Canadian Conference - Pacific Conference on Earthquake Engineering 2023
Vancouver, British Columbia
June 25th – June 30th, 2023

Influence of Weld Sequence on the Seismic Performance of Welded Steel Moment Connections

Shahriar Quayyum[1*] and Tasnim Hassan[2]

[1]Assistant Professor, Department of Civil & Environmental Engineering, Manhattan College, Riverdale, NY 10471
[2]Professor, Department of Civil, Construction & Environmental Engineering, Raleigh, NC 27695
[*]shahriar.quayyum@manhattan.edu (Corresponding Author)

ABSTRACT

An experimental study by the authors on the influence of welding sequence on the seismic performance of moment resisting connections demonstrated the influence of welding induced residual stresses on the localized low-cycle fatigue failure response. In order to get an understanding of the residual stress development and its influence on the localized failure mechanism of welded steel moment resisting connections, this study develops a numerical technique based on sequentially coupled thermo-mechanical analysis to simulate the welding induced residual stresses and their influence on fatigue responses. The finite element simulation technique is validated against the experimental temperature and strain measurements. The simulated responses demonstrate development of very high residual stresses close to the weld toe and weld access hole regions. The moment resisting connections are analyzed under ATC-24 constant amplitude cyclic loading history in presence of weld residual stresses, which demonstrates the influence of the residual stresses on the low-cycle fatigue failure mechanism of the connections. The results of the finite element investigation explain the variability of the low-cycle fatigue failure response for different weld sequences.

Keywords: Moment connection, weld sequence, residual stress, seismic performance, strain ratcheting.

INTRODUCTION

Welding induced residual stress has long been recognized as one of the primary contributors to fatigue crack initiation and failure of moment connections. Testing of post-Northridge welded steel moment connections (WSMCs) have shown that failures can initiate from localized, low-cycle fatigue cracks near the weld toe (Stojadinovic *et al.* 2000, Lee *et al.* 2005, Suita *et al.* 1998, Nakashima *et al.* 1998, Uang *et al.* 2000, Han *et al.* 2014). The influence of residual stress on this fatigue crack initiation at the weld toe in WSMCs was speculated (Chi *et al.* 2000, Matos and Dodds 2000, 2001, 2002, Righiniotis *et al.* 2002), but the failure mechanisms as well as the distribution and magnitude of residual stresses are not well understood. However, not much attention was paid to the influence of residual stress on the seismic response of the moment resisting connections because of the common notion that the residual stress relaxes after a couple of inelastic loading cycles. Due to the complexity involved in residual stress calculation, most analyses either do not consider residual stresses or use simplified methods of analysis (Matos and Dodds 2002). Hence, detail analyses on the development of welding induced residual stresses and their influence on the response of a moment connection are scarce in the literature. However, Zhang and Dong (2000) included detailed residual stress analysis in their investigations. Their calculations demonstrated that the magnitude of residual stresses in some locations can be greater than the yield stress of the material. They performed fracture analysis for crack propagation of preexisting cracks at the backing bars and demonstrated that the triaxial residual stress greatly reduce the plastic deformation capacity of the welded joint and thus induce brittle fracture. In addition, an increase in fracture driving force was observed in presence of high tensile residual stresses. However, the analysis was two dimensional and hence, the influence of weld sequence was not accounted for across the width of the beam flanges. Moreover, the influence of residual stresses was studied for fracture response with a preexisting crack, not for low-cycle fatigue failure response. Nevertheless, this study showed that even though the residual stress relaxes after few inelastic loading cycles, it can influence the fracture behavior at the welded joint of the moment connections. This is further supported by a relatively recent study by Wang *et al.* (2012) where they studied the effect of welding residual stresses on the fracture behavior of flange-plate steel reinforced connection. Their study demonstrated that the existence of welding residual stresses will highly increase the likelihood of brittle fracture of the steel in the heat affected zone of the connection. More recently, Pan *et al.* (2017) performed detailed finite element analysis of welded box beam-to-column connections considering welding residual stresses and demonstrated that welding induced residual stresses result in the increase of equivalent plastic strain at the welds which may lead to earlier fracture of the connection. An experimental study by Hassan and Quayyum (2022) on welded unreinforced flange bolted web (WUF-B) connections demonstrated the influence of welding sequence on the fatigue failure of the connections. It was observed that two welding sequences induced different strain responses of the connections. In addition, axial strain accumulation (also termed as strain ratcheting) was observed in these experiments near the weld toe, which led to crack initiation. However, residual stress measurements could not be made in these experiments, and hence, the residual stress influence on the fatigue crack initiation could not be studied. The strain ratcheting phenomenon observed in this study is an indicator of the presence of residual stresses and different strain ratcheting responses for the two weld sequences is an indicator of the effect of weld sequence on the local responses of the connection. Hence, based on the results of this study, it was concluded that the welding induced residual stress magnitudes and distribution are completely different for two different welding procedure resulting in different low-cycle fatigue failure responses for the two connection specimens.

