

Fatigue life evaluation of girth butt weld within welded cast steel joints based on the extrapolation notch stress method

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Abstract: The fatigue life evaluation of the girth butt weld within the welded cast steel joint was studied based on the extrapolation notch stress method. Firstly, the mesh sensitivity of the finite element model of the welded cast steel joint was analyzed to determine the optimal mesh size. Based on the stress field analysis of the finite element model of the welded cast steel joint at the weld toe and weld root, the sharp model of the extrapolation notch stress method was applied to derive the effective notch stress of the rounded model belonging to the effective notch stress method, in which the key problem is to calculate the extrapolation point C , and the extrapolation point C has an exponential function relationship with the geometric parameters of the welded cast steel joint. By setting different values of geometric parameters, the corresponding value of parameter C is calculated, and then the functional relationship between the extrapolation point C and the geometric parameters can be obtained by the multiple linear regression analysis. Meanwhile, the fatigue life evaluation of the girth butt weld within welded cast steel joints based on the effective notch stress was performed according to the guideline recommended by the IIW (International Institute of Welding). The results indicate that the extrapolation notch stress method can effectively simplify the process of calculating the effective notch stress and accurately evaluate the fatigue life of the girth butt weld within welded cast steel joints.

Key words: welded cast steel joint; girth butt weld; extrapolation notch stress method; effective notch stress method; fatigue life evaluation

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Cast steel joints (CSJs) have broad application prospects^[1-7], such as in bridge engineering, offshore

oil platforms, wind turbine towers, cranes, and other engineering fields. The CSJ acts as a connecting member between steel pipes and can solve the welding problem that occurs in the intersection portion within steel tubular joints. The welded CSJ is divided into the base material part and the weld seam part, so its mechanical performances are determined by the two parts above. The mechanical properties of the welded CSJ mainly include static performance and fatigue performance. Regarding the static performance of CSJ, many research studies^[8-11] have been carried out worldwide. The fatigue performance of the welded CSJ is complicated^[12]. As the welding process leads to the initial defects within the weld part, the fatigue failure of welded structures is ultimately determined by the fatigue performance of the weld seam part^[13-19], and the fatigue problem of the welded cast steel joint is no exception^[1,20]. The results of recent experimental studies^[6-7,20-21] indicate that the fatigue problem of welded cast steel joints is located at the weld seam part. Studies on the fatigue life evaluation of the welded CSJ are mainly based on the nominal stress parameter^[12], for complicated welded CSJs under complex loading conditions. There is no consistent way to define the nominal stress within the welded CSJ. Therefore, the fatigue life evaluation of welded CSJs needs to be further addressed.

The effective notch stress method (ENSM) is widely applied in the fatigue life evaluation of welded structures^[22]. Effective notch stress can represent the local stress state of the welded structure in fatigue life evaluation. Only one $S-N$ curve is needed for various types of steel welded joints^[22] in the fatigue life evaluation, thus avoiding the subjectivity and uncertainty of selecting different $S-N$ curves for different welded structures under different load modes in the nominal stress method and the structural hot spot stress method. Furthermore, the effective notch stress method can be applied in the case of weld root failure, which is currently difficult to solve using the structural hot spot stress method^[23].

The calculation of the effective notch stress relies entirely on numerical finite element simulations, which re-

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quire creating a virtual radius of 1 mm (in the case of plate thickness greater than 5 mm) at the weld toe or the weld root and a very fine element mesh should be satisfied. Compared with the nominal stress method and the structural hot spot stress method, a fine finite element model greatly increases the mesh work of the finite element model. In this article, an extrapolation notch stress method proposed by Pradana et al.^[24] is used to simplify the process of calculating the effective notch stress at the girth butt weld of welded cast steel joints, and its applicability of calculating effective notch stress at the root of welded CSJ is verified. Then, the fatigue life evaluation of the girth butt weld within welded cast steel joints is carried out according to the guideline recommended by the IIW^[22].

