Assessment of integrity and remaining working life of welded steel structures

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Abstract. Analyzing the period of exploitation of welded steel structures it can be concluded that they are predominantly exposed to the action of variable load. The welded joint as the largest stress concentrator due to the heterogeneity of structural, mechanical and operational properties is a key problem that is further complicated by the possible and realistically probable presence of crack-type faults. The assessment of integrity largely depends on a comprehensive analysis of the welded joint as the most critical place of welded steel structures. Integrity assessment is a necessary obligation for extending the working life, as well as revitalization, as a way to keep the structures in operation, despite the long period of exploitation. This paper presented an analysis of the process of fatigue crack initiation and growth, i.e. an assessment of the of the welded steel structures’ integrity and remaining service life under the influence of variable load.

1. Introduction
Welded steel structures in most cases represent significant and responsible systems whose integrity and service life must be viewed from several aspects. The conditions in which the structure was exposed, i.e. in which it works, significantly affect its integrity and service life, therefore the determination of the service life is imposed as a necessity. Operating conditions imply a set of parameters that affect the structure by directly or indirectly affecting the three basic performances: reliability, safety and durability. [1]

The causes of structural failures can generally be divided into four groups:
- causes or design errors,
- manufacturing and/or assembly errors,
- errors caused by deviation of operating conditions, and
- errors as a result of accidental circumstances.

Prevention of failure of welded structures due to weakened material by changing its physical and chemical properties in long-term operation or increasing errors above the allowable level can be achieved by systematic and continuous monitoring of material properties and the occurrence and development of defects in base material and welded joints.

It is known that certain components, when it comes to process equipment operating in conditions of low and high temperatures and pressures such as pressure vessels, are critical places due to specific operating parameters. This is especially significant, knowing that many process equipment plants around the world have been in use for so long time that individual components have been in use for
longer than the projected service life. Eventual failure of these components would pose a danger not only to the operation of the plant but also to the environment surrounding them. [2]

Welded components are also a problem, where the possibility of crack-type defects must not be ruled out. In case of such errors, it is necessary to accurately assess the integrity of the component and make a decision on its further exploitation. The integrity of welded joints is a very important factor in the exploitation of welded structures due to their heterogeneity and tendency to the appearance and growth of cracks as a consequence of the welding process. Therefore, it can be said that welded joints represent the most critical part of welded structures. [2]

In practice, in most cases, the failure of welded structures occurs due to fatigue. Research and analysis of the impact of operating conditions on the behaviour of the base material and components of the structure welded joint intended for operation under conditions of variable load, all in order to assess the integrity and remaining life of the structure, i.e. extending the service life have been increasingly present today. [3]

2. Analysis of welded structures

2.1. Materials and technology of construction
The service life of all welded structures has been conditioned by the choice of materials of appropriate properties and quality, well-chosen and implemented production and welding technology, provided that the loads were in line with expectations.

As a starting point on the applicability of the materials used in structures are the characteristics obtained by tensile testing such as yield stress, tensile strength, elongation at break, and modulus of elasticity. It is these characteristics that describe the mechanical behavior of materials and are the basis for the construction of parts. In addition to the basic characteristics of the material, one should certainly know additional data on the behavior of materials obtained by impact testing such as refractive energy which has been most often used for comparative analysis in the selection of materials. [3]

In order to ensure that the integrity of the structure remains undamaged during the expected service life, in addition to the choice of material, the activities that precede its commissioning, defining the geometry and the welding process itself should also be taken into account. When defining these activities, the most important thing is to avoid potential stress concentrations which are the most favorable places for cracks to start (and later grow). Furthermore, the welded joint due to the heterogeneity of structural, mechanical and operational properties as well as due to the presence of defects (blowhole, slag, cracks) caused that for the operational safety of welded steel structures, the most important micromechanical characteristics describing the occurrence and growth of cracks under variable load. [3,4,5]

2.2. Influence of cracks on welded structures
Problems occurring in the structure during the exploitation period most often happen due to insufficient resistance of the material to the formation and growth of cracks, especially in welded joints. In solving this problem, the classical fracture mechanics has been applied by comparative analysis of the crack growth force on the one hand and the resistance of the material on the other hand. Fracture mechanics aims to significantly reduce the risks of fractures of structures, which can often have catastrophic consequences (especially in welded pressure vessels).