The study reported herein aims to develop a detailed understanding of the evolution of residual stresses due to different welding sequences and their effect on the low-cycle fatigue response of moment connections. Advanced numerical schemes are developed to simulate welding process, and hence the residual stress and subsequent fatigue responses of welded joints. The welding process is simulated by implementing a sequentially coupled, nonlinear, transient, thermo-mechanical analysis to calculate real-time temperature history and subsequent residual stresses. The temperature history and residual stress results from the numerical simulation are validated against experimental measurements from Hassan and Quayyum (2022). The validated numerical technique is further utilized to investigate the low-cycle fatigue failure responses of WSMCs under simulated seismic loading. The fatigue responses of welded joints with the welding residual stress fields for different weld sequences are simulated by prescribing displacement controlled cyclic loading to understand the effect of weld sequences and corresponding residual stresses on the local and global failure mechanisms of the connections.

NUMERICAL SCHEME FOR WELD RESIDUAL STRESS SIMULATION

The thermo-physical and the thermo-mechanical processes associated with weld residual stress evolution during welding are extremely complex. Currently, no model is available to realistically account for the arc physics, the weld pool phenomena, and finally, the deformation and heat conduction in the solid metal. In this study, the welding process is simulated by employing sequentially coupled, nonlinear, transient, thermo-mechanical analyses to calculate temperature history and subsequently the welding induced residual stresses. First a transient thermal analysis is performed during which temperature history in the connection from the heat input of the successive build-up of the welding passes is determined. The temperature field at each time step is then used as an input into a transient thermo-mechanical analysis for evaluating the residual stress and strain fields in welded joints. Finally, the cyclic loading responses of welded joints with the residual stress fields are simulated by prescribing displacement controlled cyclic loading.

In order to study the development of weld residual stresses and its influence on the seismic response of moment resisting connections, advanced 3D numerical schemes are developed with finite element (FE) program ANSYS to simulate welding process, and hence the residual stress and subsequent fatigue response of WSMCs. 3D FE models of the exterior sub-assemblage of the welded unreinforced flange bolted web (WUF-B) connections of Hassan and Quayyum (2022) are simulated, where a single W18 × 55 ASTM A992 beam is attached to a W14 × 74 ASTM A992 column as shown in Figure 1a. The weld access hole geometry and other configurations of the connections are simulated exactly to mimic the experimental setup. The connection region is discretized with very fine mesh in order to capture the behavior of the connection region precisely. Figure 1b shows the finite element (FE) mesh generated for the analysis of the connection. Thermal analysis is performed in order to calculate transient temperature distribution from the welding sequence and subsequent cooling. In thermal finite element analysis, heat loss occurs from the material surface through both convection and radiation, which are determined using the appropriate heat transfer coefficient. The temperature-dependent material properties such as specific heat, thermal conductivity, enthalpy, heat transfer coefficient of structural steel are used in the heat transfer analysis. Latent heat/phase transformation is accounted for by defining enthalpy of the material as a function of temperature (Comini *et al.* 1974). The principal parameter of the welding heat source for the temperature field is heat flow which is assumed as the combination of both surface and body heat flux components (Hong *et al.* 1998). The multi-pass welding process is developed by using the element birth/death technique in ANSYS where the model accounts for the addition of filler material as new weld passes are deposited and the geometry of the welded joint is built-up. The steps of using this technique are depicted in Figure 2 for the beam-column welded joint. With this technique, a finite element mesh of the welded joint including the weld beads is generated first. Subsequently, the element groups representing each weld pass are deactivated (element death) before welding is included in the analysis. These elements are reactivated (element birth) sequentially as the welding arc (heat source) advances along the beam flange width direction.