1 The Extrapolation Notch Stress Method

The process of calculating the effective notch stress by the extrapolation notch stress method is similar to that of using the extrapolation strategy to determine the structural hot spot stress at the weld toe of the welded structure in the IIW specification^[25]. In the procedure of calculating the effective notch stress by the extrapolation notch stress method, it is not necessary to establish a virtual notch radius of 1 mm at the weld toe/root combined with very fine finite element mesh, thus greatly simplifying the mesh work of finite element models, especially for welded structures with complex geometry, such as a welded CSJ. The detailed content of the extrapolation notch stress method for calculating the effective notch stress is described below, and more information about this method can be found in Refs. [24, 26–27].

1.1 Basic theory

The stress field of the finite element model exhibits stress singularity at the vicinity of the weld toe or the weld root in welded structures. The irregular geometry of the weld seam and the microscopic defects within the weld seam lead to the notch effect at the weld toe or the weld root. According to the linear elastic theory of the material, the calculated notch stress at the weld toe or the weld root approaches infinity. However, materials at the local weld toe or the weld root exhibit obvious anisotropy properties, thus directly constraining and reducing the local peak stress at the weld toe or the weld root. Therefore, the notch stress solved by the notch stress field equation does not represent the actual stress state at the weld location. Sonsino et al.^[22] proposed the effective notch stress parameter to represent the actual stress state at the notch location (weld toe or weld root). The peak stress of the original notch location was weakened by increasing the notch radius. Therefore, a rounded model

with an amplified radius at the notch location can portray the actual stress state at the weld toe or the weld root, and is applied to analyze the fatigue behaviors of welded structures. Pradana et al.^[24] proposed a new way, i. e. the extrapolation notch stress method, to determine the effective notch stress with the sharp model. Fig. 1 shows the basic theory of this new method.

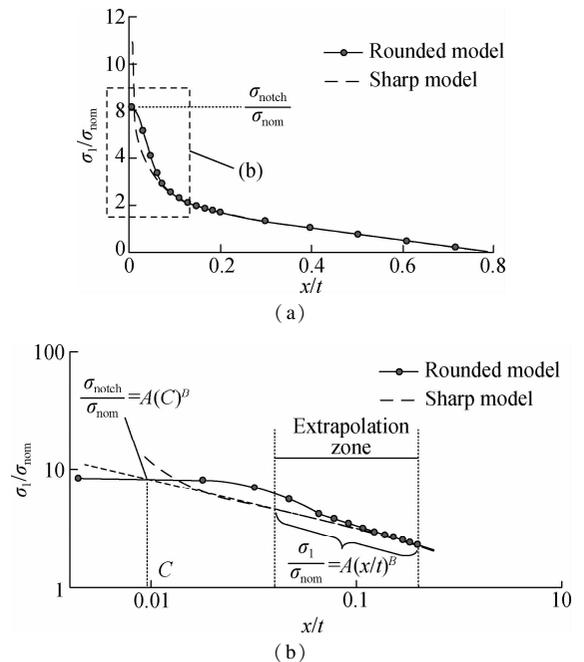


Fig. 1 Notch stress distribution at the weld toe^[27]. (a) Stress distribution of the rounded model and the sharp model; (b) A partially enlarged view of (a)

The idea of the extrapolation notch stress method^[24] comes from the comparison between the stress field of the presence of the virtual notch radius ($r_{\text{ref}} = 1$ mm) and that of the absence of the virtual notch radius ($r_{\text{ref}} = 0$ mm). Two finite element models^[27] (the rounded model and sharp model) with identical geometric dimensions, load conditions, and element mesh sizes were created, and the difference is that the rounded model includes a virtual notch radius ($r_{\text{ref}} = 1$ mm) at the weld toe, and the sharp model is not ($r_{\text{ref}} = 0$ mm). It is shown in Fig. 1 that the stress of the sharp model at the weld toe ($r_{\text{ref}} = 0$ mm) is infinite and not convergent; on the contrary, the stress of the rounded model corresponding to the effective notch stress method approaches a constant maximum value at the weld toe ($r_{\text{ref}} = 1$ mm). It can be seen from Fig. 1 (a) that, outside the distance of $0.2t$ (t is the thickness of the steel pipe) from the weld toe, the curves of the maximum principal stress (here the maximum principal stress was normalized by the nominal stress) calculated using the rounded model and the sharp model coincide with each other and maintain a linear relationship with the distance from the weld toe. It can be seen from Fig. 1 (b) that, in the double logarithmic coordinate system, the

