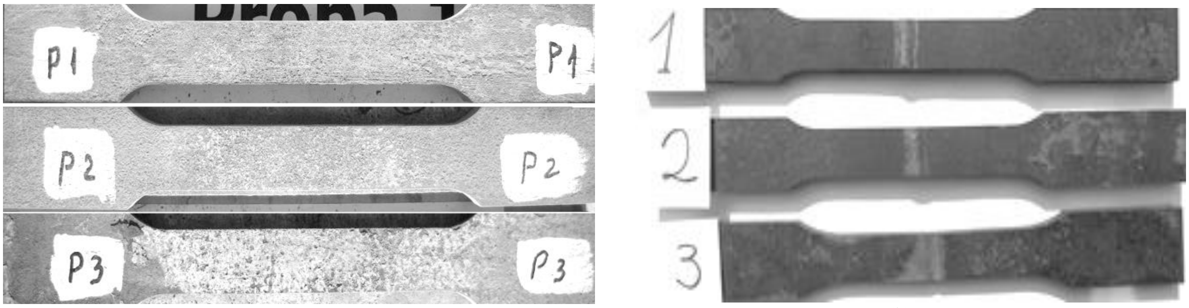


Fig. 1. Building affected by fire - photos taken after fire occurrence



(a) (b)

Fig. 2. Specimens for tensile tests (a) base material; (b) butt-welded joint

The sampling areas selection it was made taking into consideration all the aspects that could have modified the steel properties, so much as due to high temperatures, as well as to the structure's heavy cooling as a result of water usage in order to extinguish the fire [1]. A number of six specimens has been sampled (figure 2). In order to avoid heat-affected zones or mechanical stresses, all the specimens were cut using water jet cutting. Considering the study of the butt welded joints, there were taken samples from the overhead crane steel beam continuity joint – web area (figure 2b). For comparison the steel behavior, there were taken also specimens from the web area without butt welded joints. Following spectral analysis was determined the steel composition (table 1)

Table 1. The chemical steel composition

Measured	C%	Si%	Mn%	P%	S%	Cu%
Specimen P1	0,159	0,198	0,76	0,02	0,0025	0,171
Specimen P2	0,149	0,35	0,85	0,028	0,0030	0,245
Specimen P3	0,155	0,188	0,811	0,022	0,0027	0,183

From the point of view of the steel weldability properties, it was determined its value based on the published literature. The chemical composition influence on the welding of misaligned and poor aligned steels, it is expressed with the help of the equivalent carbon's concept, determined based on Deardon-O'Niell formula which was modeled after carbon-manganese steels:

$$CE = \%C + \%Mn/6 + (\%Cr+\%Mo+\%V)/5 + (\%Cu+\%Ni)/15 \qquad (1)$$

For the specimens material, the value of equivalent carbon is *CE=0.3*, which indicates a steel with good properties as it concerns weldability. All specimens were tested using hydraulic testing systems for tension application. There were measured: the minimum yield strength, the ultimate strength, strain and elongation.

2.1. Tensile strength testing results

The test results on the base material (BM) was concluded that steel has a yield strength of above 300 *MPa*. The base material is the one sampled from the steel structure exposed to flames during the fire and damaged by the abrupt changes of temperature. The ductility of the base steel from the sampled specimens is beyond the normal limit (figure 3). The ductility at the material level it is expressed through the following requirements: the relation between the ultimate strength "f_u" and the minimum yield strength "f_y" to be at least equal with 1,20 and the elongation at the failure to be at least equal with 20%.