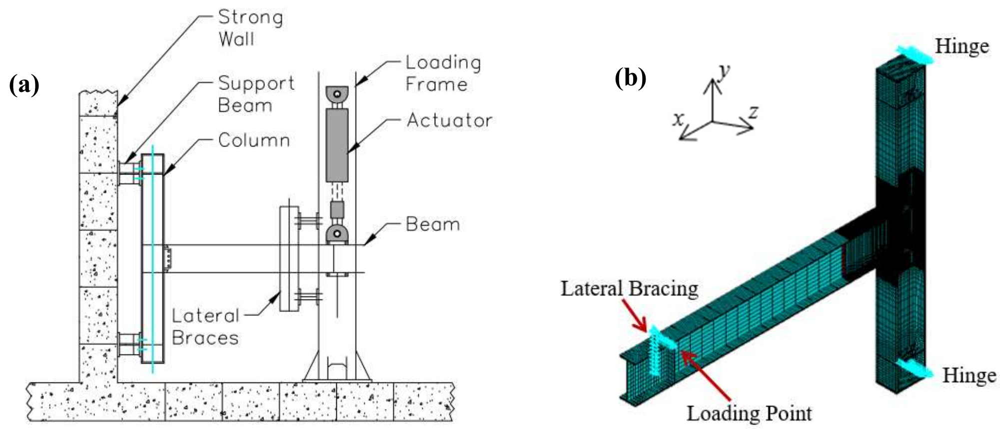


Figure 1. (a) Experimental setup, and (b) finite element mesh of WUF-B connection of Hassan and Quayyum [3].

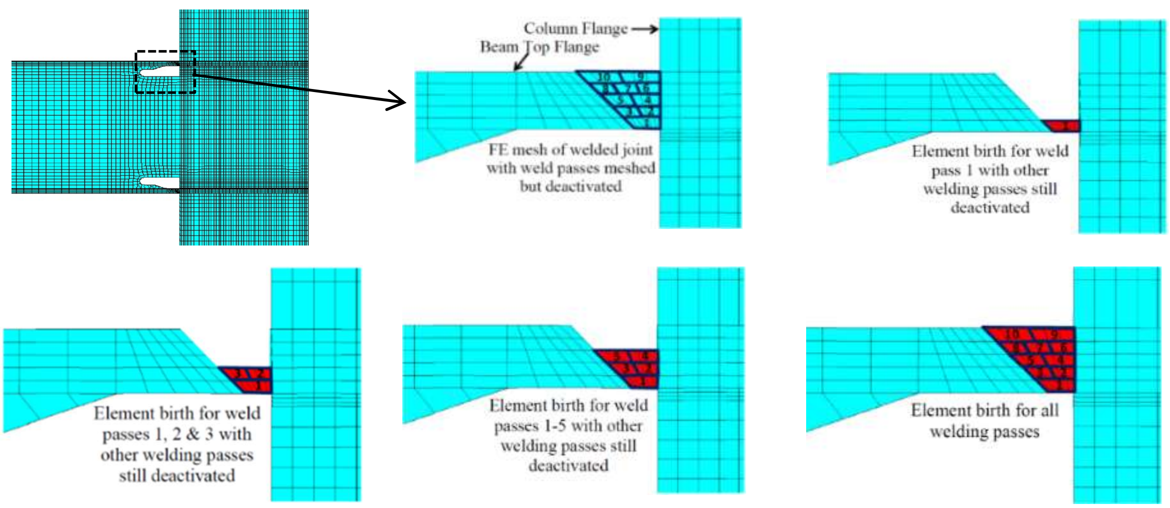
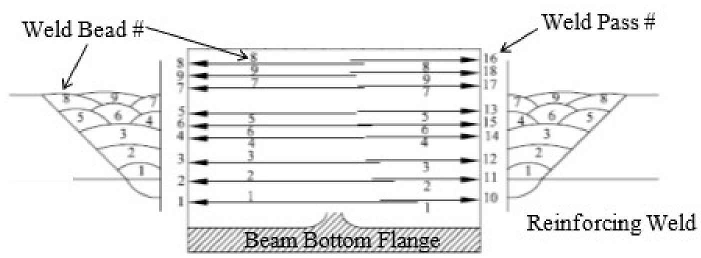


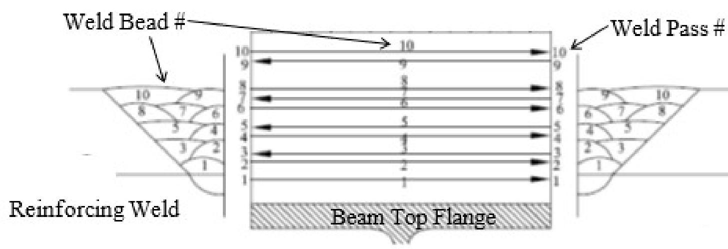
Figure 2. Element birth and death technique in the FE simulation.

