Development of a Robotic Welding System for CJP Groove Welds Meeting Requirements of Seismic Load Resistance

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In recent years, the demand for steel structures in Taiwan has surged. However, the steel manufacturing industry is experiencing a significant shortage of qualified welders, which has severely impacted industry growth (Anu 2020). Despite this, robotic welding has yet to be adopted in construction in Taiwan. Efforts to reduce manufacturing costs have resulted in increased variability and geometric errors during sheet cutting and unit assembly. These dimensional variations make traditional automated welding unable to be directly applied (Jin et al. 2017). Therefore, developing advanced robotic welding technologies has emerged as a critical solution for automating building construction in Taiwan. This advancement is essential for ensuring precise, high-quality welds, particularly in the context of the need for seismic hazard regions like Taiwan (Chou et al. 2023).

This study aims to develop a robotic Gas Metal Arc Welding (GMAW) system and qualify the resulting welds to meet the requirements specified in the AWS D1.8/D1.8M. The system is applied to weld the continuity plate to the flange plates of built-up box columns used in construction to verify its feasibility. The research explores the feasibility of applying robotic welding technology in Taiwan's steel construction industry. First, an robotic welding system was designed, and welding monitoring equipment was configured to assess the correlation between GMAW welding parameters and welding outcomes. Then, a small-scale steel specimen, emulating a special moment frame steel beam-column joint, was designed for testing the robotic welding system and welding process. Finally, non-destructive inspection and mechanical property testing of the welds were conducted to ensure that the weld bead meets seismic resistance specifications.

The integrated robotic GMAW system in this study is divided into two subsystems: the robotic welding equipment and the welding monitoring equipment. In conventional welding procedures, welders manually control their welding apparatus. Conversely, within an integrated robotic GMAW system, the manipulator replaces the welder’s hand, and the welding monitoring equipment replaces the welder’s senses. The robotic welding equipment includes a robotic manipulator, a welding machine, a water-cooled welding gun, an oxide removal device, and a wire feeder, among other components (Figure 1). The welding method is consistent with the existing weld procedure for GMAW with CO_2 as the shielding gas. Each piece of welding equipment needs to be is modified to accept welding instructions, which let the equipment could be integrated into a control system.

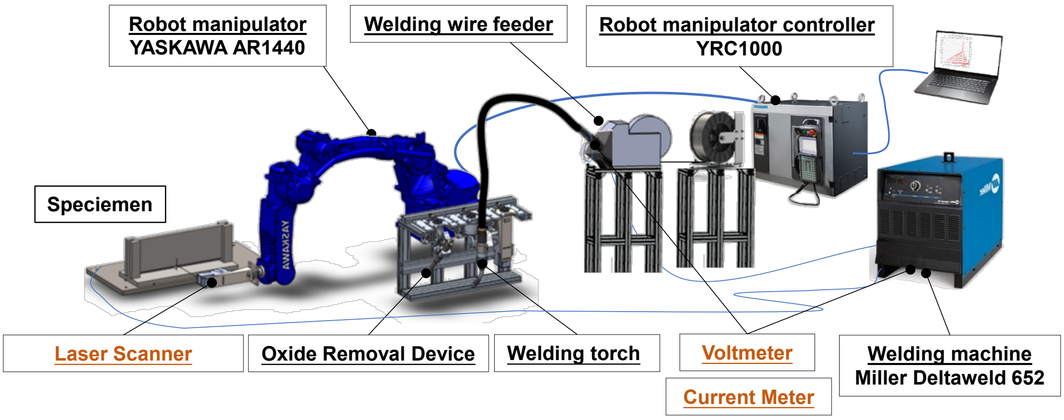
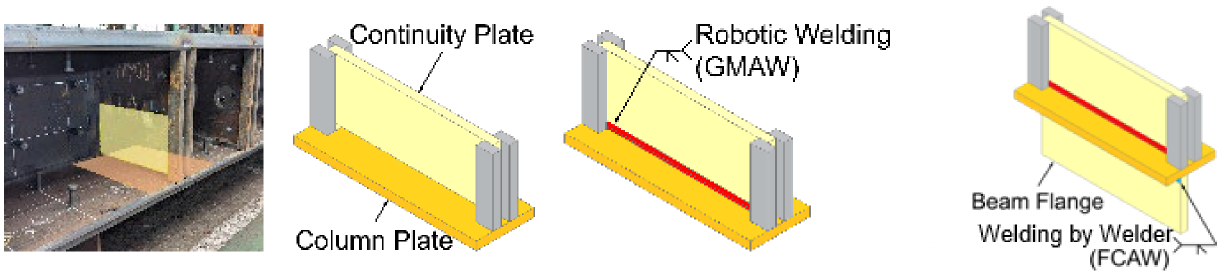