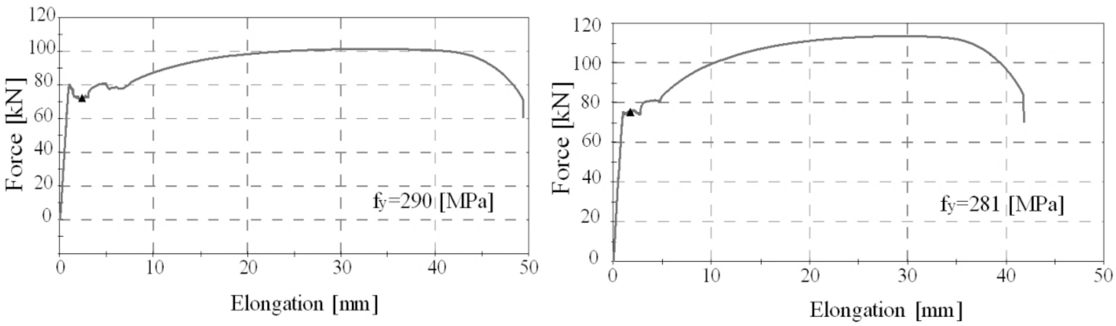


Fig. 3. Diagram force-elongation for base material steel

The results obtained on the butt weld joints have shown that the yield limit doesn't change significantly, but the elongation specific between the flowing limit and the breaking limit decreases in the case of welded elements (figure 4). During the cycle of heating-cooling at welding, the thermic source travels at a constant speed to the welding direction, which leads to the displacement of the welding bath, and respectively of the solidification front along with the thermic source. In the area of the welded seam, there are taking place a series of transformations and physico-chemical reactions depending on the temperature of the carbon steels [11].

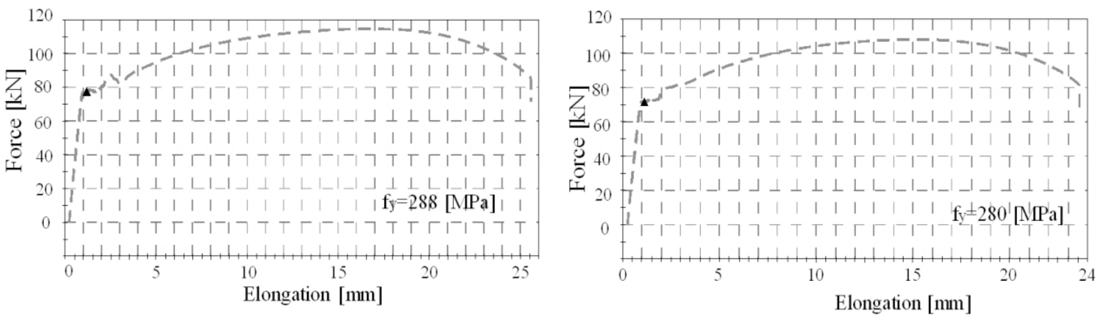


Fig. 4. Diagram force-elongation for butt welded connections

The chemical composition and the initial micro-structure of the welded material are elements which are influencing considerably the mechanical properties evolution of the welded joint. The metallurgical state of the material, the distribution and the nature of the inclusions, their quantity, the thermic treatment or the tensions' state from the material, will play a very important role in the formation and the properties of the welded joint micro-structure.

Following the base material tests results, can be concluded that the yield strength of steel does not change significantly as a result of the fire. However, in case of welded joints the material ductility decreases significantly. The ductility at the material by the welded decreases with approximate 28% (figure 5).

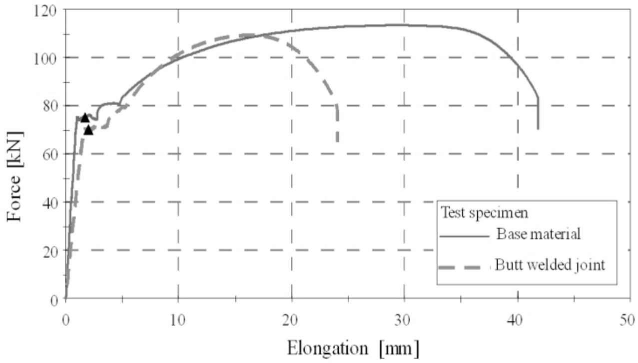


Fig. 5. Force-elongation curves for structural steel and butt welded joint

2.2. Fracture mechanics approach - assessment

Following the investigations, considering the initial site welding, there were discovered surface flaws in the continuity joints of the overhead crane steel beams (figure 6).

The determination of fracture toughness was done following the Charpy toughness correlation [12], considering a transitional behavior – Master curve approach, thus resulting K_{mat} = 84.10 $MPa{\cdot}m^{1/2}$.

In order to determine the critical value of the flaw it is used the assessment procedure is the FAD – level 2 [10]. The method is presenting an assessment line given by an equation of a curve and a cut-off line. If the assessment point is in the interior of the surface limited by the assessment line, the flaw is acceptable and if the assessment point is at the outside area, the flaw is considered unacceptable [10].

There were considered and assessed ten types of flaws – surface flaws (FP-SF type) and buried flaws (FP-BF type) and it was determined the limit value of the flaw for each flaw type and position (table 2 and figure 7). The input data for FAD-2 assessment was: yield strength f_Y = 355 *MPa*; ultimate strength f_u = 510 *MPa*, specific for S355J2 steel type; K_{mat} = 84.10 $MPa{\cdot}m^{1/2}$, P_m =289.44 N/mm^2- Primary stress with value determined following FEM analysis.

