EXPERIMENTAL INVESTIGATION ON WELDED S700 HIGH STRENGTH STEEL TUBULAR X-JOINTS UNDER LOW-CYCLE FATIGUE LOADING

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This paper presents an experimental investigation on welded tubular X-joints of grade S700 high strength steel under low cycle fatigue loading. This study is motivated by the need for improving the fatigue performance of offshore wind energy structures under extreme loading condition. The test specimens were manufactured with hot-rolled steel tubes of steel grade S700, and they were designed to represent X-brace joints in a fixed offshore wind tubular jacket structure with scaling factor of 1:3. Three specimens were tested under strong fully-reversed cyclic in-plane bending, which simulates extreme loading conditions for offshore structures. The relationship between bending moment and displacement for each specimen were recorded, and local strains were measured at the chord member at the two crown locations. It was observed that through-thickness fatigue cracking occur within less than 100 cycles. It was observed that strength degradation started at low rate, then rapid reduction of resisting bending moment was observed as the specimen approached failure, indicating two distinct stages of damage evolution. Through-thickness crack was initiated at one of the four chord crown locations for all specimens.

Keywords: High-strength steel, low-cycle fatigue, offshore structures, welded tubular joints.

1 Introduction

The Europe 2020 growth strategy foresees a massive installation of offshore wind farms for energy production. Within this framework, offshore wind power capacity in Europe is expected to grow tenfold in this decade (EWEA 2011). Future offshore wind farms are aimed for deeper water, moving further away from the shore and with a larger wind turbine, in order to meet the increasing energy demands. Offshore wind farms currently under construction, approved, or planned are up to 200 km from shore and in water depths of up to 215 m, compared with the average distance to shore of 43.3 km and water depth of 27.1m in 2015 (EWEA 2016). However, the material strength and resilience requirements of platform structures form one of the primary barriers preventing expansion of wind energy to the deeper sea (EWEA 2013). The development of advanced high-strength steel (HSS) material offers a new opportunity for

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construction of cost-efficient offshore structures in deeper water, in order to produce more wind energy.

Currently, offshore wind structures are constructed using normal strength steel members with yield strength of around 355 MPa. Larger section sizes are required to resist the higher load levels encountered in progressively deeper waters. This substantially increases cost, complicates logistics, generates installation difficulties, and causes greater environmental impacts. HSS material has the twin advantages of reducing the self-weight of structures and accruing associated cost savings. The installation costs typically represent up to 20% of the capital expenditure of an offshore wind farm. There is a need for more compact and lighter structures that can be easily sited on the seabed by standard installation vessels with lower crane capacity. Furthermore, the use of HSS provides increased structural resilience against strong cyclic loading in deep water environments, and reduces welding time due to reduced wall thickness. Several research projects (DOWNVInD 2009, INNWIND 2018, Cordle et al. 2011, King et al. 2013, Tomasicchio et al. 2012) have been aimed at improving design of offshore structures with normal strength steel (Grade S355). However, limited research is available on the use of high-strength steel in offshore structures (FATHOMS 2010, HITUBES 2013). The benefit of HSS in static loading capacity is obvious, due to its increased strength. But there is a concern on deformation capacity for HSS connection, due to its lower ductility than normal-strength steel. In addition, the fatigue strength of HSS, especially at welded connections, remains an open question. Tubular joint is a common structural element in offshore wind platforms, and severe cyclic load, induced by wave and wind in the harsh offshore environment, may lead to fatigue fracture and failure at the vicinity of the welds. Reliable estimation of fatigue behaviour and resistance of HSS welded tubular connections constitutes an engineering challenge, essential for the platform structural integrity. Therefore, experimental investigation has been performed to examine fatigue resistance of tubular welded joints with HSS material up to grade S700 (yield strength of 700 MPa), with a load ratio of -1 inducing plasticity in both tension and compression.

2 Experimental program

2.1 *Specimens and experimental setup*

The three X-joint specimens are denoted as X1 – X3. They were manufactured by steel tubes of grade S700 provided by SSAB in Sweden, and fabricated by Hollandia Systems in Netherlands according to the American Welding Society (AWS D1.1 2004) provisions. The tubular brace and chords have equal external diameter and thickness of 273 mm and 10 mm, respectively. The free ends of the tubular joints were capped with welded plates for testing. The test specimen configuration is shown in Fig. 1.