This procedure includes detecting the location of defects in the structure and determining their impact on its integrity, i.e. determining the moment when these defects (primarily cracks) would exceed the standards prescribed by the standards and lead to failure. [6]

The application of fracture mechanics has been based on the determination of appropriate parameters (stress intensity factor, crack tip opening and J-integral) on the basis of which the remaining service life of the structure was determined. These parameters are related to the presence of cracks which in the case of welded joints have been inevitable, to a greater or lesser extent. [7]
Depending on their position and the loads acting in their environment, these cracks can start to grow and when they reach a certain length they can lead to failure and fracture of the structure. Therefore, it is very important to monitor their behaviour during exploitation as well as to prevent their occurrence (although it is impossible to do it fully), and/or to keep them within the permitted limits which depend primarily on the conditions of exploitation.

2.3. Cracks under the influence of variable loads
Parts of structures and machines can be exposed to variable loads during operation, both in size and in the direction of action. Due to the long-term effect of the variable load there is a gradual destruction of the material, i.e. fatigue, which can result in a fracture called fatigue fracture. It was estimated that 50-90% of all structural damage in operation occurs due to material fatigue.

Fatigue represents the gradual destruction of a material until the moment when its cross section can no longer bear the load and due to changes in the material caused by a load that is cyclical in nature, i.e. whose value changes over time. In such conditions and after a sufficiently large number of cycles, the fracture of the structure can occur at voltages significantly lower than the yield strength, in contrast to static fracture, which is a special problem. It is generally considered that the total lifetime consists of the crack initiation period and the crack propagation period until the final fracture. With this in mind, researches have been mainly focused on establishing independent procedures for the formation and growth of cyclic cracks. [8]

The collected knowledge on fatigue crack growth made it possible to determine with sufficient certainty the remaining life of the crack component and thus assess whether the component can operate until the next inspection.

3. Integrity of welded structures
The integrity of structures, i.e. their ability to function in an inefficient and safe way in the intended conditions of exploitation is a very important aspect from the point of view of safety.

The term structural integrity assessment means the following:
• analysis of the existing condition of the structure including diagnostics of behaviour and failure with an assessment of the remaining strength and service life;
• the structure revitalization with the application of measures in order to preserve functionality.

Based on the input data, most often obtained experimentally, it is possible to determine the actual behaviour of the structure during operation, to estimate the service life, but also the causes of bad behaviour or even the failure of the structure. Based on this knowledge, the parameters of choices and decisions were obtained, the realisation of which improves the construction, and thus prolongs the service life. [10]

The application of failure analysis methods and the determination of the estimated service life of a welded structure imply knowledge of fracture mechanics, methods of stress and strain testing and knowledge of mathematical and statistical methods in data analysis and processing. Taking into account the operating conditions, the following parameters characterising the welded structure and its joints are to be usually checked: fatigue strength, resistance to brittle fracture and permanent strength (often in combination with fatigue strength if the operating temperature causes creep). [11]

Estimation of the service life of structures loaded with variable loads is also needed to define the control interval for detecting and eliminating damage caused in operation. The procedure for determining the fatigue characteristics and estimating the service life of a structure exposed to a variable load was shown in figure 1.
The process of fatigue and fracture can be divided into three time phases:

- The phase of micro-crack formation \( a_0 \) and its further growth to a size called an engineering crack, \( a_0 \). This may be the minimum crack length that can be detected, \( a_{pr} \).
- Phase of stable macro-crack growth until instability occurs at length \( a_{cr} \).
- Phase of unstable growth and final fracture.

Experience gained by testing aircraft structures with simulated loads corresponding to flight conditions has shown that the crack formation time for most structural details was relatively short and that the life of the structure was determined by the time required for crack growth to fracture, which was about 95% of life. Therefore, it is common to view the entire process of damage accumulation only as a crack growth process.

