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Fatigue Life Prediction of Welded Box Structures

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Прогнозирование усталостной долговечности сварных коробчатых конструкций

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Проведено прогнозирование усталостной долговечности сварных коробчатых конструкций. Результаты расчета усталостной долговечности с использованием аналитической схемы, базирующейся на объемном методе, хорошо согласуются с соответствующими экспериментальными данными.

Ключевые слова: сварные коробчатые конструкции, объемный метод, относительный градиент напряжений, эффективное напряжение, отношение усталостной прочности образца без надреза к усталостной прочности образца с надрезом.

Notation

σ_{eff} – effective stress

$\sigma_{yy}(x)$ – normalized fatigue crack opening stress

χ – relative stress gradient

x_{eff} – effective distance

σ_g – global stress

$\phi(x)$ – weight function, which depends upon the distance x and the relative stress gradient

Introduction. Unfilled boxes of square or rectangular cross sections are usually applied in metal constructions since they combine both high stiffness and low weight. These structural elements are susceptible to fatigue failure for various causes (Fig. 1). Usually, the welding process is held responsible for structure weakening and the reduced fatigue strength because of the heterogeneities created within joined plates (Fig. 2). In fact, metal fusion followed by rapid cooling results in residual stress generation in box walls.

Stress concentration zones are observed to be located along the weld line, which is attributed to global geometrical discontinuities and specifically metal filling at weld base line. Under bending loading conditions, weld line failure is initiated as longitudinal crack at the slab intrados subjected to tensile stresses. Life prediction of welded boxes did not retain enough research work. Insofar as any complex structure consists of several elementary joints, it is recommended, in order to predict the structure fatigue life, to study separately each joint's endurance limit. The latter is function of weld quality in terms of weld line geometry and induced residual stress field either by the assembling process or by inherent microscopic defects. Welded joint behavior can be precisely assessed under cyclic loading through laboratory experiments using specimens with representative dimensions compared to the actual structures. Based on such experiments at constant or variable load amplitude, each type of welded joint is then characterized by an allowable stress corresponding to structure life and estimated service loadings.

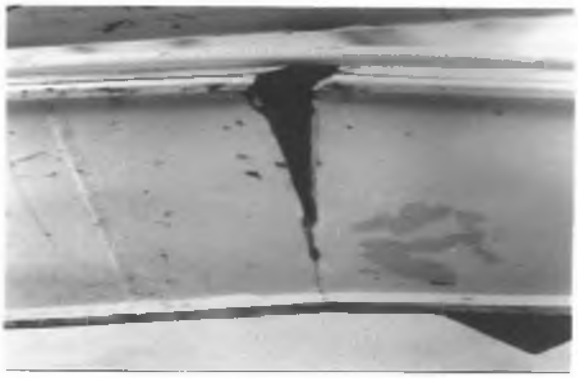

Fig. 1. Cracked part of excavator bucket.

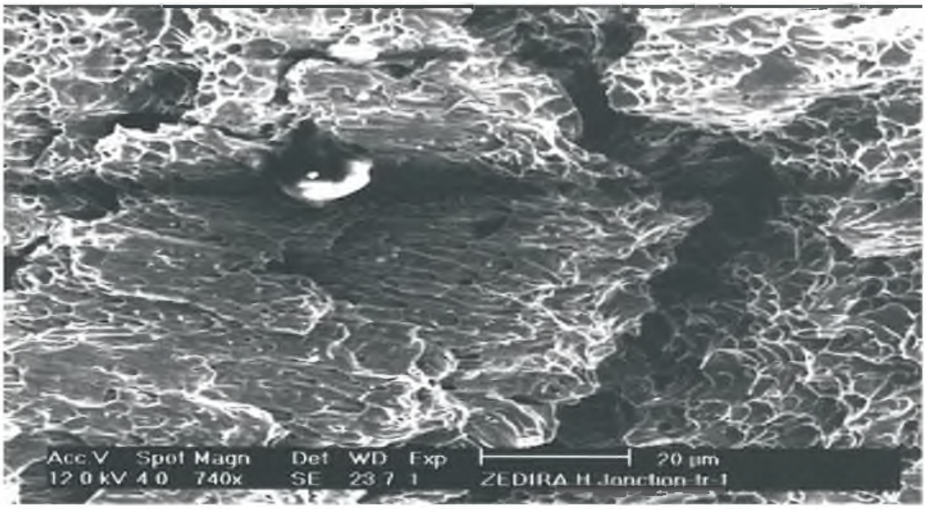

Fig. 2. Micrograph of the weld joint after cracking.