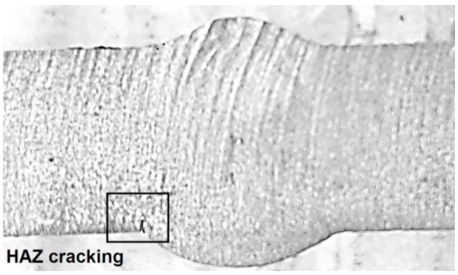
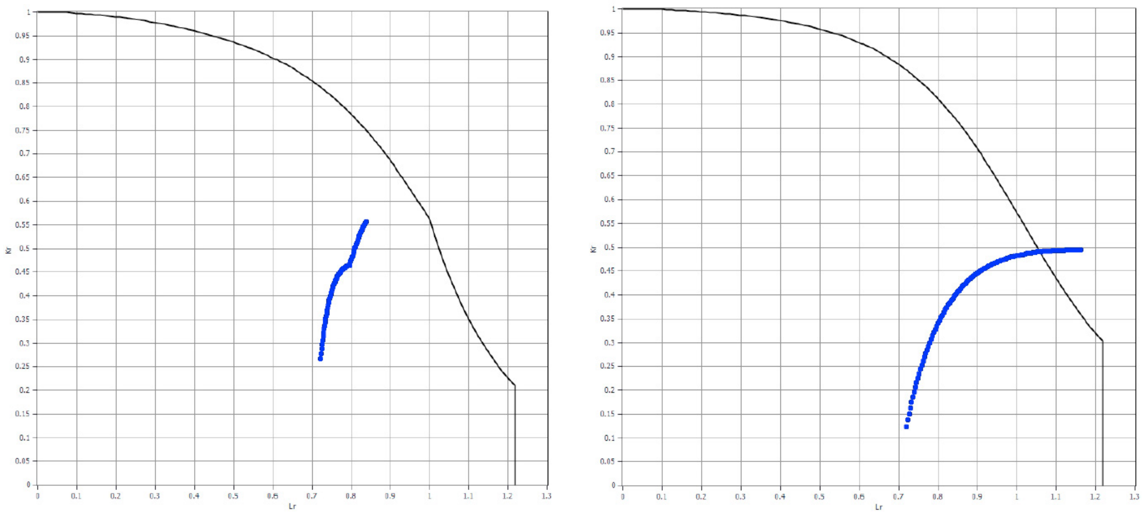


Fig. 6. Flaws in the butt weld

Table 2. FAD 2 – in case - flaws assed: geometry and critical flaw dimensions

Case name	B	W	$2a_0$	a_0	$2c_0$	p_0	r_0	h_0	t_w	Flaw Height	Flaw
	mm	*mm*	*mm*	*mm*	*mm*	*mm*	*mm*	*mm*	*m*	*mm*	*mm*
FP-SF-1	16	200		5	30					5.690	34.440
FP-SF-2	32.63	200		5	30					18.261	49.395
FP-SF-3	200	32.63		5	10					10.734	23.800
FP-SF-4	25	200		5	30					14.755	42.870
FP-SF-5	25	120		5	30					14.505	42.420
FP-BF-1	16	200	5		30	3				7.590	30.160
FP-BF-2	32.63	200	5		30	3				10.984	30.360
FP-BF-3	200	32.63	5		10	3				OK	OK
FP-BF-4	25	200	5		30	3				10.190	30.365
FP-BF-5	25	120	5		30	3				10.106	30.360



(a) (b)

Fig. 7. Critical flaws assessment: (a) FP-SF-2; (b) FP-BF-2

3. Conclusions

The paper presents a study for fire behavior of the butt-welded joints subjected to low cycle fatigue loading, taken into account the post fire conditions and the possibility of welding strengthening. There is presented a case study – a building structural element subjected to dynamic loading after fire exposure. For the in case study, post fire investigations revealed several welding flaws including crack type flaws. From the fracture mechanics point of view, a Failure Assessment Diagrams level 2 – FAD 2 procedure was applied in order to determine the in service safety of the structure. There were considered surface type flaws and buried type flaws. The results revealed the buried flaw type as a critical type one. The assessment results can be used for damage assessment and strengthening technique of post fire steel structures.

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