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The effect of seismic loading on the fatigue strength of welded joints

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Abstract

Earthquakes sometimes damage steel structures. Structures which are not seriously damaged are still used after earthquakes but their fatigue strength may have been reduced by the large cyclic loadings imposed by the earthquakes. In order to clarify the effect of seismic loading on the fatigue strength of welded joints, high cycle fatigue and variable amplitude fatigue tests after a number of large initial strain cycles were performed. The large strain cycles formed a short crack at the toe of the weld in a low cycle fatigue that triggered a high cycle fatigue strength reduction. The high cycle fatigue limit of welded joints after initial strain cycles is governed by the threshold stress intensity factor of the short crack. The formation of short cracks also enhanced the damage accumulation for subsequent variable amplitude loading. It is important to keep all of the stress variations after earthquake below the fatigue limit of the cracked welded joints to avoid fatigue damage accumulation after an earthquake.

Keywords: Welded Joints; Seismic loading; Large strain cycling; Earthquake; Fatigue strength; Fatigue limit

1. Introduction

Steel structures sometimes collapse during major earthquakes. Structures beyond repair are removed but less seriously damaged steel structures continue to be used. However, their fatigue strength may be reduced below the pre-earthquake level. A peculiar characteristic of seismic loading is the application of a few cycles of high cyclic strain that exceed the material yield strength. These strain cycles may cause small fatigue cracks at a notched location, which reduces the fatigue strength [1]. The objective of this study is to produce a method of evaluating the integrity of welded joints that have experienced seismic loading. High cycle fatigue and variable amplitude loading tests were conducted on welded joints which had been subjected to initial large cyclic strains to evaluate their residual fatigue strength.

2. Experimental procedures

The material used was an as rolled steel used for architectural construction designated as SN400B in the Japanese Industrial Standard. This steel is often used for welded joints in steel structures. The chemical composition and mechanical properties are shown in Tables 1 and 2, respectively. The welded joint shown in Fig. 1 was used as the specimen. Two steel plates with thicknesses of 32 and 12 mm were welded by automatic CO_2 gas shielded welding. The surface of the plates was as rolled. The welding method was the both-side fillet welding with one layer. The welded plate was machined into the shape shown in Fig. 1. The welding conditions were as follows: welding current of 300 A, welding voltage of 31 V, welding velocity of 245 mm/min, distance of 20 mm between the tip and base material, gas flow rate of 20 l/min, and wire electrode extension of 15 mm with downward position welding.

A uniform bending moment was applied to the specimen. A strain gage was placed 20 mm away from the weld toe to measure the nominal strain. Since the stresses exceeded the yield strength, the test condition was described by the strain measured by a strain gage placed on each specimen. The test condition for the high cycle fatigue test was described by $E\varepsilon_a$ using the measured strain amplitude ε_a and Young's modulus $E = 206$ GPa. The high cycle fatigue test was performed at a frequency of 28 Hz at ambient temperature in laboratory air.

In order to obtain a calibration for crack depth using a dye penetrant and a strain gage located 5 mm from the weld toe, a 1 mm deep crack was taken to define fatigue failure. As the crack grows, the strain near the crack is released and the strain measured by the strain gage decreases. A relationship between the reduction of strain amplitude and the crack depth was obtained.

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Table 1
Chemical composition of material (wt.%)

Material	SN400B
C	0.14
Si	0.13
Mn	0.71
P	0.018
S	0.008
C_{eq}	0.27

Table 2
Mechanical properties of material

Material	SN400B
Yield strength (MPa)	288
Tensile strength (MPa)	431
Elongation (%)	29

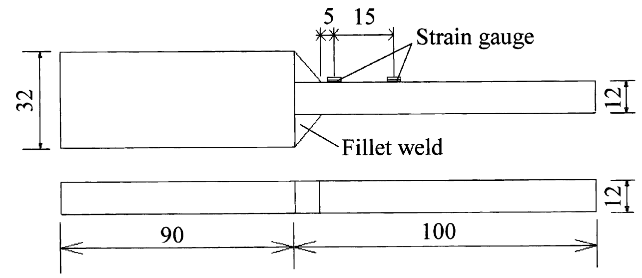

Fig. 1. Fatigue test specimen (dimensions are in mm).