1. **Experimental**. Welded boxes with dimensions 100×100×300 mm and wall thickness 3 mm were produced from welding steel Q36 plates using SG-3 steel as the weld metal. Chemical compositions and mechanical properties of these steels purchased from the CPG, Algeria, are given in Tables 1 and 2, respectively. These welded boxes simulated those used in excavator loading wheels depicted in Fig. 3.

Table 1

Chemical Composition of Steels Q36 and SG-3

Material	C, % max	Si, % max	Mn, % max	P, % max	S, % max	Ti, % max
Q36	0.16	0.50	1.60	0.03	0.03	0.12
SG-3	0.07–0.14	0.80–1.20	1.60–1.90	–	–	–

Table 2

Mechanical Properties of Steels Q36 and SG-3

Material	R_e, MPa	R_m, MPa	$K_{cv\,\min}$, J	Elongation, %
Q36	355	490–690	27	25
SG-3	470	590	–	30

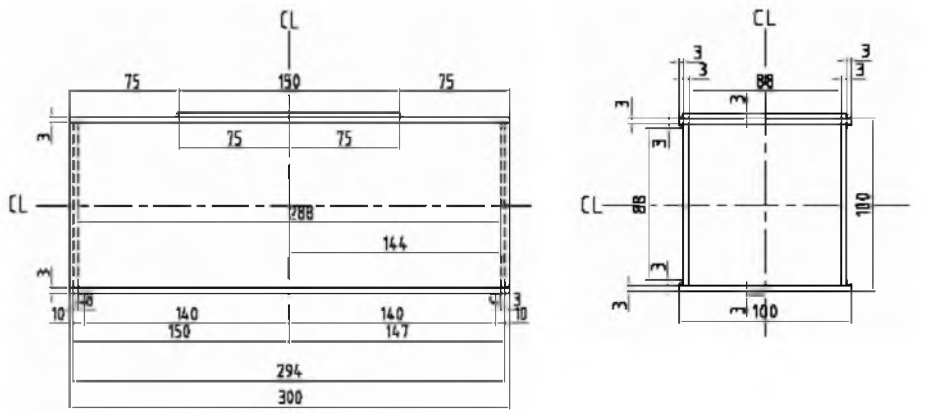

Fig. 3. Geometry of the welded box structures of loading wheels.

Using the Instron test machine providing the maximal tensile/compressive load ±100 kN, welded boxes were subjected to three-point-bending cyclic loading with frequency of 6 Hz and load ratio $R = \sigma_{\min}/\sigma_{\max} = 0.1$ (see Fig. 4). For construction of the experimental fatigue curve we tested 6 welded boxes.

2. **Volumetric Approach**. In order to take into account the notch effect, a notion of fatigue notch factor is used [1]. The most practical definition of fatigue notch factor k_f is the ratio of the fatigue strength of smooth specimen to that of notched specimens under the same test conditions and the same number of cycles

$$k_f = \frac{\sigma_s}{\sigma_n}, \tag{1}$$

where σ_s and σ_n are smooth and notched specimen fatigue strength, respectively.

Fig. 4. Three-point bending test of welded box structures.

However, no general, brief, practical and low-cost method for determination of k_f has yet been formulated [2]. Therefore, as an alternative, the volumetric approach has been introduced [3–5] for modeling of the fatigue failure process. The assumption made in this approach is that the fatigue failure needs a physical volume to occur. The method is applied for an elastoplastic stress distribution calculated using the finite element method and taking into consideration the particular material cyclic behavior, in order to allow for the plastic and damage relaxation. The effective stress is first determined as the stress value corresponding to the stress distribution for the effective distance. For application of the volumetric approach one needs the fatigue curve, the cyclic stress-strain curve and the finite element analysis for determination of the stress distribution near the notch tip.

