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Experimental and numerical investigation on seismic performance of corroded welded steel connections

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ABSTRACT

The objective of this work is to investigate experimentally and numerically the effect of neutral salt-spray corrosion damage on the seismic capacity of welded steel connections. Firstly, the surface morphology characteristics and mechanical properties of corroded steel were discussed by testing the standard specimens fabricated from the welded connections with different exposure corrosion time. Then, the inelastic cyclic loading tests of 4 deteriorated connection specimens with different corrosion damage degrees were conducted to evaluate the changes of cyclic behavior and failure mode. Test results showed that the bearing capacities and the stiffness of corroded connections decreased due to the sectional area losses of the beam and the column, while the existence of severe pits in the welded zone accelerated the brittle fracture failure of corroded beam flange, resulting in the significant degradations of ductility and total energy dissipation. In addition, a series of parametric numerical simulation was performed to analyze the effects of different corrosion parameters on the seismic performances of connections. Analytical results indicated that the larger value could be chosen from the beam flange corrosion and the column web corrosion to estimate the remaining ultimate bearing capacity of existing connections, while the pitting damage and the uniform corrosion on the beam flange could be regarded as the main factors affecting the degradation degree of deformation capacity and energy dissipation capacity.

1. Introduction

Welded steel beam to column connections have been widely applied for steel moment-resisting frames in areas of high seismicity because this type of connection is believed to be able to provide sufficient strength, ductility and energy dissipation capacity to resist strong seismic loading. However, numerous welded beam to column connections in steel moment-resisting frames eventually failed with the local brittle fracture during the Northridge and Kobe Earthquake, causing the losses of lives and property [1,2]. While for the aging steel moment-resisting frames exposed in an aggressive corrosion environment, the welded connections not only suffer from the damage caused by earthquake loading but also face serious corrosion problems, which further weaken the structural safety and integrity.

It is well known that the reduction of the sectional area due to uniform corrosion and pitting damage may result in the decrease of bearing capacities. In addition, the stress concentration caused by severe pitting damage may change the local triaxial stress state and increase the plastic damage accumulation, reducing the ductility of steel, resulting in the initiation and propagation of ductile cracks at a relatively lower level of loading and deformation [3]. Furthermore, due to differences in material microstructure and material properties, the pitting damage in the weld-heated area is more severe than that of the base metal in the neutral salt-spray environment [4,5]. Based on these reasons above, welded connections may face the higher failure risk compared to the other steel members of the aging steel moment-resisting frames under the earthquake loading. Therefore, it is necessary to study the degradation of seismic performance for welded steel structures under the interaction between the cyclic loading and the corrosion damage.

To determine possible failure causes of uncorroded connections under earthquake loading, numerous experimental and numerical analyses had been carried out to investigate the cyclic behavior of welded connections. In a series of parametric studies, the effects of different design parameters on the seismic performances of welded connections were evaluated and discussed, these design parameters respectively include the geometry of weld access holes, beam web attachment detail, panel zone strength, continuity plates, and composite slab. Additionally, the research results also demonstrated that the stress concentration formed at the weld zones and the plastic damage accumulation caused by cyclic loading were the two main factors influencing the crack initiation [6–9]. Furthermore, the micro-mechanics

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models based on plastic damage mechanisms were considered to provide an accurate method to predict fracture behavior of beam to column connections under inelastic monotonic and cyclic loadings [10,11].

Currently, in order to assess and repair the corrosion damage steel structures, the degradation laws of mechanical properties for steel with various corrosion patterns were investigated through the experimental and numerical analyses [12,13]. Moreover, some researchers have studied the effects of thickness loss caused by severe corrosion damage on the bearing capacity and the failure mode of the corroded steel column and beam [14–17], proposing the damage evaluation methods calculating the remaining capacities. However, although the degradation mechanism of the welded connection is more complicated than that of the corroded beam and column, there are few research results related to the seismic performances and damage mechanisms of corroded steel connections.

The main purpose of this paper is to investigate experimentally and numerically the effect of general corrosion damage on the seismic performances of welded steel connections. Accelerate corrosion testing of three welded steel connections were conducted in outdoor salt-spray atmosphere for eight months at most. The surface morphology and mechanical properties of corroded steel were obtained based on optical surface measurement and tensile tests. In addition, the cyclic loading tests were performed to analyze the degradation of bearing capacities, rotation capacity, stiffness, energy dissipation capacity and the change of failure mode with the increasing corrosion degree. At last, a series of nonlinear finite element analyses were applied to clarify the influences of different corrosion parameters on cyclic behaviors of welded steel connections.