stress of the sharp model is still linear with the distance from $0.04t$ to $0.2t$. Then, the linear curve part is extrapolated to the weld toe direction and intersects with the stress curve of the rounded model at the extrapolation point C . Since the effective notch stress calculated by the rounded model tends to be constant near the weld toe, it can be seen from Fig. 1(b) that the extrapolation point C is located precisely in the stable region of the stress curve of the rounded model. When parameter C is obtained, the effective notch stress of the rounded model at the weld toe can be derived from the stress curve of the sharp model at location C . Pradana et al. [24,26] verified that the stress curve of the rounded model and that of the sharp model intersect within the distance of $0.02t$ from the weld toe, so in this paper, the study of the welded CSJ finite element model focuses on the stress field within the distance of $0.02t$ from the weld toe and the weld root.

1.2 Calculation steps

As shown in Fig. 1(b), it is indicated that the linear part of the stress field of the rounded model and that of the sharp model are on top of each other from $0.04t$ to $0.2t$, so the linear part of the curve can be expressed as

$$\log m = a + b \log n \quad (1)$$

Let $m = \sigma_1 / \sigma_{\text{nom}}$, $n = x/t$, where σ_1 is the maximal principal stress, and σ_{nom} is the nominal stress. Then, substituting m , n into Eq. (1), we derive

$$\log \frac{\sigma_1}{\sigma_{\text{nom}}} = a + b \log(x/t) \quad 0.04 \leq x/t \leq 0.2 \quad (2)$$

Removing the logarithmic symbol on both sides of Eq. (2), we obtain [24]

$$\frac{\sigma_1}{\sigma_{\text{nom}}} = 10^a (x/t)^b = A (x/t)^B \quad (3)$$

$$\frac{\sigma_{\text{notch}}}{\sigma_{\text{nom}}} = A (C)^B \quad (4)$$

where A and B are the coefficients, and the nominal stress [24] σ_{nom} is the stress resulting from the applied external load, which ignores the effect of the local notch effect. Setting $x/t = C$ and substituting it into Eq. (3), the effective notch stress σ_{notch} at the weld toe can be obtained by Eq. (4) [24]. Parameter C is related to the structural geometric parameters and load modes. Let $\alpha, \beta, \gamma, \zeta, \eta$, etc. be the structural geometric parameters, and then C can be expressed as [24]

$$C = f(\alpha\beta\gamma\zeta\eta) \quad (5)$$

To apply Eq. (4) for calculating the effective notch stress σ_{notch} , the key problem is to determine coefficients A , B , and the extrapolation point C . The effective notch

stress σ_{notch} at the weld toe can be solved by the rounded model, and coefficients A , B can be defined by fitting the linear part (from $0.04t$ to $0.2t$) of the stress curve of the sharp model, and then the value of C can be obtained by the inverse analysis of Eq. (4). By setting different geometric parameter values, parameter C can be also calculated by Eq. (4), and then the relationship between C and the geometric parameters in Eq. (5) can be established by fitting. It should be noted that the extrapolation notch stress method is different from the effective notch stress method, and it is necessary to verify the mesh sensitivity problem of the finite element model when performing the effective notch stress calculation through the extrapolation notch stress method.

2 Application of the Extrapolation Notch Stress Method in Welded Cast Steel Joints

2.1 Mesh size definition

A typical welded cast steel joint [6-7] is shown in Fig. 2, which consists of a cast steel pipe, backing plate, weld seam, and connecting steel pipe. The elastic modulus E_1 and Poisson's ratio of cast steel material are equal to 211 GPa and 0.29, respectively. The elastic modulus E_2 of the steel pipe is 206 GPa, and Poisson's ratio is 0.3. The mechanical properties of the backing plate are consistent with those of the steel pipe. A tension load F of 20 MPa is applied to the end of the connecting steel pipe of the welded cast steel joint shown in Fig. 2(a), and the end of the cast steel pipe is fixed. As shown in Fig. 3, the Solid 185 element is chosen to mesh the finite element model of the welded cast steel joint. The maximum principal stress (σ_1) is selected for the stress analysis for both the rounded model and the shape model.