In order to investigate the development of residual stresses due to welding, and the effect of welding sequence on the residual stress distribution as well as on the low-cycle fatigue response of WSMCs, two specimens of welded steel moment connection (namely MC1 and MC2) are considered in the finite element analysis. Each specimen has different weld sequence at the beam bottom flange similar to the experimental specimens of Hassan and Quayyum (2022), whereas beam top flange is welded in a similar fashion for both the specimens. The welding details of the two specimens for bottom flange are shown in Figures 3 and 4. The top flange welds are deposited in a similar fashion for both the specimens, only the number of beads and the size of the beads are different. On the other hand, the bottom beam flange welds are laid in a completely different manner for the two specimens. In specimen MC1, the welder fills the groove with all the welding beads on one side of the beam web before he switches to the other side of the beam web to complete the weld. On the contrary, in specimen MC2, the welder alternates sides of the beam web after placing each weld bead. All the welding sequences in beam top and bottom flange for specimens MC1 and MC2 are simulated accordingly in the finite element analysis by using the element birth and death technique and using the appropriate thermal properties of structural steel. Figure 5 shows comparison between the measured and simulated temperature profiles (T) during the welding process for both the specimens at the top flange of the beam measured at a distance of 75 mm away from the weld toe and 50 mm away from the edge of the beam flange. It is observed that the simulated responses resembled the experimental temperature profiles closely for both the specimens. Similar temperature profiles are compared at several other locations of both beam top and bottom flanges and good agreement was observed between the simulated and experimental results. This validates the thermal finite element model and it indicates that the element birth-death technique can simulate the welding process with good accuracy.

The residual stress analysis is conducted after the thermal analysis is finished and the time dependent temperature field during the welding process is determined. The temperature solution obtained from the thermal analysis, which normally depends on position and time, is read into the stress analysis as a predefined field i.e. the nodal temperature field at each time step from the thermal analysis is applied as thermal load to the corresponding node in the structural model. Similar to the thermal analysis, element birth/death is used in the residual stress analysis. Once the real time temperature fields are fed into the structural model for each of the nodes at each time step, then residual stresses are calculated based on the temperature dependent material properties of structural steel (such as density, initial yield stress, elastic modulus, Poisson's ratio, thermal expansion coefficient) and relevant constitutive equations.

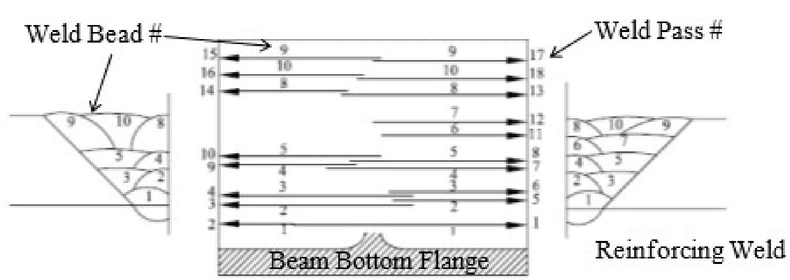


(a)

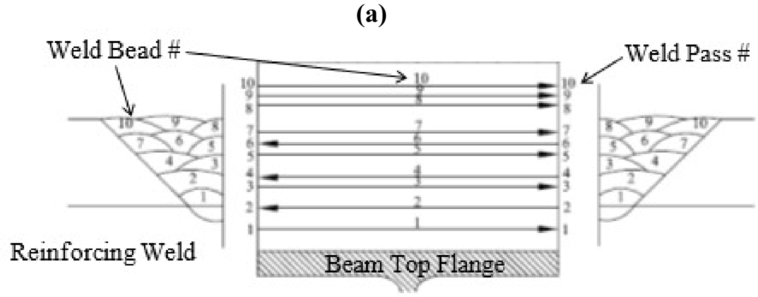


(b)

Figure 3. Sketch of weld bead and pass sequences of specimen MC1, (a) bottom flange, and (b) top flange.



(a)



(b)

Figure 4. Sketch of weld bead and pass sequences of specimen MC2, (a) bottom flange, and (b) top flange.

During welding, the base material is exposed to high temperatures, which induces microstructural changes in the material leading to change in the material properties. The material heterogeneity is incorporated in the model by defining five sets of temperature-dependent material properties of A992 steel based on the study by Johnson and Ramirez (2002) on stainless steel SS304. The residual stress distributions in longitudinal direction denoted as σ_{Rx} (dominant direction for seismic loading) for specimen MC1 is shown in Figure 6. It is evident that significant amount of residual stresses develops close to the welded region of the connection in longitudinal direction. The magnitude of the residual stresses at several locations near the weld toe are very close to the yield stress of the base metal, and around the weld access hole the residual stresses are higher than the yield stress (Figures 6, 7a, 7b). The residual stresses in the longitudinal direction are higher at the weld toe and weld access hole, and gradually decrease as the distance from the weld toe increases (Figure. 7c). The higher values of residual stresses close to the weld toe and around the weld access hole may play a significant role under service conditions. However, the magnitude and distribution of residual stresses obtained in the specimens could not be validated due to the lack of experimental data from Hassan and Quayyum (2022).

