A Revisit of Fatigue Performance Based Welding Quality Criteria in Bridge Welding Provisions and Guidelines

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Keywords: Complete joint penetration, welding inspection, fatigue life, acceptance criteria.

Abstract. Evaluation of workmanship is usually used as welding quality criteria in bridge welding provisions or guidelines. There is, however, no clear relation between workmanship and welding performance. In some cases, the welding quality criteria cannot guarantee actual performance, in particular for fatigue related issues. Existing acceptance criteria of steel bridge welding is summarized. Further discussion is made on the impacts of fatigue performance of a weld on welding quality criteria. The findings show that the fatigue performance based welding quality criteria have a potential to improve acceptance criteria in steel bridge welding.

Introduction

Welding joints in welded steel bridges are vulnerable to fatigue-induced damage, while cracks often initiate from relatively small flaws resulting from welding during shop and/or construction site. Inspection of welds in a steel bridge is thus necessary to ensure the welding quality during bridge fabrication, construction process and later in-service stage. Various nondestructive examination (NDE) methods and procedures have been stipulated in current AASHTO/AWS D1.5 - Bridge Welding Code [1] and other guidelines wordwide. The development of NDE techniques, in particular enhanced ultrasonic testing techniques (e.g., phase array ultrasonic testing technologies [2]), allows considerable improvements in operator efficiency and in accurate sizing and positioning of welding defects. All welded bridge joints contain flaws. Some defects may not impair the structural integrity but others may initiate cracks, and ultimately lead to fatigue-induced failure.

A decision, therefore, has to be made on whether the defects are severe enough to impair the serviceability of the bridge under fatigue loading. The existing acceptance criteria in D 1.5 Bridge Welding Code for welding quality control, however, is usually based on quality of workmanship [1, 3,4], as specified in Art. C1.1.2, which cannot account for the impacts of material discontinuity, due to welding defects, on structural fatigue performance. Previous studies have demonstrated that use of concept of good workmanship for acceptance criteria leads to a weak relation between quality rules and fatigue strength [3,4]. As a result, in some cases, some welded steel bridge members containing flaws have performed satisfactorily in service while others may not. It is clear that there is still a lack coherent consistency for welding criteria from fatigue-based design to inspection assessment.

This objective of this study is to provide a background of welding quality criteria in existing steel bridge codes. The effects of defects on fatigue performance of a weld is discussed. The impacts of fatigue performance of welds on the welding quality highlight the importance of fatigue performance based acceptance criteria.

Existing Acceptance Criteria in Bridge Welding Codes and Guidelines

AASHTO/AWS D 1.5 steel bridge welding specifications (2010). Section 6 of the D1.5 code addresses the requirements for specific NDE procedures and accpetance criteria for welding practices in bridges. Provisions of conventional NDE methods codified in the D 1.5 code include ultrasonic testing (UT), radiography testing (RT) and magntic particle testing (MT). Detailed summary of these three methods can be found in the literature [5,6]. RT is used for examination of CJP groove welds in butt joints while all CJP groove welds in T- and corner joints should be tested by UT system. The UT technology is based on the amplitude of the ultrasound reflected from the artificial indication. The threshold acceptance levels is determined in decibels (dB) and the indication length, as specified in Tables 6.3 (for tension welds) and 6.4 (for compression welds) in the D1.5 Code [1]. The conventional RT or UT technology has their limitation in the ability to determine the size, location and shape of welding defects [6].

The UT measures amplitude of a reflection from an indication in terms of artificial reflector sizes, which do not correspond completely to the actual defeat. Also, the physics of the UT is based on amplitude of a reflection while the response amplitude can be affected by many factors [7,8], including welding defect type, orientation and size, surface texture, reflectivity, and noise ratio, thereby leading to high deviation. Because of the response amplitude variability, it is difficult to determine the size of the defect relative to the current D 1.5 code. Moreover, there is a small difference between rating an indication as acceptance or rejection. For example, the difference between class D and class C in Table 6.3 or 6.4 may be as small as 1 dB [8].