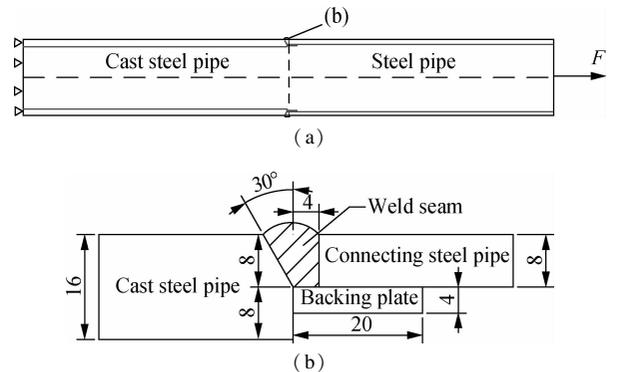


Fig. 2 A typical welded cast steel joint. (a) Boundary condition; (b) Geometry size (unit: mm)

The optimal mesh size is determined by controlling variables. As shown in Fig. 3(a), firstly, the length of the element (e_{length}) is maintained at a constant value of $0.01t$, and the thickness of the element is changed, and then its effect on the normalized max principal stress

(σ_1/σ_{nom}) distribution is studied. As shown in Fig. 4, the stress within the distance of $0.25t$ from the weld toe is selected for the mesh sensitivity analysis of the depth of the element. It can be seen from Fig. 4 that when e_{depth} is less than or equal to $0.01t$, the linear part of the normalized maximal principal stress curve of the sharp model coincides with that of the rounded model. Therefore, e_{depth} takes the value of $0.01t$ in the following analysis.

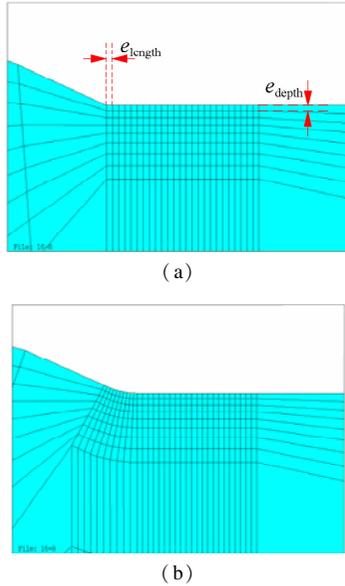


Fig. 3 Mesh size of two kinds of models. (a) Sharp model; (b) Rounded model

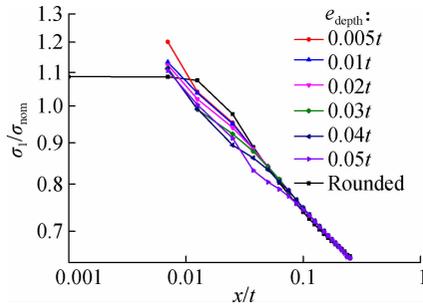
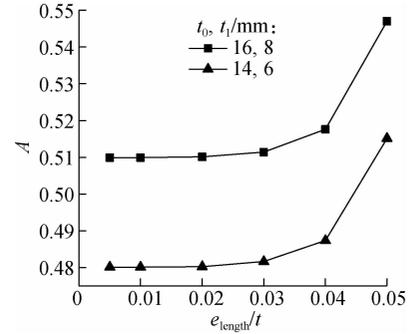


Fig. 4 Normalized stress corresponding to finite element models with elements of different thicknesses

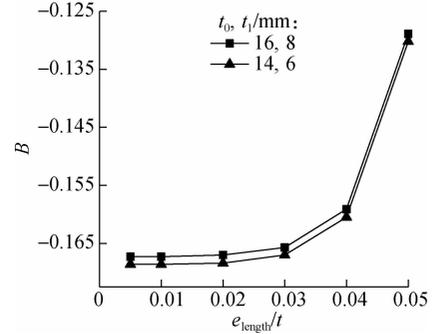
The element length e_{length} can be determined by its influence on coefficients A , B , parameter C , and the effective notch stress. According to the sharp model, the normalized maximal principal stress of all nodes at the linear extrapolation zone ($0.04t-0.2t$) is logarithmically fitted to quantify coefficients a and b in Eq. (1), and then coefficients A and B can be obtained by Eq. (3). As the effective notch stress can be obtained by the rounded model, C can be calculated by Eq. (4).