Figure 1. Robotic GMAW system.

To evaluate the robotic welding system and study the effects of welding parameters on weld quality, a small-scale steel specimen was designed. Figure 2 shows the fabrication process of the specimens. The specimens were designed to emulate the connection details of a continuity plate, column flange, and beam flange in a typical steel box column. Figure 2(a) illustrates the initial assembly, where the continuity plate (marked in yellow) is placed in a position relative to the column flange (marked in orange) inside a built-up box column. As shown in Fig. 2(b), the specimen is composed of the continuity plate. Once all plates are positioned, a manipulator performs GMAW using different trial parameters to join the continuity and column plates, as shown in Fig. 2(c). The welding quality is then assessed by non-destructive testing (NDT). If the welding quality meets the AWS D1.1 standard, another steel plate representing the beam flange is manually welded using flux-cored arc welding (FCAW) to the opposite side of the column plate. This emulates the current construction practice in Taiwan, as shown in Fig. 2(d). The specimens were formed from SN490 steel plates. Finally, steel coupons are created by cutting and grinding the specimens for subsequent material testing, which follow AWS D1.1 and AWS D1.8.



(a) (b) (c) (d)

Figure 2. The specimen manufacturing process.

After welding dozens of specimens and making improvements to welding machine equipment, such as gas nozzle, wire supply servo motors, and other components, along with suggestions from the welding engineers, we adopt a method of stacking welds and suitable welding parameter combinations. The relationship between welding parameters and weld bead stacking was established using monitoring equipment. The weld of the small-scale specimen, performed using robotic welding system as shown in Figure 3, was completed with the optimal combination of welding parameters. A laser scanner was utilized to assess the results of the weld stacking, providing precise measurements of the weld geometry. This approach ensures consistency in weld quality and allows for detailed analysis of the robotic welding system's effectiveness under controlled conditions.

The specimen was cut and ground to produce coupons for mechanical testing. The specimen's cross-section, as shown in Figure 4, includes two welds created by a robotic manipulator and a human welder. Mechanical tests, including tensile, cyclic loading, side bending, and Charpy impact test, were conducted according to AWS D1.1, AWS D1.8, and ASTM E190 standards. Figure 5(a) illustrates the tensile test coupon, comprising the continuity plate, the GMAW weld by the manipulator, the column flange plate, the FCAW weld by the welder, and the beam flange. Necking occurred at the continuity plate before failure, and both the robotic and manual welds remained intact, as shown in Figure 5 (b) and (c). The stress-strain curve in Figure 5 (b) demonstrated satisfactory ductility with a strain exceeding 7%, suitable for large seismic events. The cyclic loading test showed a stable hysteretic loop up to 4.5% axial strain without visible damage. Additionally, the lateral bending test confirmed the weld met specification requirements, with no cracks observed in the curved weld portion (Figure 5 [d]).