The specimens were instrumented to record the force-displacement response and induced strains at specific locations and to detect through-thickness cracking. Two string potentiometers were placed at the two brace ends to measure the vertical brace end displacement. Local longitudinal strains were measured at the crown locations of the chord with uni-directional five-element-strip strain gauges (FXV-1), oriented perpendicular to the weld toe. Two FXV-1 series strip strain gauges were used in each specimen, placed on chord crown points at 5 – 9 mm from the weld toe. Two additional strain gauges were attached at the chord side at distance of 5 – 25 mm from the weld toe, where the maximum principal strains/stress arise during the linear elastic analysis under monotonic/cyclic in-plane bending.

In the present test, initiation and propagation of surface cracks was monitored with a camera. Failure is defined as through-thickness cracking. To detect the stage at which the crack develops through the thickness of the tube wall, a small hole was drilled on the capping plate of each specimen, prior to testing, and two smoke flares were inserted into the chord; subsequently the hole was sealed with a re-usable envelope. Occurrence of through-thickness crack can be detected when the trapped smoke escaped through the crack, and the corresponding number of cycles to failure was recorded.

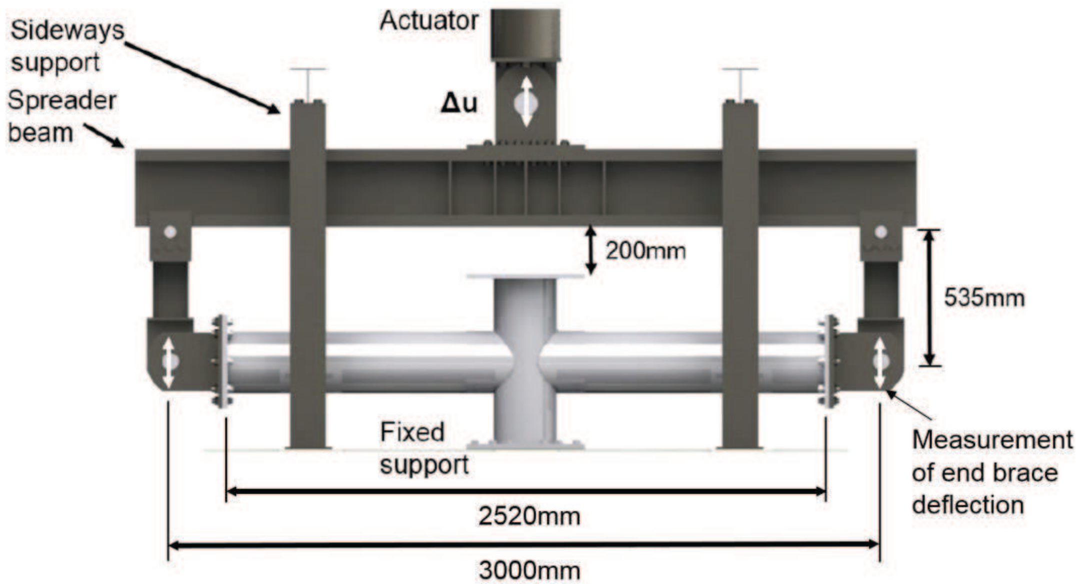
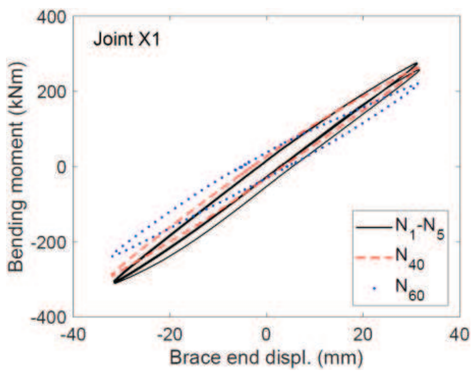


Figure 1. Test specimen configuration and test setup.