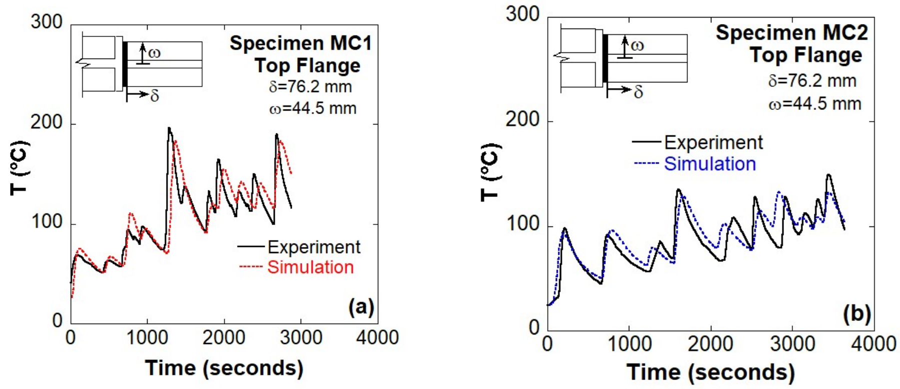


Figure 5. Measured and simulated temperature profiles at the beam top flange for the two specimens. (a) Specimen MC1, (b) specimen MC2.

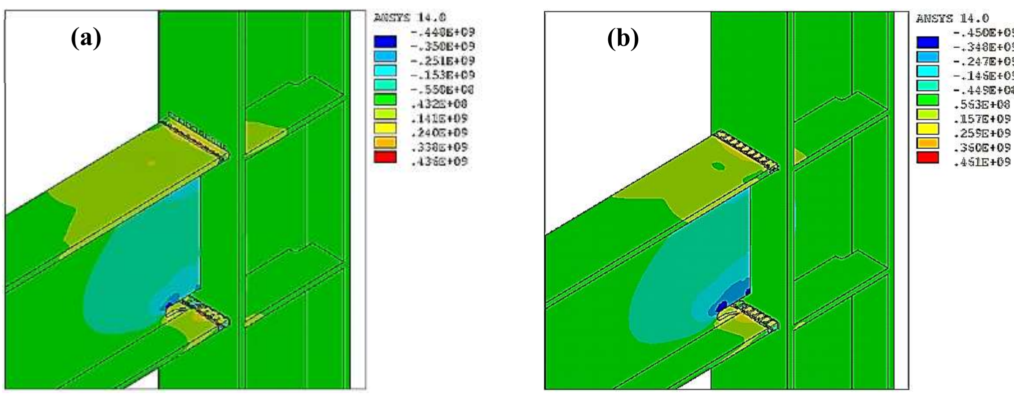


Figure 6. Residual stress distribution (in Pa) for (a) specimen MC1, (b) specimen MC2.

EFFECT OF WELD SEQUENCE ON THE RESIDUAL STRESS DISTRIBUTION

To investigate the influence of the weld sequences on the residual stress distribution, the residual stresses are plotted across the width of the beam flange at the location of peak residual stresses as shown in Figures 7a-b. It is observed that for the top flange, specimen MC1 develops higher residual stresses compared to specimen MC2 (Figure 7a). The residual stresses at the beam top flange are almost constant along the width of the flange except at the edges of the flange. This is expected as each of the welding beads in the top flange weld is laid in one pass with no discontinuity during welding. For beam bottom flange, there are several locations across the width of the beam flange where welding is stopped and restarted, and hence depending on the temperature distribution, the two specimens experienced different magnitudes of residual stresses and distribution across the width of the flange for the two weld sequences. It is observed that specimen MC1 develops higher residual stresses in the beam bottom flange than that in specimen MC2 (Figure 7b). The nonuniform temperature gradient produced in the beam bottom flange in specimen MC1 leads to the development of higher residual stresses compared to that of specimen MC2. It is observed that the residual stresses have larger values at the start and stop location of the weld as can be seen from Figure 7b.