In order to ensure the safety of welded components, it is necessary to clarify their behaviour under the action of low-cycle fatigue and in the presence of crack type error (fatigue crack growth rate \( da/dN \), and the fatigue threshold \( \Delta K_{th} \)), as well as the behavior under the action of shock (impulse) load on parts that contain a notch-type stress concentration.

Analysis of the stress state and deformation at the top of the rising fatigue crack using linear-elastic fracture mechanics (LEML) led to the formulation of the Paris equation, which relates the fatigue crack growth rate to the range of stress intensity factors at the crack tip. [11]

Although the Paris equation of crack growth was not valid in the whole range, between low velocities near the fatigue threshold, \( \Delta K_{th} \) in figure 2, and high velocities (\( K_{IC} \)) the large linear mean part of the curve covered by the Paris relation proved to be by far the most important from a practical point of view. At the same time it allows a distinction to be made between the initiation and growth of a fatigue crack. From sharp stress concentrators, under conditions of variable load, after a certain number of cycles, a crack will be initiated and its growth will occur if the fatigue threshold \( \Delta K_{th} \) is exceeded.

As the structure will not be endangered under certain conditions until the crack reaches a critical size, it is possible, with previous analyses, to allow the exploitation of the structure with a crack during the crack growth period. An important piece of information for the decision on further exploitation of the structure is the knowledge of the crack growth rate depending on the load that acts on it.

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**Figure 1.** Methodology for determining fatigue characteristics and estimating the service life of structures exposed to variable loads
Figure 2. Functional dependence of fatigue growth rate cracks and stress intensity ranges; \( \frac{da}{dN} = f(\Delta K, R) \) [2]

If the Paris equation for determining the crack growth rate:

\[
\frac{da}{dN} = C \cdot (\Delta K)^m
\]

is presented in the following form:

\[
\frac{da}{dN} = \frac{\Delta a}{\Delta N} = f(K_{\text{max}}, \text{or } \Delta K, R, \ldots)
\]

The structure service life can be determined by integrating the previous equation from the initial \((a_0)\) to the final crack length \((a_f)\):

\[
T_k = \int_{a_0}^{a_f} \frac{da}{f(K_{\text{max}}, \ldots)}
\]

Estimating the fatigue life under conditions of constant load amplitude was given by the precise integration of the Paris equation written in the form:

\[
\left( \frac{da}{dN} \right)_i = C_i (\Delta K)^{m_i}
\]

where: \(C_i\) and \(m_i\) are constants, i.e. exponents for certain values of the stress intensity range \(\Delta K\), for which the equation also holds.

Therefore the lifespan of the construction is:

\[
T_k = \sum \Delta T_j = \int_{a_0}^{a_i} \frac{da}{C_j (\Delta K)^{m_j}} + \int_{a_i}^{a_{i-1}} \frac{da}{C_{i-1} (\Delta K)^{m_{i-1}}} + \ldots + \int_{a_{j-1}}^{a_{j}} \frac{da}{C_{j-1} (\Delta K)^{m_{j-1}}}
\]

Models for predicting fatigue life under variable amplitude (load spectrum) originate from various researchers. These models have been based on the crack growth rate delay due to overload and provide an estimate for certain materials and load conditions.
4. Conclusion
This paper presented a general analysis and presentation of the influence of crack-type defects that occur in welded structures and the process of assessing the integrity and service life of welded steel structures based on the application of fracture mechanics. Fracture mechanics is extremely suitable for determining the development of damage which occurs as a result of crack growth. In cases where the life depends on the crack growth the fracture mechanic is able to determine the residual strength and life at any point in exploitation. However, the assessment of the condition of the structure was not based solely on the examination of cracks, as this may be too late from the point of view of preventing sudden fractures.

For successful and economical maintenance of components in order to prevent sudden failures and fractures, the reduction of strength parameters and service life of structures should be determined and taken into account. This paper can be a good basis for more detailed research of the influence of variable loads on the process of initiation and crack growth in welded steel structures, the results of which can be the basis for reliable assessment of integrity and remaining life of welded steel structures exposed to variable loads during exploitation.

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