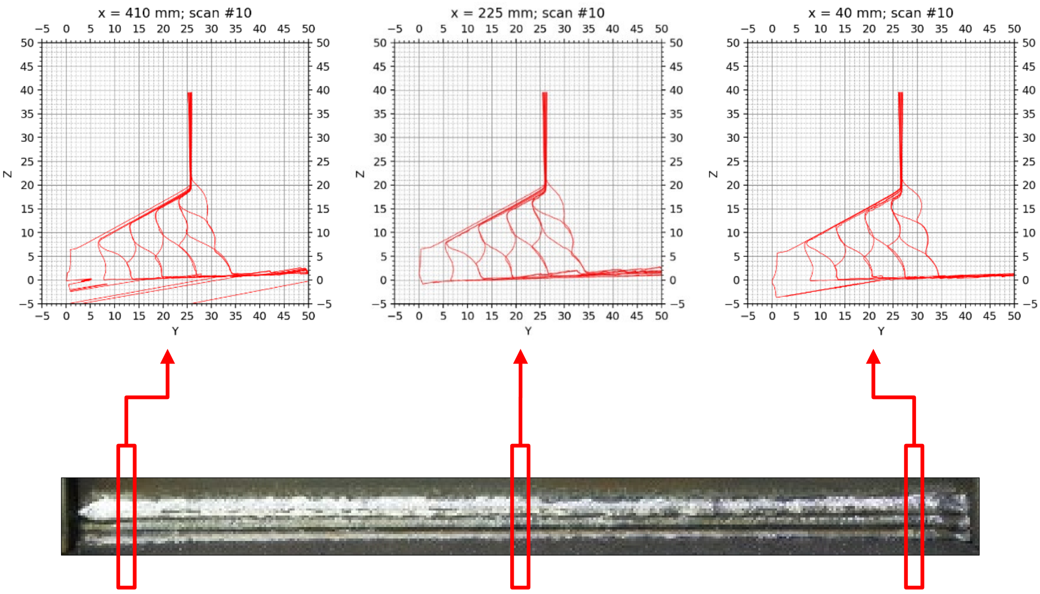


Figure 3. The weld appearance of small-scale steel specimen by robotic welding system.

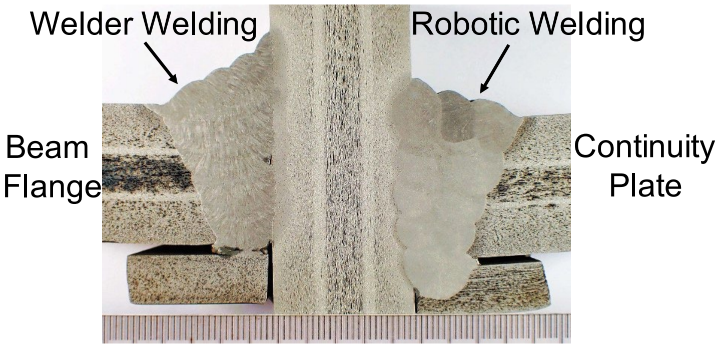
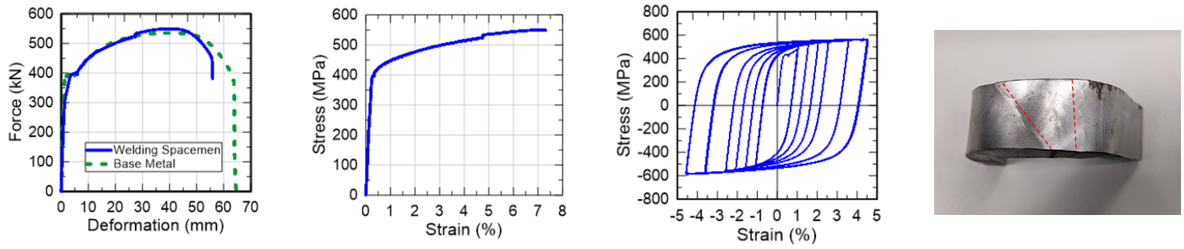


Figure 4. The specimen cross section.



(a) (b) (c) (d)

Figure 5. Mechanical test results: (a) Force-displacement curve for the tensile test, (b) Stress-strain curve of the weld zone for the tensile test, (c) Stress-strain curve of the weld zone for the cyclic loading test, and (d) Coupon after the bending test

This study aims to develop a robotic welding system capable of performing multi-layer, multi-pass complete joint penetration (CJP) welding between continuity plates and column flange plates in the fabrication of steel composite box columns for construction. A series of specimen welds and monitoring procedures were conducted, leading to the completion of the procedure qualification record and mechanical property tests. The results demonstrate that the robotic welding system can achieve satisfactory mechanical properties. Monitoring equipment allows for precise control of weld dimension variability, ensuring stable welding quality. The data collected during the welding procedures will further support the development of advanced automated welding procedures decision-making systems.

Acknowledgments

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