To simulate the actual geometry of the welded cast steel joint in engineering applications, the outer diameter of the welded cast steel joints (d) studied in this section is equal to 160 mm, and the thicknesses of the cast steel section

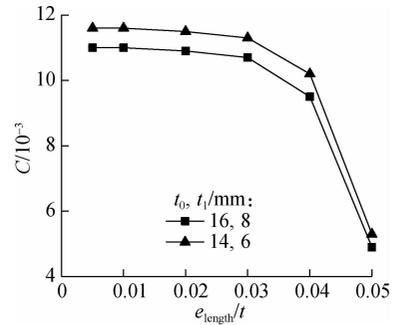
(t_0) are 16 and 14 mm, respectively. The thicknesses of the steel pipe (t_1) are 8 and 6 mm, respectively. The element length e_{length} is increased from $0.005t$ to $0.05t$, and the result is shown in Fig. 5. As can be seen from Figs. 5 (a) to (c), the smaller the element length, the more the parameters A , B , C tend to be constant. As can be seen from Fig. 5 (d), there is almost no correlation between



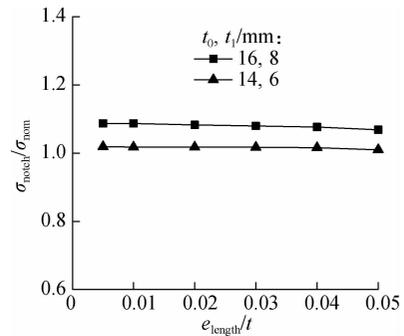
(a)



(b)



(c)



(d)

Fig. 5 The influence of e_{length} . (a) The influence of e_{length} on coefficient A ; (b) The influence of e_{length} on coefficient B ; (c) The influence of e_{length} on parameter C ; (d) The influence of e_{length} on effective notch stress

the normalized effective notch stress and the element length e_{length} . For computational efficiency, e_{length} should not be too small. Therefore, it is set to be $0.01t$ in the following analysis.

2.2 Calculation of effective notch stress at the weld toe

Tab. 1 lists the main geometric parameters of the welded cast steel joint, including the thickness of the cast steel pipe t_0 , the thickness of the connecting steel pipe t_1 , the outer diameter of the connecting steel pipe and the cast steel pipe d . For convenience, t_0, t_1, d are replaced by $\alpha (t_0/t_{\text{ref}}), \beta (t_1/t_{\text{ref}}), \gamma (d/(2t_1))$, respectively, where t_{ref} is the reference thickness.

Tab. 1 Geometry parameters of welded cast steel joint for calculating effective notch stress at the weld toe

Parameters	Values
t_0/mm	10,12,13,14,15,16,18,20
t_1/mm	5,6,7,8,9,10,11
$d/(2t_1)$	12,15,18,21,25
t_{ref}/mm	10

As mentioned in Eq. (5), the following equation is used as the functional relationship between the value of extrapolation point C and geometric parameters α, β, γ :

$$C = \lambda (\alpha)^{X_1} (\beta)^{X_2} (\gamma)^{X_3} \quad (6)$$

where $\lambda, X_1, X_2,$ and X_3 are the coefficients. By the multiple linear regression analysis performed using Matlab software, the coefficients $\lambda, X_1, X_2,$ and X_3 , and the correlation coefficient R^2 can be obtained, which are shown in Tab. 2. The predicted effective notch stresses (σ_{pred}) calculated by Eq. (4) and Eq. (6) and the effective notch stresses (σ_{calc}) calculated by the rounded model of the effective notch stress method under remote tension and remote bending are shown in Fig. 6. It can be seen from Fig. 6 that the ratio of the above two effective notch stresses is linear and proportional, and the error between the predicted value (σ_{pred}) and the actual value (σ_{calc}) is small. It is verified that the extrapolation notch stress method can be applied to calculate the effective notch stress at the weld toe of welded cast steel joints.