2.1. **Graphical Method of the Volumetric Approach [3–5]**. The relative stress gradient is defined as the ratio between the first derivative of stress distribution function and the stress value at a point:

$$\chi = \frac{1}{\sigma_{yy}(x)} \frac{d\sigma_{yy}}{dx}. \tag{2}$$

The effective distance x_{eff} is an inflexion point, corresponding to the minimum value of the relative stress gradient. In the volumetric approach, the effective distance is considered to be the boundary of the stress relaxation and fatigue process zone (see Fig. 5).

The effective stress σ_{eff} is defined as the average weighted stress in the fatigue process volume:

$$\sigma_{eff} = \iiint_{V_{eff}} \sigma_{yy}(x) dV. \tag{3}$$

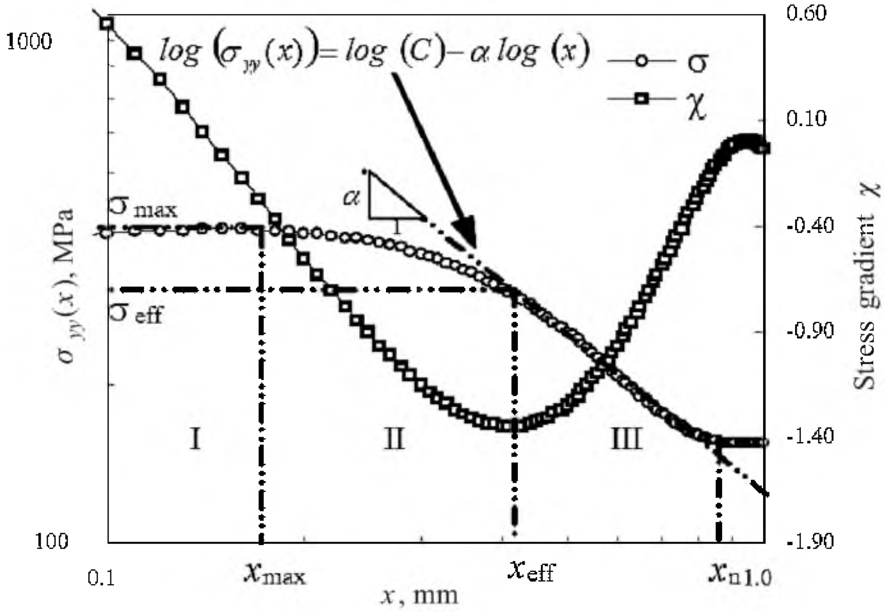

Fig. 5. A typical elastic-plastic fatigue crack opening stress distribution for notch root and relative stress gradient [6].

During fatigue propagation, the crack path is always normal to the maximum principal stress. In bending, this stress is conventionally denoted by $\sigma_{yy}(x)$. We can write in bi-dimensional case:

$$\sigma_{eff} = \frac{1}{x_{eff}} \int_{0}^{x_{eff}} \sigma_{yy}(x) dx. \tag{4}$$

2.1. **Analytical Method of the Volumetric Approach**. In order to use the analytical method based on the volumetric approach, it is needed to perform an elastic or elastoplastic finite element calculation, by using the real law of behavior of material. Material behavior equation is used taking into account the relationship between stress and strain in the form:

$$\varepsilon_a = \frac{\sigma_a}{E} + \left(\frac{\sigma_a}{K'}\right)^{1/n'}. \tag{5}$$

The steps consist in obtaining the stress distribution as a function and subsequently establishing the equation of the opening stress $\sigma_{yy}(x)$. A curve fitting is then performed to assess a polynomial representation in the form:

$$\sigma_{yy}(x) = \sum_{i=0}^{n} a_i x^i. \tag{6}$$

Relative stress gradient $\chi(x)$ is given by the relationship:

$$\chi(x)=\frac{1}{\sigma_{yy}(x)}\frac{d\sigma_{yy}(x)}{dx}=\frac{\sum_{i=0}^{n} ia_i x^{i-1}}{\sum_{i=0}^{n} a_i x^{i}}. \tag{7}$$