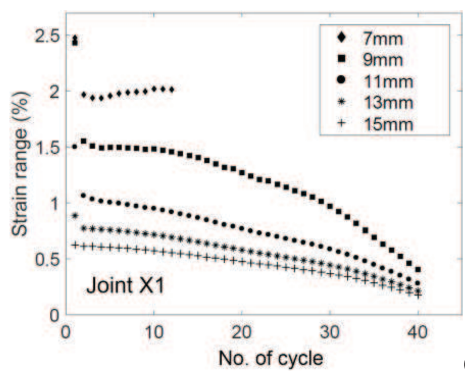
The experiments were conducted using an Instron 8800 servo-hydraulic actuator system of 1MN capacity. The three-dimensional configuration of the experimental setup is presented in Figure 1. The hydraulic actuator was pin-connected at the center of a 3.3 meter long spreader beam. The loading was then transferred to the two ends of the braces through two pin-ended columns connecting the spreader beam and the end braces. The X-joint specimens were rigidly supported at the base of the chord member, while the top edge of the chord is capped with a welded plate to preserve symmetry. Two lateral support systems were fixed on the test-rig to ensure the safe operation of the actuator by restricting sideways movements of the crossbeam, which was free to move in the vertical direction. The actuator imposed a repeated vertical displacement of alternating direction at the brace ends, introducing in-plane cyclic bending loading at the welded connection. The experiments were conducted under a displacement-control scheme with ratio of maximum displacement in the upwards and downwards direction equals to R=-1 (fully-reversed displacement) and the movement of the hydraulic actuator was controlled via the Instron WaveMatrix software. The specimens X1, X2 and X3 were subjected to ±31.6 mm, ±38 mm and ±48 mm during testing, respectively. A preliminary finite element analysis was conducted prior to the experiments to support the selection of the testing displacement amplitudes. The value of the maximum applied moment M_{max} normalised with respect to the yield bending moment M_y for the joints X1, X2 and X3 are equal to 1.16, 1.32 and 1.51, respectively. The yield bending moment M_y is defined as the bending moment that corresponds to first yielding of the joint. It is obtained numerically through the finite element model under monotonic loading conditions, and it is equal to 239 kNm. The resisting bending moment decreases gradually over the loading cycles due to material degradation.

2.2 *Test results*

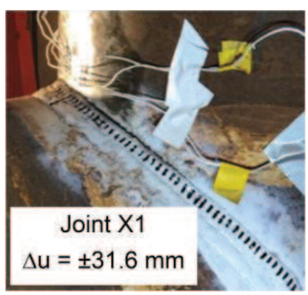
The relationships between bending moment and brace end displacement of the three joints were recorded. The bending moment – displacement diagram for joint X1 is presented in Fig. 2(a). It is observed that all specimens experienced a small amount of cyclic hardening during the first load cycle, while the hysteresis response changes slightly prior to damage initiation. Strength degradation started at low rate, then rapid reduction of resisting bending moment was observed as the specimen approached failure, indicating two distinct stages of damage evolution. Local strains were measured at the chord member at the two crown locations, and the test result of joint X1 is presented in Fig. 2(b). The distance of each strain gauge from the weld toe is denoted at the legend. Strain measurements were analyzed in terms of strain-range evolution with respect to loading cycles. It shows that the induced strain-range due to cyclic loading increased slightly during initial load cycles, reached a constant value and subsequently decreased when cracks were formed at the weld toe. The final fractured shapes of specimen X1 is illustrated in Fig. 2(c). In all specimens, through-thickness crack was initiated at one of the four chord crown locations.



(a)



(b)



(c)

Figure 2. (a) Bending moment-displacement response for joint X1; (b) Strain range evolution over load cycles for joint X1; (c) Failed specimen.

3 Conclusions

The present work investigates the fatigue performance of tubular welded X-joints, made of S700 steel material under severe cyclic loading conditions, using large-scale experiments. The work refers to extreme loading exerted on representative tubular X-joints of an offshore wind structural system designed for installation in water depth of 55 meters, which may lead to low-cycle fatigue. Three large-scale specimens were tested under intense cyclic in-plane bending, leading to failure with a number of cycles less than 100, which is referred to as "ultra low-cycle fatigue". Experimental results were presented in terms of bending moment-displacement relation, local strain measurements and the number of cycles to failure, which is defined as the stage where through-thickness crack occurs. It is observed that strength degradation started at low rate, then rapid reduction of resisting bending moment was observed as the specimen approached failure, indicating two distinct stages of damage evolution. Through-thickness crack was initiated at one of the four chord crown locations for all specimens. The main purpose of the current experimental program is to provide additional information regarding the ultra low-cycle fatigue performance of steel tubular welded connections made of S700 steel, as very limited guidance is available in relevant codes and standards, especially for high-strength steel.

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