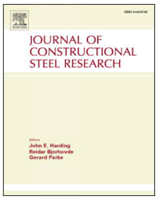
Journal of Constructional Steel Research 148 (2018) 436–449

Contents lists available at ScienceDirect

Journal of Constructional Steel Research



Effect of pitting degradation on ductile fracture initiation of steel butt-welded joints

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ARTICLE INFO

Article history:
Received 15 March 2018
Received in revised form 31 May 2018
Accepted 1 June 2018
Available online xxxx

Keywords:
Steel butt-welded joints
Corrosion pits
Pitting parameters
Equivalent ductile fracture criterion
Ductility degradation

ABSTRACT

Monotonic tensile experiments and corresponding finite element (FE) analyses including a ductile fracture damage criterion have been conducted to investigate the ductility degradation behaviours of steel butt-welded joints with corrosion pits. The results showed that the ultimate elongation of welded joint samples rapidly decreased because the existence of pits led to the earlier initiation of ductile cracks after necking. Pit location was the main factor affecting ductility degradation, pits located in the weakest region of sectional stiffness were the biggest threat to the overall deformability of welded joints. In addition, both pit depth and aspect ratio had a significant effect on local ductile crack initiation and propagation, the local stress triaxiality and plastic strain accumulation increased steadily with the increase of pit size, resulting in the decrease of equivalent plastic fracture strain. Furthermore, based on the parametric numerical analyses, equivalent ductile fracture criterion considering pitting parameters was proposed to replicate the effects of actual pits on ductility degradation.

1. Introduction

Welded connection is one of the main connection forms in different steel structure systems. However, for the welded steel structures exposed to aggressive corrosion environment, weld seams and their adjacent heat affected zone (HAZ) are prone to suffer from the more severe pitting corrosion because of the suboptimal coating protection and the changes of material microstructure and properties caused by welding [1, 2], which causes that welded zones become the vulnerable regions affecting the safety and durability of aging welded steel structures.

Compared with the uniform corrosion, pitting corrosion not only leads to the material lose reducing the carrying capacity of steel components, but also enhances the local stress concentration factor [3] and accumulates more plastic damage [4], so that pitting damage would pose a larger threat to the ductile crack initiation and plastic deformability of steel. Some previous research results indicated the occurrence of pits rapidly decrease the ductility of steel plates, based on which some estimation models in terms of the maximum pit depth were proposed to evaluate the remaining ultimate elongation [5–8].

For the welded structures are subjected to large plastic deformation, due to the interaction between weld strength mismatch and weld geometrical feature, a more complicated local stress status and plastic strain concentration can be observed in the welded zones, which make ductile cracks tend to occur primarily at and near the welds, affecting the final failure mode and performance of welded structures [9]. Kang et al. [10–12] investigated the ductile fracture behaviours of welded joints and small welded connections through experimental and numerical analyses, proposing the ductile fracture models and related parameters of different welded zones. Results in Ref. [13, 14] indicated that ductile fracture models could be utilized to accurately predict the ductile fracture behaviours of welded connection under large strain condition. However, for the corroded welded structures, the introduction of pitting damage undoubtedly intensify the geometrical discontinuousness of welded zones, further reducing the fracture resistance and accelerating cracks initiation and propagation, which may significantly degrade the plastic development ability and energy dissipation ability of welded connection parts, limiting the performance of welded structures to resist extreme loads with large displacement. Xu et al. [15] founded that corroded welded joint samples showed a more significant degradation trend of ductility compared to the steel plates with the same corrosion degree, which indicated that welded joints were more susceptible to the local geometric discontinuousness due to pits. Yeom et al. [16] studied the effect of corrosion length and depth on the failure modes and integrity of API X70 pipe with corroded girth and seam welds, and proposed the modified equation to evaluate the burst pressure. Chong et al. [17] investigated the effects of temperature, environment, crack location and weld strength mismatch on the fracture behaviours of modern pipeline girth welds under high strain conditions. Zhang et al. [18] discussed the influence of corrosion defects parameters on remaining strengths of girth welded pipelines. However, currently, most papers about corroded welded structures concentrate on the effects of pits on

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https://doi.org/10.1016/j.jcsr.2018.06.001

Table 1
Material specifications of Q235 steel and ER50-6 welding filler.

Material	C (%)	Si (%)	Mn (%)	S (%)	P (%)
Q235	0.18	0.19	0.41	0.029	0.026
ER50-6	0.1	1.05	1.5	0.02	0.015

the remaining carrying capacity, few researches involved the relationship between the ductility degradation of weldments and the pitting parameters, which still need to be further investigated.

In this paper, the effects of pits on the ductility degradation behaviours of butt-welded joints have been observed through the monotonic tensile experiments, and the pitting profiles with different exposure time have been measured by using surface scanning technology. Besides, a series of numerical simulation analyses with variable pitting parameters were conducted to investigate the main factors affecting fracture position, failure mode and ductile crack initiation of corroded butt-welded joints. Finally, an equivalent fracture criterion with respect to the relative pitting dimensions was proposed to estimate the ductile fracture initiation of corroded welded joints under axial tensile loading.