A 6% reduction of the strain amplitude corresponded to the crack depth of 1 mm. The fatigue limit was defined as a run-out at 10^7 cycles.

3. Test results for constant amplitude fatigue

Seismic loading may induce plastic deformation in structural components. Since the deformation may be constrained at the deformed position, knowledge about the effect of residual strain on the fatigue strength is important for the evaluation of integrity after earthquakes. Therefore, constant amplitude high cycle fatigue tests were conducted under four levels of mean strains, i.e. 0, 1, 3 and 5% to provide base data.

Fig. 2 shows the results of the high cycle fatigue tests. The $E\varepsilon_a$–N curve for 0% mean strain is usually used as a baseline in fatigue design. The welded joint used in this study is classified as a fillet welded joint without surface finish, with a load transfer type and toe failure type described in the fatigue design guideline of the Japanese Association of Steel Structure [2]. In the guideline, the allowable stress amplitude $\Delta\sigma_f/2$ at 2×10^6 cycles for this detail is given as 32.5 MPa. Test results showed that the specimen satisfied this fatigue strength for all the mean strains applied. Although the finite fatigue lives were shorter for positive mean strains, the fatigue limits were not affected even by the large mean strains that all exceeded the yield strength. This is because a high tensile residual stress already existed in the as welded specimen and the strain cycling did not significantly increase it. From Fig. 2, it is clear that the mean strains used did not affect the fatigue limit.

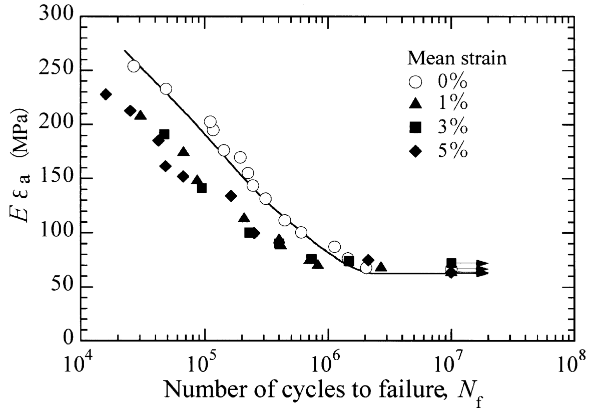

Fig. 2. Constant amplitude $E\varepsilon_a$–N curves.

4. High cycle fatigue behavior after large strain cycling

In order to investigate the effect of large initial strain cycles on the residual fatigue strength of welded joints the test history shown in Fig. 3 was used. A large cyclic strain ε_1 was initially applied to the specimen for n_1 cycles followed by a high cycle fatigue test in which the mean strain was set equal to the maximum strain of the large initial strain cycle to simulate the continuation of loading after earthquake loads.

The application of a small number of large strain cycles results in a short crack. Such a short crack acts as a pre-crack and reduces the high cycle fatigue strength. Prior to the test, the development of short cracks at the weld toe caused by the large strain cycling was examined. The relation between crack depth and number of cycles is shown in Fig. 4. Multiple specimens were used and each data point corresponds to a separate specimen. Since a large scatter was anticipated in the initiation and growth of short cracks from the weld toe, the continuous measurement of crack growth using a single specimen was not adopted. The crack depth was measured on the fracture surface of each specimen. A small number of large strain cycles formed a crack at the weld toe. For example, 200 cycles of 1% strain amplitude formed a 0.1 mm deep crack.

Fig. 5 shows the $E\varepsilon_a$–N curves. The application of a few hundred cycles of 1% strain substantially reduced the fatigue strength. An example of a crack is shown in Fig. 6. A few tenths of a millimeter deep fatigue crack was formed by the initial

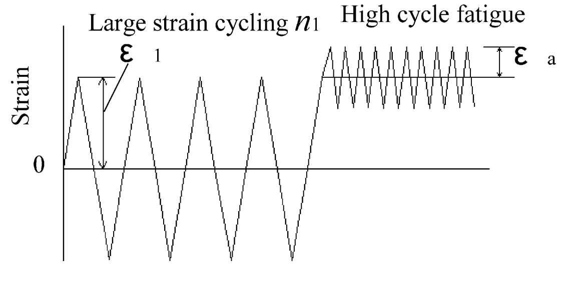

Fig. 3. Strain pattern for high cycle fatigue after large strain cycling.