Tab. 2 Parameters of Eq. (6) and correlation coefficient R^2 at the weld toe

Load modes	$\lambda/10^{-3}$	X_1	X_2	X_3	R^2
Remote tension	5.255	0.043 1	-1.337 2	0.053 7	0.999 7
Remote bending	4.452	0.033 2	-1.368 2	0.073 3	0.998 3

2.3 Calculation of effective notch stress at the weld root

Tab. 3 lists the main geometric parameters of the welded cast steel joint. The calculation of the effective notch stress at the weld root is similar to that at the weld toe.

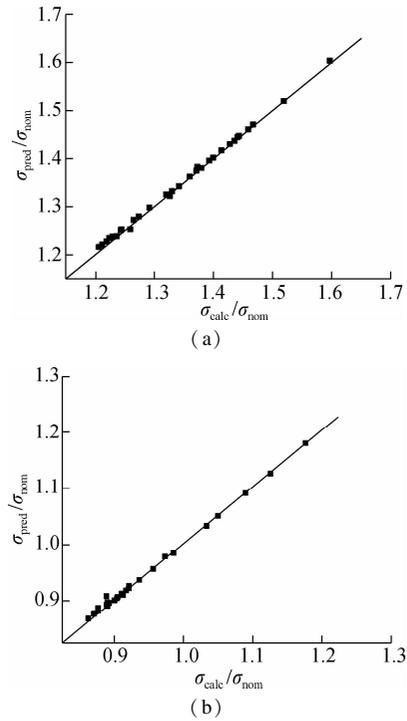


Fig. 6 Comparison of the effective notch stress calculated by two methods at the weld toe. (a) Remote tension load; (b) Remote bending load

Tab. 3 Geometry parameters of welded cast steel joint for calculating effective notch stress at the weld root

Parameters	Values
t_0/mm	16,18,20,21,22,25,26,30
t_1/mm	8,10,12,14,16,20
$d/(2t_1)$	10,12,15,18,20,25,30
t_{ref}/mm	10

The multiple linear regression analysis is performed using Matlab software to obtain the coefficients of Eq. (6) and the correlation coefficient R^2 , which are shown in Tab. 4. The effective notch stresses σ_{pred} predicted by the extrapolation notch stress method and the effective notch stresses σ_{calc} calculated by the effective notch stress method under remote tension load are shown in Fig. 7. The result of Fig. 7 indicates that the relative error of the effective notch stresses calculated by the two methods at the weld root is greater than that at the weld toe due to the large stress concentration at the weld root but the stress ratio is still around 1. The extrapolation notch stress method can still be applied to calculate the effective notch stress at the weld root of the welded CSJ within a certain allowable error.

Tab. 4 Parameters of Eq. (6) and correlation coefficient R^2 at the weld root

Load mode	λ	X_1	X_2	X_3	R^2
Remote tension	0.012 36	0.402 2	-2.028 2	-0.587 1	0.988 1

3 Fatigue Life Evaluation of the Welded Cast Steel Joint

The fatigue life evaluation accuracy of the extrapolation

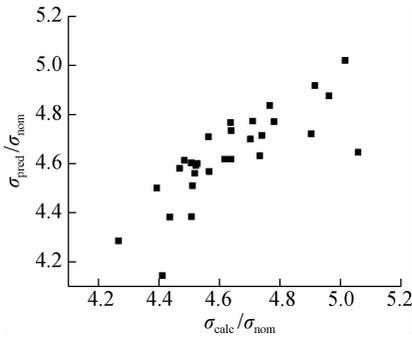


Fig. 7 Comparison of effective notch stresses of two methods at the weld root under the remote tension load

notch stress method and effective notch stress method is compared in this section. For steel welded structures, the IIW^[28] recommended FAT225 curve as the designed $S-N$ curve for the fatigue life evaluation based on the effective notch stress parameter $\Delta\sigma_e$. The inverse slope m of the curve is equal to 3, and the $S-N$ curve is shown as