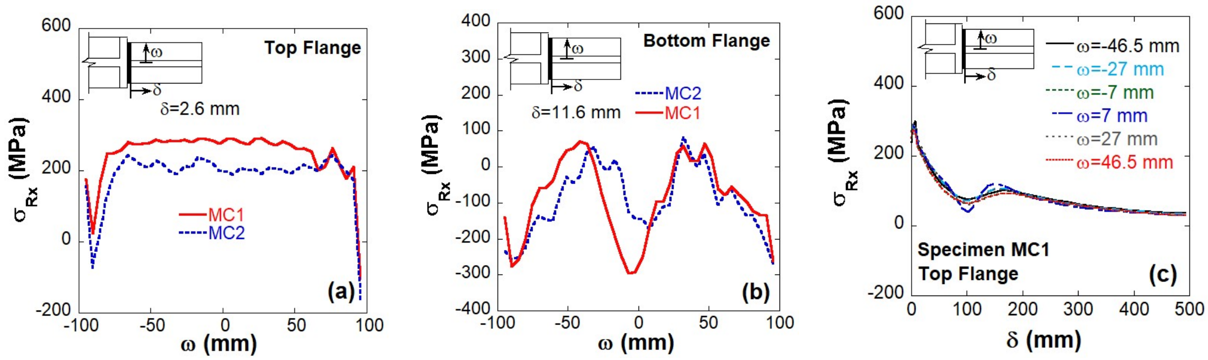


Figure 7. Simulated residual stresses across (a) width of beam top flange, (b) width of beam bottom flange, and (c) length of beam top flange for specimen MC1.

EFFECT OF RESIDUAL STRESSES ON THE FATIGUE RESPONSES

The mechanisms of localized fatigue damage accumulation and crack initiation in presence of residual stresses are not usually considered in the design approaches. In the low-cycle fatigue range, the influence of residual stresses is usually ignored because of the assumption that the residual stresses relax to zero after only a few loading cycles. The finite element analysis results demonstrate that both tensile and compressive residual stresses in welded joints can be as high as the yield stress at the weld toe and higher than yield stress at the weld access hole. The development of the residual stresses can act as mean stresses to the fatigue loading cycle and thus lead to degradation and failure of structures due to accumulation of axial strain which is known as ratcheting. In order to investigate the influence of residual stresses on the seismic response of WSMCs, the finite element models of the moment connections are subjected to simulated constant amplitude cyclic loading from Hassan and Quayyum (2022) as shown Figure 8a to investigate the localized failure mechanisms with and without residual stresses where θ is rotation with respect to column centerline and *N* is the number of loading cycles.

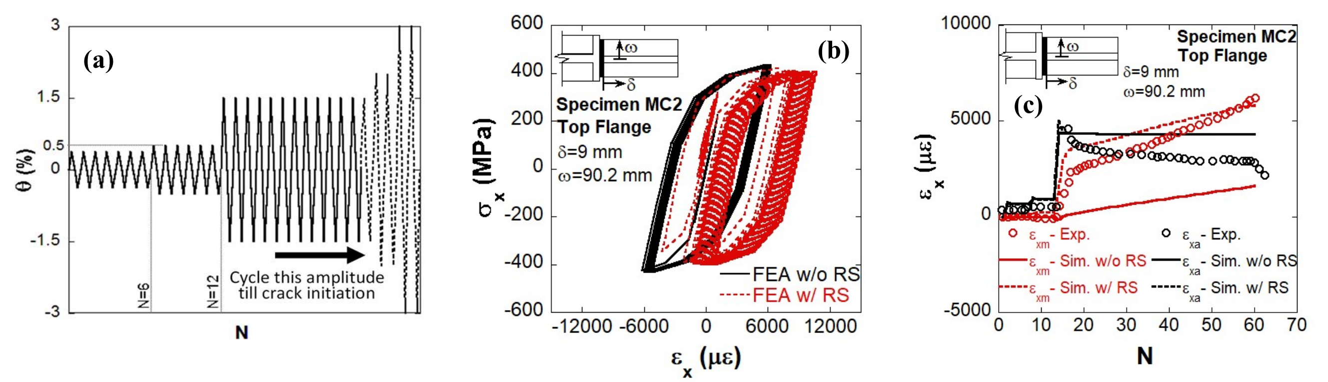


Figure 8. Constant amplitude loading history used in the experiments by Hassan and Quayyum (2022); *(b) axial stress-strain hysteresis cycles, and (b) axial mean strain and amplitude plotted against number of loading cycles for specimen MC2.*