International Institute of Welding (IIW) Standards (2003). The ISO 5817 system includes three quality classes B, C, and D. B is the highest quality level while D is the lowest level. Similarly to D 1.5 code, the physics behind the standard tend to assess the quality of welding workmanship. As a result, the research [3,4] showed little or no relation between fatigue life and different weld classes. In some cases, even quality level B would be insufficient to achieve the fatigue strength according to the IIW Recommendations. The fatigue life can vary by one or two decades ($*10\sim10^2$) depending on types of imperfection. Research has indicated that the type of defect plays a big role in fatigue performance [3,4,9]. Some defect types in the existing quality systems are important with respect to fatigue while others are not. Also, with existing systems, raising quality from, e.g., D to C, does not guarantee that fatigue strength will be increased [4]. As such, specifying a certain welding class level may not ensure a desired fatigue life.

Fatigue Performance of Material Discontinuity and Its Impacts of Welding Criteria

The research [3,4,9] demonstrated the importance of defect types in welding quality and fatigue life. ISO 5817 classifies 26 different types of welding imperfections, such as cracks, porosity, inclusions, lack of penetration, lack of fusion, undercut, insufficient weld throat, misalignment, cold lap. Some defect types in the existing quality systems are important with respect to fatigue while others are not. For example, for a crack or cracklike defect, it reveals that reducing the initial crack length/size of a material, can dramatically increase the number of cycles, thereby leading to much high fatigue life [10]. Hobbacher [3] defined a categorization of weld defects and their corresponding assessment (Table 1). Porosity and inclusion are classified as local notch effect and their fatigue resistance is tabulated. For cracks, lack of fusion and lack of penetration, they are classified as crack or cracklike defeats, and thus their assessment should be based on the fracture mechanics.

Table 1. Categorization and assessment procedure for weld defects (after [3])

Effect of Defect	Type of Defect	Assessment
Rise of general stress level	Misalignment	Formulas for effective stress concentration
Local notch effect	Weld shape defects	Tables given
	Porosity and inclusion not near the surface	Tables given
Cracklike defects	Cracks, lack of fusion and penetration, others	Fracture mechanics

The three critical defect types are present below to demonstrate the their impacts on fatigue strength. On the other hand, it also demand the new acceptance criteria of a steel bridge weld on the basis of fatigue strength.

Porosity. Porosity is one type of volumetric defeats. Studies found in the literature [3,4] indicated that the levels of porosity as high as 7-10% by volume are dangerous from fatigue prospective in stress concentration regions because of the resultant over-stressing of the remaining sound weld metal.

On the other hand, the tests of welded specimen with porosity level up to 4% by volume showed all data fell off upper limited welding level, suggesting high fatigue resistance (Fig. 1). For a single pore, Jonsson et al. [4] reported a relation between pore size and fatigue life. As clearly indicated in Fig. 2, under certain constant fatigue stress level, acceptance criteria for classes VB, VC, and VD are approximately 2, 4, and 6 mm, respectively.

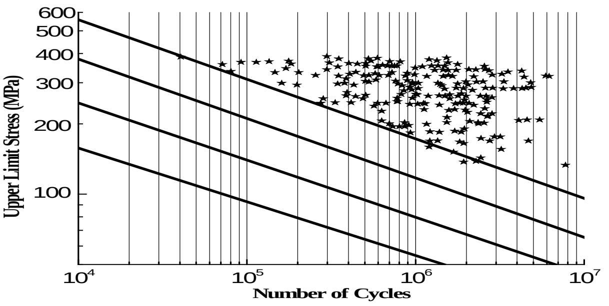

Fig. 1 Porosity level up to 4% [5]

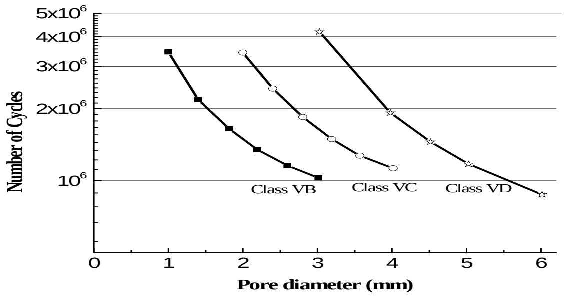

Fig. 2 Pore size vs. fatigue life [6]

Lack of fusion (slag). Incompletely fused spots due to improper welding lead to lack-of-fusion defects (slag). It is usually divided into three types [11]: a) lack of side-wall fusion; b) lack of inter-run fusion, and c) lack of fusion at the root of the weld. It generates a notch effect. Test results of the welds containing lack-of-fusion defects, illustrated in Fig. 3, revealed that it can dramatically lower the fatigue life depending on the defect location. If the lack of fusion is close to the root side or close to the surface or toe area, then the fatigue strength becomes very sensitive to the size of the defect.