Effective distance x_{eff} is given by [7]:

$$\frac{d\chi(x)}{dx}=0\Rightarrow x_{eff}, \tag{8}$$

$$x_{eff}\approx\frac{-a_1}{2a_2}-\frac{3a_3a_1^2}{8a_2^3}+\frac{-9a_3^2a_1^3+4a_4a_2a_1^3}{16a_2^5}. \tag{9}$$

Fatigue notch factor can be written as below [6]:

$$k_f=\frac{1}{x_{eff}\sigma_g}\int_0^{x_{eff}}\sigma_{yy}(x)(1-x\chi)dx, \tag{10}$$

$$\phi(x)=1-x\chi. \tag{11}$$

For $i=4$ we can write relationship (6) as

$$\sigma_{yy}(x)=a_0+a_1x+a_2x^2+a_3x^3+a_4x^4. \tag{12}$$

Finally, k_f is given by relationship (13):

$$k_f=\frac{1}{\sigma_g}\left(a_0-\frac{a_2}{3}x_{eff}^2-\frac{a_3}{2}x_{eff}^3-\frac{3a_4}{5}x_{eff}^4\right). \tag{13}$$

The effective stress is given by (14):

$$\sigma_{eff}=k_f\sigma_g. \tag{14}$$

3. **Elastoplastic FEM Analysis**. In order to apply the volumetric approach to these experimental results, finite element calculation of the stress distribution at the welded joint has been accomplished using a multi-purpose finite element Cast3m software developed at the CEA (French Atomic Research Center). For the steel Q36 the following parameters of stress–strain diagram were obtained (Fig. 6):

- hardening coefficient $K'=485$;
- cyclic hardening exponent $n'=0.0794$.

Table 3

FEM Calculation Results for Specimen under Study and the Respective Loading Conditions

σ_g, MPa	$F_{\max}$, kN	$F_{\min}$, kN	$R = F_{\min}/F_{\max}$	k_f	σ_{eff}, MPa
106	90	9	0.1	1.33	141

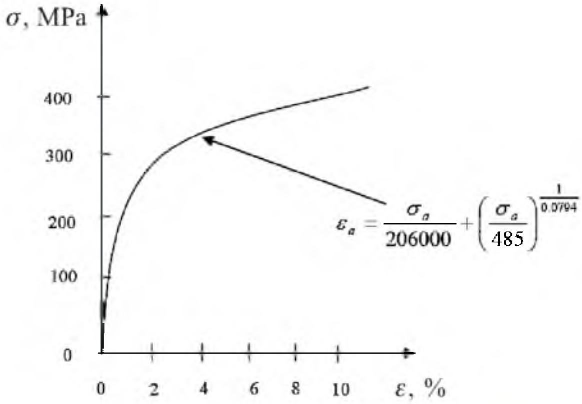

Fig. 6. Cyclic stress–strain curve of Q36 steel.

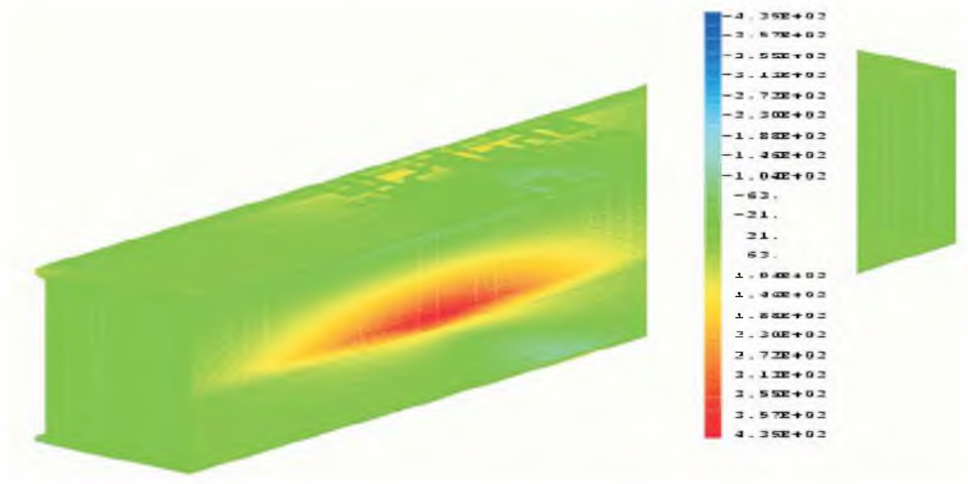

Fig. 7. Finite element analysis for a welded box.