For cyclic response simulation of WSMCs, the advanced nonlinear kinematic hardening model of Chaboche (1989) in ANSYS is used. For Chaboche model parameter determination, stable hysteresis loops obtained from single amplitude, strain-controlled cycle are fitted. It is seen that axial stress-strain ($\sigma_x - \varepsilon_x$) hysteresis cycles shift in the direction of axial strain indicating axial strain accumulation when residual stresses are considered in the analysis, whereas with no residual stress, the hysteresis loops are cycling almost in the same location (Figure 8b). A comparison of the axial mean strain (ε_{xm}) and amplitude (ε_{xa}) obtained from the finite element analysis with that of the experimental results is shown in Figure 8c for specimen MC2. It is interesting to note that finite element simulation results predict the axial strain accumulation or ratcheting correctly when residual stresses are considered in the analysis. Similar observations were made in other location of strain gages for both specimens MC1 and MC2. The agreement between the mean axial stress simulation results with those of the measured values serves as another validation of the numerical scheme developed. Based on the experimental and simulated responses, it is apparent that the increase in the axial strain accumulation observed in the experiments is attributed to the presence of high residual stresses near the welded joint of the connection, which can be simulated properly by considering residual stresses in the analysis. Moreover, it is interesting to note that there is a sharp jump in the mean axial strain for the locations near weld toe during transition from elastic to inelastic loading cycles (Figure 8c) and at the same time the mean stresses relax to zero i.e. the sharp jump in the mean axial strain triggers ratcheting even though the mean stresses relax after that. This unique feature of strain ratcheting even after relaxation of the mean axial stresses is also observed by Cheng (2009) in his experimental and numerical study on cyclic response of welded piping joints. When the mean strain and strain amplitudes are plotted at different locations across the beam top and bottom flanges for both the specimens it is apparent that the axial strain accumulation rate is completely different for the two specimens with different weld sequences. One set of the results is presented in Figure 9. It is noted that in most of the locations across the weld toe and weld access hole, specimen MC1 develops significantly higher strain ratcheting compared to specimen MC2 for both beam top and bottom flanges. However, there are very few locations where the axial strain ratcheting for specimen MC2 is either equal or slightly higher than those for specimen MC1. However, although the influence of weld sequence on the mean axial strain is noticeable, the axial strain amplitude responses are not influenced by the weld sequence as much as the mean axial strain. In several locations, specimen MC1 has higher strain amplitudes compared to specimen MC2 as anticipated. Subsequently, there are several locations where specimen MC2 has equal and higher strain amplitudes compared to specimen MC1. Hence, the direct influence of weld sequence on the axial strain amplitude is not as clear as its influence on the mean axial strain. The results of this study demonstrated that the residual stress distribution can be substantially influenced by the sequence of welding which inevitably may lead to different stress-strain response at different locations of WSMCs, especially near the weld toe region of the beam flanges. It is anticipated that an optimized sequence of welding can be obtained with a broad set of finite element analyses as presented in this study to reduce the residual stresses near the weld toe and access hole region and thereby, increase the fatigue life of the connections.

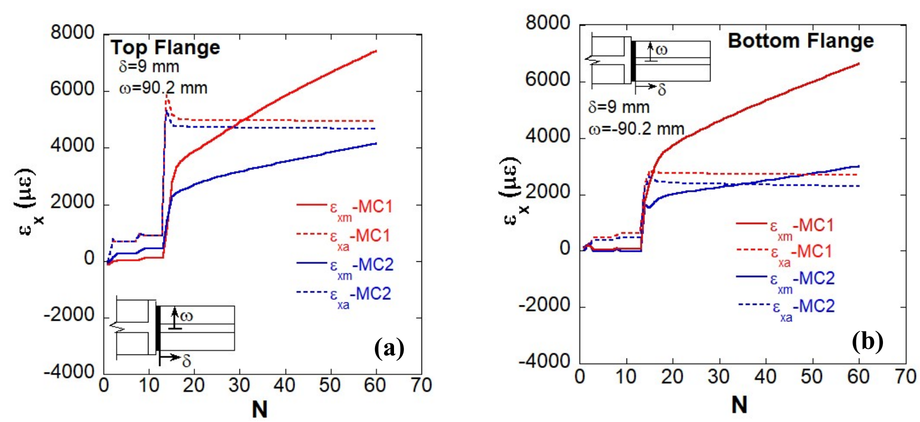


Figure 9. Axial strain mean and amplitude plotted against number of loading cycles for the two specimens at (a) beam top flange, and (b) beam bottom flange.

CONCLUSION

The study presented herein demonstrated development of welding induced residual stresses in moment resisting connections by using advanced numerical techniques which exhibited good correlation with the experimental observations. The development of welding residual stresses can be properly simulated by using advanced numerical techniques as described in this study, and three-dimensional modeling of the welding process is required in order to model the weld sequence effect. The results of the finite element analysis revealed that significant amount of residual stresses develop close to the weld toe and weld access hole of the connection because of the welding procedure, which gradually diminishes with increase in the distance from the weld toe. The peak value of residual stresses can be higher than the yield stress of the base material and it can be either tensile or compressive or a combination of both. The presence of such high residual stresses may lead to axial strain ratcheting near the weld toe and weld access hole region, and subsequently may lead to low-cycle fatigue failure of the connection. Hence, the low-cycle fatigue failures that have been observed in the cyclic testing of the post-Northridge connections can be attributed to the development of damage accumulation near the weld toe and weld access hole as a result of the axial strain ratcheting. The study also demonstrated that different weld sequences induce different distribution and magnitude of residual stresses around the welded joint, and hence, the ratcheting phenomenon can be different for different weld sequences, which subsequently influence the fatigue life of the connections.