$$\log N = 13.558 - 3\log \Delta\sigma_e \quad (7)$$

According to the welded cast steel joints applied in practical engineering cases, the fatigue life evaluation of four typical geometric sizes of the welded cast steel joints at girth butt weld shown in Fig. 2 is carried out. The results are listed in Tab. 5, and it can be seen from Tab. 5 that the fatigue life predicted by the extrapolation notch stress method is very close to that by the effective notch stress method, and the maximum relative error is 4.4%. The effective notch stress range-fatigue life curves of the effective notch stress method and the extrapolation notch stress method are shown in Fig. 8. It can be seen that the fatigue life of welded cast steel joints predicted by these two methods is nearly the same. The fatigue life evaluation by the extrapolation notch stress method is more conservative than that by the effective notch stress method, so the extrapolation notch stress method is also safe for the fatigue design of welded cast steel joints.

Tab. 5 Fatigue life predicted by the effective notch stress method and extrapolation notch stress method

t_0/mm	t_1/mm	Effective notch stress/MPa		Fatigue life N	
		Calculation	Extrapolation	Effective notch stress method	Extrapolation notch stress method
16	10	174.204	176.824	6 836 370	6 536 963
20	12	231.906	230.885	2 897 770	2 936 385
22	12	382.415	381.632	646 242	650 228
25	8	451.785	456.060	391 926	381 008

Note: $d/(2t_1) = 15$.

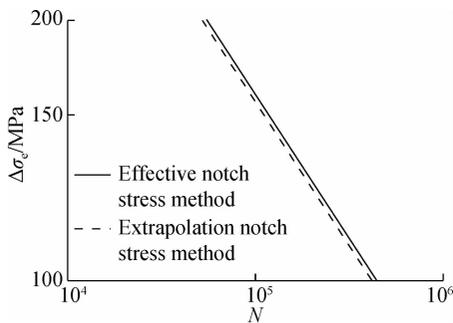


Fig. 8 $S-N$ curves of the two methods

4 Conclusions

1) When the extrapolation notch stress method is applied to calculate the effective notch stress at the weld toe or the weld root of welded cast steel joints, the length, and thickness of the element in the finite element model should be set to be $0.01t$ or less near the weld toe or the weld root, and the extrapolation zone should be $0.04t-0.2t$. The extrapolation notch stress method has shown greater improvement in modeling convenience and computational efficiency than that of the effective notch stress method.

2) The geometry parameters t_0 , t_1 , and d of the wel-

ded cast steel joint are the main factors affecting the effective notch stress at the weld toe or the weld root under remote tension and remote bending load conditions. The extrapolation point C is the most relevant to the thickness of the steel pipe. The effective notch stress calculated by the extrapolation notch stress method is consistent with that calculated by the effective notch stress method.

3) The fatigue life predicted by the extrapolation notch stress method is very close to that calculated by the effective notch stress method, and the extrapolation notch stress method is more conservative than the effective notch stress method, so it is safer for the fatigue design of welded cast steel joints.

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基于外推缺口应力法的铸钢节点环形对接焊缝的疲劳寿命评估

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摘要:运用外推缺口应力法研究了铸钢节点环形对接焊缝的疲劳寿命. 首先分析了焊接铸钢节点有限元模型的网格敏感性以确定最优网格尺寸. 基于焊接铸钢节点有限元模型焊趾和焊根处的应力场分析, 使用外推缺口应力法的 sharp 模型推导有效缺口应力法 rounded 模型的有效缺口应力, 其关键问题是计算外推点 C , 而参数 C 与焊接铸钢节点的几何参数之间具有指数函数关系. 通过设置不同的几何参数值, 确定相应的 C 值, 通过多元线性回归分析可得到外推点 C 与几何参数之间的函数关系. 最后, 基于有效缺口应力疲劳参量, 根据 IIW 规范评估了典型铸钢节点环形对接焊缝的疲劳寿命. 研究结果表明, 外推缺口应力法有效地简化了有效缺口应力的计算过程, 同时可准确地评估铸钢节点环形对接焊缝的疲劳设计寿命.

关键词:铸钢节点; 环形对接焊缝; 外推缺口应力法; 有效缺口应力法; 疲劳设计寿命评估

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