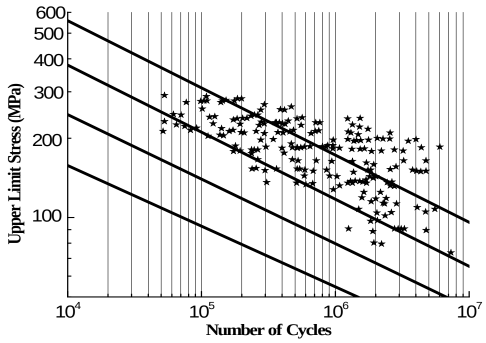

Fig. 3 Slag inclusions and slag lines [3]

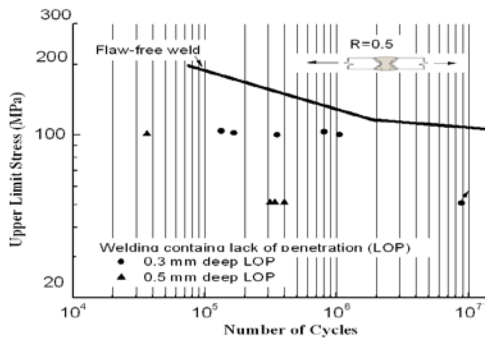

Fig. 4 Fatigue life for welds with LOP [9]

Lack of penetration. Lack of penetration or lack of fusion close to surface, root or toe areas is defined as a cracklike defect. Thus, the fatigue strength has a high sensitivity to the size, orientation and location. A weld containing lack of penetration (LOP) should have a fatigue assessment in terms of fracture mechanics, as shown in Table 1. Caravaca et al. [9] reported an experimental study a butt weld containing lack of penetration. Though there were limited data points through tests, the test results in Fig. 4 still gave a clear indication that, compared to sound reference weld, the welds containing lack of penetration have considerable lower fatigue strength by 60-70 percent when lack of penetration is 0.3 mm long, and 40-55 percent for 0.5 mm long. It is clear that lack of penetration is one of the most serious weld defects. The more quantitative data, including the effects of defect length, orientation and location, are required to generate suitable correlation with fatigue strength.

Discussions

The welding acceptance criteria on the basis of quality of workmanship in existing welding codes and guidelines cannot ensure the fatigue performance and a desired fatigue life. Weld defects could be resulted from steel shop, construction or in service. As clearly illustrated in Table 2. The fatigue properties of a weld are thus dependent of quality system from initial design, fabrication, and construction and in-service, but unfortunately in practical application of welding, each responsibility of them is separated. Thus, the acceptance criteria based on NDT system in existing D 1.5 code cannot ensure a desirable fatigue performance. In particular, once a weld defect is identified using existing NDT system in D 1.5 code, it is not clear which guidelines should be met. Also, the "fitness-for-purpose" concept has been developed [12], as shown in Table 2, but there is still no connection between this concept and welding acceptance criteria. As pointed out by Hobbacher [3], a strong interaction between initial design, fabrication, and in-service should be built up to quantify a weld and its impact on quality assurance systems related to fatigue performance.

Table 2. Responsibilities at weld defects (revised after [3])

Area of consideration	Operation	Responsibility
Bridge welding joints (no defect assumed)	Analysis of the welded joint (fatigue resistance included)	Bridge designer
Quality system in shop	Appropriate welding/NDT	Welding fabricator/inspector
Quality system in construction	Appropriate welding/NDT	Welding inspector
Quality system in service	Application of NDT	Welding inspector
Fitness for purpose	Analysis of the welded joint	Welding designer

Conclusions

The following main observations and conclusions can be drawn from this study:

1) Existing steel bridge welding codes are on the basis of measurement of workmanships, thus leading to a little or no correlation between welding quality and their fatigue strength.
2) The welding quality is highly dependent of defect types, while the findings show that defect types have high impacts on welding fatigue strength.
3) The new acceptance criteria is a highly demand in terms of fatigue strength of a weld.
4) Future studies are directed to quantify the fatigue assessment of a welding containing different types of defects and their corresponding acceptance criteria.

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