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Experimental study on fatigue behavior of butt-welded thin-walled steel plates strengthened using CFRP sheets

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ABSTRACT

Welded steel joints in structures are susceptible to fatigue failure. In this context, advanced carbon fiber reinforced polymer (CFRP) possess a demonstrated potential for the fatigue strengthening of steel structures. However, limited information is available on CFRP strengthening of butt-welded joints, which are the most common joint types in steel structures. This paper presents a study on fatigue behavior of butt-welded thin-walled steel plates strengthened using CFRP sheets. A total of 34 specimens with both single-sided and double-sided strengthening were performed via constant amplitude tensile fatigue loading, and another four specimens were employed for hot-spot stress measurement. The effect of CFRP strengthening on fatigue behavior was investigated by varying the strengthening scheme (single-sided or double-sided) and the number of CFRP sheet layers. Test results showed that the fatigue life of butt-welded steel plates with CFRP strengthening increased by approximately one to ten times when compared to the fatigue life of butt-welded steel plates without CFRP strengthening. Triple-layered double-sided specimens seemed to exhibit the best effect on fatigue life; their fatigue strength at 2 million cycles increased by 34% compared to that of specimens without CFRP strengthening. Specific fatigue design S–N curves of butt-welded thin-walled steel plates with and without CFRP strengthening were proposed directly. The fatigue test results were used to calibrate a fatigue design approach for CFRP strengthened butt-welded steel plates. In addition, the effect of CFRP strengthening on stiffness degradation was also discussed.

1. Introduction

Aging of steel structures is a problem being encountered across the world; a large number steel structures such as roads and railway bridges, pipelines, communication towers, and offshore structures are aging [1]. For example, nearly 70% of all the steel bridges in Europe are more than 50 years old, and 28% of them are more than 100 years old [2,3]. In the USA, more than 62,000 steel bridges are considered to be structurally deficient [4]. Similar situations exist in Australia [5] and Japan [6]. In China, the first steel bridge, the Garden Bridge of Shanghai, has a history of over 100 years. Thus, the demand for strengthening old steel structures is increasing, especially now that the traffic load is much higher than the load for which these bridges were originally designed.

Fatigue is a major issue in welded steel structures under repeated loading, and these structures often contain welding defects. Meanwhile, significant stress concentration is formed in the welded areas due to the sudden changes in structural geometry and size. Stop holes, welding repair, and steel plate attachment are conventional methods to extend the fatigue life of cracked structures. However, they may cause new problems such as difficulties in manufacturing complex shapes with heavy steel plates, the need for electrical equipment, and the introduction of additional defects due to welding or drilling [7]. Strengthening with carbon fiber reinforced polymer (CFRP) offers great advantages because of their light weight, high strength, adaptability for construction, and improved fatigue resistance. CFRP is widely applied for strengthening masonry and concrete structures, and it is also being adopted gradually for strengthening steel structures [8,9]. For instance, CFRP were used to strengthen steel members under static loading and impact loading [10–14]. In terms of CFRP strengthening under fatigue loading, research has been mainly focused on the CFRP strengthening of

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steel plates [15–18] and steel beams [19–21]. The results of these studies indicated that the fatigue behavior of steel members strengthened with CFRP improved significantly. Furthermore, CFRP reduced the crack growth rate and extended the fatigue life of these steel structures [22]. The most significant factors affecting these results were the elastic modulus of CFRP, strengthening layout, number of CFRP sheet layers, and usage of the prestressing technique. Nevertheless, there is very limited work based on the CFRP strengthening of welded steel joints, from which fatigue cracks are usually initiated and propagated. Most of the previous studies based on the CFRP strengthening of welded joints only considered static loading [23–27] and very few studies considered fatigue loading [28]. Recent research has been mainly focused on the CFRP strengthening of non-load-carrying cruciform welded joints under axial fatigue loading using experimental testing [7,29] or finite element analysis [30] and CFRP strengthening of welded web gusset joints under axial fatigue loading [31–33] or bending fatigue loading [34–36]. However, there is a lack of detailed study on CFRP strengthened butt-welded thin steel plates under fatigue loading [37,38]. Recently, a fatigue design was proposed for CFRP strengthened steel members including butt-welded thin plates [39]. However, the proposed design rules for butt-welded plates were not explicitly verified by fatigue testing data. To fill this gap, this study intends to conduct a detailed investigation on butt-welded thin steel plates strengthened using CFRP sheets under fatigue loading.