REFERENCES

[1] Chaboche, J. L. (1989). Constitutive equations for cyclic plasticity and cyclic viscoplasticity. *International Journal of Plasticity*, *5*(3), 247-302.

[2] Cheng, P. Y. (2009). Influence of residual stress and heat affected zone on fatigue failure of welded piping joints. *Ph.D. Dissertation*, North Carolina State University, Raleigh, NC.

[3] Chi, W. M., Deierlein, G. G., and Ingraffea, A. (2000). Fracture toughness demands in welded beam-column moment connections. *Journal of Structural Engineering*, *26*(1), 88-97.

[4] Comini, G., Del Guidice, S., Lewis, R. W., and Zienkiewicz, O. (1974). Finite element solution of non-linear heat conduction problems with special reference to phase change. *International Journal for Numerical Methods in Engineering*, *8*(3), 613-624.

[5] Han, S. W., Moon, K. H., and Jung, J. (2014). Cyclic performance of welded unreinforced flange-welded web moment connections. *Earthquake Spectra*, *30*(4), 1663-1681.

[6] Hassan, T., and Quayyum, S. (2022). Influence of Weld Sequence on the Low-Cycle Fatigue Failure of WUF-B Connections. *Journal of Structural Engineering*, *148*(7), 04022072.

[7] Hong, J. K., Tsai, C. L., and Dong, P. (1998). Assessment of numerical procedures for residual stress analysis of multipass welds. *Welding Research Supplement*, 372s-382s.

[8] Johnson, M. Q., and Ramirez, J. E. (2002). Preliminary evaluation of heat affected zone toughness in structural shapes used in the construction of seismic moment frames. SAC Joint Venture.

[9] Lee, D., Cotton, S. C., Hajjar, J. F., and Dexter, R. J. (2005). Cyclic behavior of steel moment-resisting connections reinforced by alternative column stiffener details, I. Connection performance and continuity plate detailing. *Engineering Journal*, *42*(4), 189-213.

[10] Matos, C. G., and Dodds, Jr., R. H. (2000). Modeling the effects of residual stresses on defects in welds of steel frame connections. *Engineering Structures*, *22*(9), 1103-1120.

[11] Matos, C. G., and Dodds, Jr., R. H. (2001). Probabilistic modeling of weld fracture in steel frame connections part i: quasi-static loading. *Engineering Structures*, *23*(8), 1011-1030.

[12] Matos, C. G., and Dodds, Jr., R. H. (2002). Probabilistic modeling of weld fracture in steel frame connections part ii: seismic loading. *Engineering Structures*, *24*(6), 687-705.

[13] Nakashima, M., Suita, K., Marisako, K., and Maruoka, Y. (1998). Tests of welded beam-column subassemblies. I. Global behavior. *Journal of Structural Engineering*, *24*, 1236-1244.

[14] Pan, J., Chen, S., Lai, Z., Wang, Z., Wang, J., and Xie, H. (2017). Analysis and fracture behavior of welded box beam-to-column connections considering residual stresses. *Construction and Building Materials*, *154*, 557-566.

[15] Righiniotis, T. D., Omer, E., and Elghazouli, A. Y. (2002). A simplified crack model for weld fracture in steel moment connections. *Engineering Structures*, *4*(9), 1133-1140.

[16] Stojadinovic, B., Goel, S. C., Lee, K. H., Margarian, A. G., and Choi, J. H. (2000). Parametric tests on unreinforced steel moment connections. *Journal of Structural Engineering*, *126*, 40-49.

[17] Suita, K., Nakashima, M., and Morisako, K. (1998). Tests of welded beam-column subassemblies II: Detailed behavior. *Journal of Structural Engineering*, *124*(11), 1245-1252.

[18] Uang, C. M., Yu, Q. S. K., Noel, S., and Gross, J. (2000). Cyclic testing of steel moment connections rehabilitated with RBS or welded haunch. *Journal of Structural Engineering*, *126*(1), 57-68.

[19] Wang, W., Zhang, C. H., Wang, G. F., and Zhang, J. (2012). Welding Residual Stress of Flange-Plate Steel Reinforced Connections. In *Advanced Materials Research* (Vol. 446, pp. 3495-3498). Trans Tech Publications Ltd.

[20] Zhang, J., and Dong, P. (2000). Residual stresses in welded moment frames and implications for structural performance. *Journal of Structural Engineering*, *26*(3), 306-315.