2. Experimental procedure

2.1. Specimens descriptions

Four full-scale specimens of the exterior beam to column connection with the same size were designed and fabricated to conduct the following accelerate corrosion testing and cyclic loading testing, these specimens were made of a common Q235 grade Chinese structural steel with yield strength of 235 MPa, tensile strength of 370–500 MPa (equivalent to ASTM A36 mild steel), and named S0, S1, S2 and S3, respectively. In order to make sure the plastic hinge form at the beam end adjacent to the column, a design concept of strong column-weak beam and strong connection-weak member was adopted according to Chinese design specifications “Code for design of steel structures” [18] and “Code for seismic design of buildings” [19], where the ratio of beam-to-column design moment is 0.5, and the ratio of panel zone-to-column design moment is 1.08. Referring to Fig. 1, the connection specimen comprised a hot rolled H 350 × 175 × 7 × 11 beam connected to a hot rolled H 250 × 250 × 9 × 14 column, and the column continuity plates were as thick as the beam flanges; the weld access hole had to be cut on the beam web to enable the full penetration groove welding between the beam flange and the column flange, while the beam web was fillet welded to the column flange. To avoid the initial artificial crack, the backup bar was removed. Besides, ultrasonic tests were applied to check the quality of groove welds between the beam flanges and the column flanges. The weld details and the dimensions of the weld access holes were set based on the requirement of Chinese specification JGJ 81-2002 [20]. The mechanical properties of steel and filler metal were listed in Table 1.

2.2. Accelerated corrosion test

To simulate the corrosion degradation of welded connections in neutral salt-spray atmosphere, the accelerated corrosion testing method was applied. According to the standard of GB/T 24517-2010 [21], those specimens were exposed to the outdoor atmosphere and sprayed with NaCl solution 8 times per day, lasting 5 min every time. To further study the seismic behaviors of connection specimens with different corrosion degree, the specimen S0 was chosen as the uncorroded control welded connection, while corrosion duration for specimens S1, S2 and S3 were 4, 6 and 8 months, respectively. Based on requirement of standard of GB/T 10125–2012 [22], the NaCl solution concentration was 50 mg/L, the PH value was 6.2–7.2, the diameter of the nozzle and the rate of mist spray of the spraying equipment were 0.5–1.5 mm and 0.5–1.5 L/(min m^2), respectively.

2.3. Optical surface measurement and tensile tests

Three groups of small-scale dog-bone tensile specimens with a 50 mm gauge length were cut from the beam end away from the column of corroded welded connections (an extra region with 400 mm length at the beam end of each connection specimen was left for extracting the above small samples, see Fig. 1(a)), each group included one flange specimen and one web specimen. In order to analyze the corrosion degree and pitting details of each corroded connection, all tensile specimens with cleaning the surface rust were weighed with an analytical balance, then these specimens were tested to obtain the geometric morphology data about pitting damage based on optical surface measurement technology. The two sides of gauge part for each specimen were measured by using a non-contact PS50 3D profiler produced by NANOVER, where the measurement range is 50 mm long and 20 mm wide, and the interval of measurement data is 100 μm. Subsequently, to investigate the effect of general corrosion on mechanical properties of steel, all tensile specimens were tested by using a servo-hydraulic universal testing machine (NO. DNS300) according to GB/T 228.1–2010 specification [23], where the loading rate was 0.75 mm/min, and deformation in the gauge length range was measured by an extensometer.

2.4. Cyclic loading test

The schematic plot and general view of the test setup and specimen are shown in Fig. 1. The test setup was designed to simulate the boundary conditions of a beam to column connection in a moment-resisting frame subjected to lateral loading. Thus, the end of the beam was pin connected to rigid link using cylindrical bearings to simulate the mid-span (inflection point) of the beam, where the rigid link enabled horizontal movement at the ends of the beam. The bottom of the column was pinned to the foundation beam. Besides, at the top of the column, a horizontal servo-controlled MTS actuator, capable of applying loads up to 500 kN and displacements up to ± 150 mm, was applied to impose cyclic loading or displacements on the connection specimen. The axial constant force of 220 kN, which was equal to 10% of the yield bearing capacity of the column, was imposed to the top of the column by a jack (maximum load up to 1000 kN). To completely restrict out-of-plane displacement and twisting of the connection specimen, two pairs of lateral bracings were provided separately to the beam and the column, as shown in Fig. 1. The connection specimen was instrumented with strain gauges and inclinometer (SCA120T-60, range: ± 60°) to measure strain at critical locations and rotations of different parts of the specimen. The total displacement was measured by MTS displacement transducer (range: 50 mm) at the horizontal loading point. Both the actuator and the rigid link were instrumented with calibrated load cells (BLR-1) to record the total applied load and reactions at the end of the beam.

The protocol of quasi-static cyclic test prescribed a symmetric cyclic loading pattern defined in terms of the Chinese specification JGJ 101-96 [24]. In the test of control specimen S0, cyclic loading was applied by force control before the yielding of the connection, where the force multiples were 20 kN, 40 kN, 60 kN and 80 kN until yielding occurred, within each increment of force amplitude, two cycles were repeated. Follow by the displacement controlled testing stage, the cyclic displacements were imposed to the connection specimen, and