2. Experimental scheme

2.1. Specimen design

The entire experimental study was divided into two parts: fatigue testing and hot-spot stress measurement. Test specimens were divided into four groups, one of these groups was not strengthened with CFRP (reference group). The details of the four groups are listed in Table 1. A total of 34 butt-welded thin-walled steel plate specimens with same geometry were manufactured and strengthened by CFRP for fatigue testing. Meanwhile, for hot-spot stress measurement, another four CFRP-strengthened butt-welded thin-walled steel plate specimens were used. These groups differed in terms of their bonded sides and the number of CFRP layers on each side. Specimen labels were defined as "BDLX" or "BSLX", where "B" represents butt-welded steel plates, "D" and "S" represent double-sided (D) or single-sided (S) strengthening, respectively, "L" indicates layer, and "X" represents the number of CFRP layers on each side. Thus, in group BL0, no CFRP sheets were bonded to the surfaces of butt-welded steel plate specimens. In group BDL1, single-layered CFRP sheets were bonded to both sides of the surfaces. In group BDL3, triple-layered CFRP sheets were bonded to both sides of the surfaces. In group BSL1, a single-layered CFRP sheet was bonded to the top surfaces of butt-welded steel plate specimens.

Mild carbon steel Q345B (with a nominal yield strength at least 345 MPa according to the Chinese standard GB/T 700–2006 [40]) in the form of 10 mm-thick rolled plates was used as the base material in this study. Each CFRP sheet was 0.167 mm thick and carbon fibers were arranged unidirectionally in these sheets. Unidirectional CFRP sheets were applied along the tensile direction of butt-welded steel plate specimens and arranged to cover the full length of the transition and testing areas. CFRP strengthening schemes in different butt-welded steel plate specimen groups are shown in Fig. 1.

Table 1
Specimen groups of butt-welded steel plates.

Specimen group	Bonded sides	Number of CFRP layers on each side	Number of specimens	
			Fatigue testing	Hot-spot stress measurement
BL0	0	0	8	1
BDL1	Double sides	1	8	1
BDL3	Double sides	3	9	1
BSL1	Single side	1	9	1

To eliminate the influence of welding stop-starts, two large steel panels were butt welded initially and then cut into the specified shape by mechanical processing (Fig. 2). The dimensions of butt-welded steel plate specimens should not be too small considering the strengthening effect of CFRP. At the same time, specimen dimensions should not be too large because the capacity of the test setup is limited. The basic geometry dimensions of butt-welded steel plate specimens and the butt weld are illustrated in Fig. 3. Double-sided full penetration "V-shaped" butt welds without a backing plate were employed for specimen manufacturing using the CO_2 gas-shielded welding method. The specimens were finished on a grinding machine into the final shape to make sure that the height of weld convexity was less than 10% of the weld width with smooth transition to steel plate surfaces. The surface roughness (Ra) of the testing area should be no more than 0.2 μm to meet the requirements of the Chinese standard GB/T 3075-2008 [41]. Thus, the testing area of the specimens was milled after wire electrode cutting. Welding quality was carefully examined by ultrasonic detection after the butt-welded steel plate specimens were manufactured and the manufacturer reported 100% conformity.

CFRP sheets and structural adhesive were used to strengthen butt-welded steel plate specimens. The specimen preparation procedure included the following steps.

Step 1: Surface preparation

Surface treatment must be conducted on the bonding area of butt-welded steel plate specimens before CFRP patching to facilitate adhesion. Therefore, the surfaces of the specimens were ground with sandpapers and cleaned with ethyl alcohol to remove any rust and oil stains.

Step 2: CFRP installation

CFRP sheets were cut to the appropriate size to cover the testing and transition areas. The structural adhesive was composed of epoxy resin and curing agent mixed in a volume ratio of 2:1. Following surface preparation, the structural adhesive was applied over the bonding area of the specimen and the bottom surface of the first layer of the CFRP sheet to be attached. After the CFRP layer was correctly placed, the extra adhesive was squeezed out by a roller to ensure uniform thickness in the bonding area. This was done to ensure that the CFRP sheet was tightly bonded to the surface of the butt-welded steel plate specimen and that a good bonding performance was obtained. The adhesive was subsequently applied on the top surface of the first CFRP layer and the bottom surface of the second CFRP layer (if necessary) before attaching and rolling. This wet lay-up process was repeated until all the CFRP sheets were glued to the butt-welded steel plate specimen surfaces. Care was taken to keep the CFRP sheets taut during the installation procedure.

Step 3: Curing and measurement

The adhesive that was used hardened at room temperature and reached the required bond strength in one day. To eliminate the dispersion caused by the curing condition of the structural adhesive, strengthened specimens were cured at a same room temperature (26 °C) and ambient humidity (30%) for more than one week. The surface treatment, bonding technology, and curing process were similar to those in a previous study [27] wherein effective patching was achieved. Cross-sectional dimensions of the specimens were measured before and after CFRP strengthening, and the average thickness of each adhesive layer was calculated to be 0.65 mm, assuming that the thickness of all the adhesive layers was the same.