2. Monotonic tension experimental studies

2.1. Experimental program and tested specimens

Two steel plates (thickness is equal to 10 mm) were welded together to fabricate the single V-groove weld assemblies with CO_2 gas shield arc welding, where the steel used is normal Chinese structure steel with yield strength of 235 MPa, tensile strength of 400 MPa and total uniform elongation >22%. In order to protect the weld zone from deformations and hence limit the risk of failure at the weld joint, overmatching weld filler metal is usually required in many welding codes [19], thus the filler material used in this paper is ER50-6 welding wire with yield strength of 420 MPa, tensile strength of 500 MPa and total uniform elongation >22%. Material specifications and welding parameters are listed in Table 1 and Table 2, respectively. To simulate the offshore corrosion environment, the outdoor exposure test under cyclic wet-dry condition was conducted based on the standard of GB/T 10125-2012 [20] and GB/T 24517-2009 [21]. All welded assemblies were placed on the exposure test fixture and sprayed for 15 min 8 times a day by using 5.0% sodium chloride solution, then 8 groups of butt-welded joint specimens with the same size were extracted from corroded welded assemblies corresponding to different exposure time including 0, 1, 2, 3, 4, 6, 9 and 12 months. Herein, each group included two tensile specimens and one scanning specimen, it should be noted that the weld reinforcement of scanning specimen had been removed before corrosion to reduce the effect of weld height difference on the scanning accuracy, as shown in Fig. 1. Monotonic tensile tests were performed by using a servo-hydraulic universal testing machine (NO. DNS300), the loading rate was 0.75 mm/min, and deformation in the gauge length range was measured by an extensometer. While corrosion profiles of scanning specimens (corrosion products had been cleared away) were measured by using a non-contact PS50 3D profiler produced by NANOVER.

2.2. Experimental result discussion

Corrosion damage of structural steel exposed to the neutral salt spray environment includes two parts: one is the relative uniform corrosion caused by the rust layer; the other one is the local corrosion due to the pits. Because different types of corrosion damage have different effects on mechanical behaviours of steel, therefore, using the mass loss ratio as the comprehensive evaluation indicator is not accurate to describe the corrosion degree of steel. In the present paper, because idealized butt-welded joints with the overmatching weld metal generally fracture away from the weld seam, the average thickness losses of base metal on both sides of weld seam were measured as the uniform corrosion damage value t_{ave}, while the pitting parameters including pitting depth, pitting radius and pitting volume were calculated based on the point cloud data obtained from the scanning specimens. Besides, it should be noted that as the pitting parameters were obtained only from the scanning specimen in each group, thus there was only one group of pitting data could be used to evaluate the pitting degradation degree in each corrosion exposure time. Where degradation degrees of uniform corrosion η_t and pit corrosion η_p can be defined as:

$$\eta_t = \frac{t_{ave}}{t_0} = \frac{t_0 - t_c}{t_0} \tag{1}$$

$$\eta_p = \frac{t_p}{t_0} = \frac{V_p}{lbt_0} \tag{2}$$

where t_0 is the original thickness of the base metal of joint specimens, t_c is the average remaining thickness of base metal after corrosion, t_p is the equivalent thickness loss caused by pits, V_p is the pitting volume loss. Pitting parameters are listed in Table 3.

Fig. 2 presents the load-displacement curves of tensile specimens with and without corrosion damage. It should be noted that the load-displacement curve for the butt-welded joint can be divided into the elastic stage, hardening stage and softening stage. Compared with steel plate specimen, the obvious yield platform cannot be found for the joint specimen, the possible reasons may be attributed to the material and geometrical discontinuousness of welded joint, which causes that base metal and weld seam in gauge length range cannot reach the yielding stage simultaneously. As shown in Fig. 2, the carrying capacity of tensile specimen decreases as the exposure time increases, which can be attributed to the thickness loss due to corrosion damage. Besides, the hardening stage and softening stage are also shortened with the increasing corrosion time, which can be explained below. Firstly, due to the difference of original thickness between the base metal plate and weld seam, the same corrosion damage presents a significant effect on the reduction of sectional stiffness for HAZ and near base metal zone. Thus more plastic strain would be accumulated on above two zones, accelerating the occurrence of necking. Secondly, the existence of larger pits causes the local stress and plastic strain concentration, when the strain around pits reaches the critical value, the crack would initiate earlier in the above regions and propagate rapidly to cause the total fracture, which limits the further plastic deformation from necking to final failure.

The tensile experiment results of corroded butt-welded joint samples are listed in Table 4. Where the nominal yield/tensile strength σ_y/σ_u is the ratio of the yield/maximum load to the original base metal plate, the tensile strain ε_u or fracture strain ε_f is the ratio of the displacement corresponding to the maximum load or the ultimate fracture displacement to the gauge length. Fig. 3 presents the degradation trends of different mechanical properties with the total corrosion loss ratio, it can be seen that all the mechanical properties decline linearly with the increasing corrosion degree. As shown in Fig. 3, the strength degradation degree is equal to the total corrosion loss ratio, which shows that the

Table 2
Welding parameters of CO_2 gas shield arc welding.

Current (A)	Voltage (V)	Welding speed (cm/min)	Heat input (kJ/cm)	Wire diameter (mm)	Shielding gas	Angle of V-groove (°)	Thickness of plate (mm)
280	29	50	10	1.2	CO_2	60	10