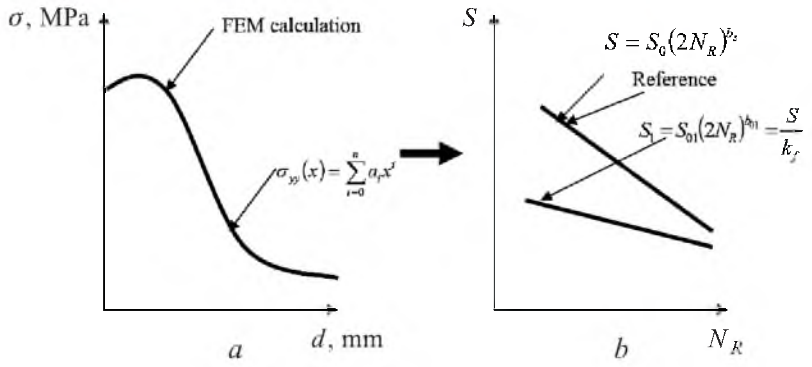

Fig. 8. Volumetric approach procedures.

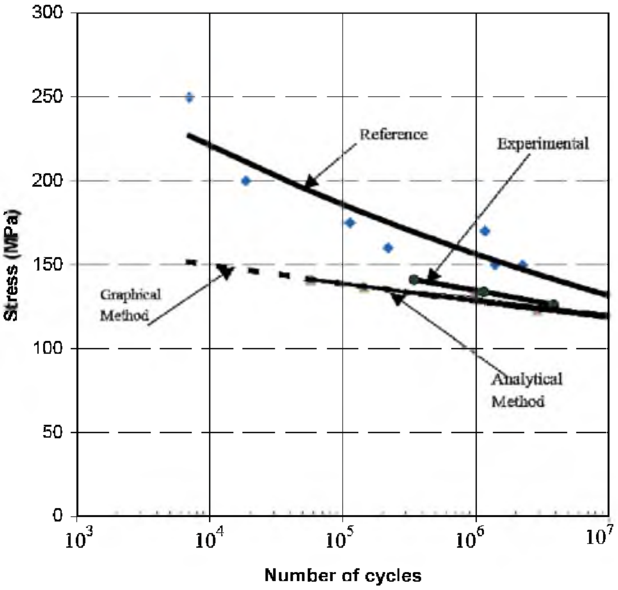

Fig. 9. Comparison of the results.

Based on the calculated stress distribution (Fig. 7), the effective stress is calculated according to the procedure described in Fig. 8a and plotted versus the experimental number of cycles to failure as shown on Fig. 8b. In tabular form the effective stress is given it Table 3. The effective stress obtained by volumetric approach reported on fatigue reference curve gives directly the fatigue life of the welded box structure (Fig. 9).

Conclusions. A simple procedure for fatigue life estimation based on volumetric approach is illustrated, using the reference fatigue curve, the material behavior curve, and finite element analysis. The fatigue life prediction, which is carried out by the volumetric approach, has very good agreement with experimental results. The advantages of the volumetric method include the possibility of predicting fatigue life for many loading cases using notched geometry welded structures, the absence of the empirical and ambiguous coefficients used in traditional methods and the opportunity to obtain rapid and cost-effective results using a finite element method. The volumetric approach makes it possible to predict fatigue life for arbitrary structures. To apply this method, one needs only 1) reference fatigue curve and 2) cyclic stress–strain curve of the material. The effective stress obtained by the volumetric approach superimposed on the reference fatigue curve gives directly the fatigue life of the structure.

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Резюме

Проведено прогнозування довговічності зварних коробчастих конструкцій від утомленості. Результати розрахунку довговічності від утомленості з

використанням аналітичної схеми, що базується на об'ємному методі, добре узгоджуються з відповідними експериментальними даними.

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