The 2017 World Congress on
Advances in Structural Engineering and Mechanics (ASEM17)
28 August - 1 September, 2017, Ilsan(Seoul), Korea

Experimental investigation of axial load on low cycle fatigue performance of steel H piles in integral bridges

*Memduh Karalar[1)] and Murat Dicleli[2)]

[1)] *Department of Civil Engineering, Bülent Ecevit University, Zonguldak, TURKEY*
[2)] *Department of Engineering Sciences, Middle East Technical University, Ankara, Turkey.*
[1)] *memduhkaralar@gmail.com*

ABSTRACT

In this study, the effect of axial load on the low cycle fatigue performance of integral bridge steel H–piles is investigated. Review of literature revealed that there is no experimental research data on the effect of axial load on the low cycle fatigue performance of integral bridge steel H-piles. For this purpose, experimental studies on full scale steel H-pile specimens are conducted to simulate cyclic behavior of steel H-piles under thermal effects in integral bridges by considering the effect of axial load combined with large amplitude strain cycles with various amplitude levels. Using experimental test results, the effect of axial load level is investigated on the low cycle fatigue performance of integral bridge steel H–piles. It is observed that the effect of axial load on the low cycle fatigue performance of integral bridge steel H-piles are so important to reduce the bending stresses in the steel H-piles and also increase the low-cycle fatigue performance of steel H-piles at the abutments of integral bridges at the moderate strain amplitudes. Moreover, it is observed that at large strain amplitudes the effect of local buckling should be considered more than the effect of axial load on the low cycle fatigue life of steel H piles at the abutments of integral bridges.

1. INTRODUCTION

Integral bridges possess a continuous deck with no physical expansion joints at the ends. In these types of bridges, the superstructure is connected monolithically to the abutments supported on a single row of piles that provide the required lateral flexibility to allow for longitudinal movement of the bridge under thermal effects. A typical two-span, slab-on-girder integral bridge is shown in Fig.1. The most common type of piles used at the abutments of integral bridges is steel H-piles. The daily and seasonal temperature changes result in imposition of cyclic horizontal displacements on the continuous bridge deck of integral bridges and thus, on the steel H-piles supporting the abutments.

---

1) Assistant Professor
2) Professor

As the length of integral bridges increases, the temperature-induced lateral cyclic displacements in the steel H-piles at the abutments become larger as well. Consequently, the piles may experience cyclic plastic deformations. This may lead to a reduction in the service life of the bridge due to low-cycle fatigue effects in the steel H-piles. The number and amplitude of thermal-induced cyclic flexural strains in integral bridge steel H-piles are important parameters that effect their low cycle fatigue life. Close examination of the existing field measurement data for integral bridges revealed that the measured thermal-induced cyclic flexural strains in steel H-piles at the abutments consist of large, primary small and secondary small strain cycles (Dicleli and Albhaisi, 2004).

Although a few research studies on the low cycle fatigue effects in the steel H-piles of integral bridges at the abutments are found in the literature (Dicleli and Albhaisi, 2004, Girton et al.,1991, Lawyer et al., 2000, Arsoy et al., 2004, Dicleli and Albhais , 2003, French et al., 2004, Hällmark et al., 2006, Pétursson et al., 2010, Razmi and Ladani, 2013), none of these research studies provide analytical or experimental results on the combined effects of pile axial load together with large flexural strain cycles with various amplitudes on the low cycle fatigue life of steel H-piles at the abutments of integral bridges. Accordingly, the main objective of this research study is to investigate the individual and combined effects of axial load, large flexural strain cycles as a function of the strain amplitude on the low cycle fatigue life of integral bridge steel H-piles at the abutments. For this purpose, a series of parametric full scale experimental tests are conducted on HP220x57 steel H-pile specimens, where the pile specimens are subjected to; (i) only large flexural strain cycles with various amplitudes in the absence of axial load, (ii) only large flexural strain cycles with various amplitudes in the presence of a typical axial load. The observations from this experimental research study may become important as they provide information about the effect of various important parameters on the low cycle fatigue life of steel H-piles and provide guidance for the assessment of the adequacy of the current design methods in relation to the low cycle fatigue life of steel H-piles at the abutments. The outcome of such a research study may also be used to develop design guidelines that may be employed in the design of steel H-piles to endure low cycle fatigue effects throughout the service life of the bridge.

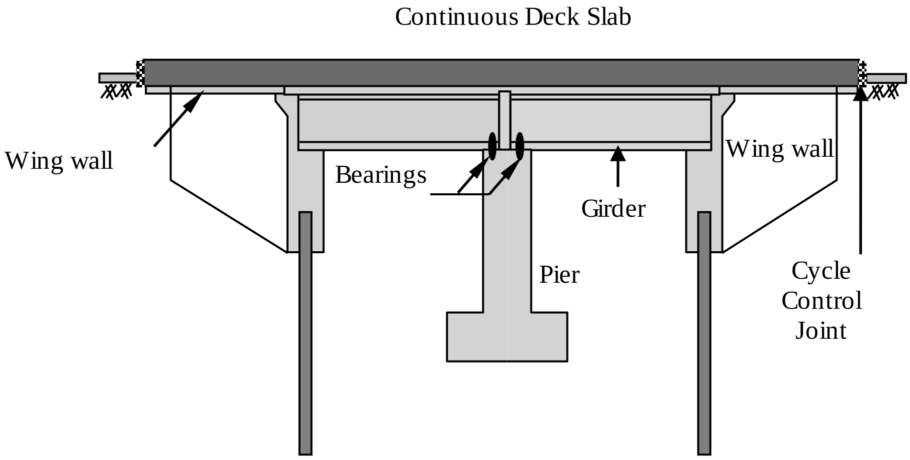


Figure 1. *Typical two-span integral bridge*

2. FLEXURAL STRAIN CYCLES IN STEEL H-PILES DUE TO SEASONAL TEMPERATURE CHANGES

A change in temperature causes a material to change its length. This property of materials is accountable for expansion and contraction of the integral bridge superstructures. Each daily variation in temperature completes a cycle of expansion and contraction of the integral bridge superstructure and the cycles repeat over time. The maximum expansion occurs during summer days while the maximum contraction forms during winter nights. These seasonal and more frequent, daily/weekly temperature changes result in imposition of cyclic horizontal displacements on the continuous bridge deck of integral bridges and thus on the abutments and steel H-piles. Consequently, the abutments are pushed against the approach fill in the summer time and then pulled away in the winter time, causing lateral deflections at the tops of the piles that support the bridge at the abutments as shown in Fig.2.

Accordingly, the thermal-induced longitudinal movement of the integral bridge deck results in one dominant cyclic lateral displacement of steel H-piles at the abutments each year due to seasonal (summer and winter) temperature changes and numerous smaller cyclic lateral displacements due to more frequent temperature fluctuations. This is confirmed by the strain vs. time records of instrumented steel H-piles for several integral bridges (Girton et al., 1991, England and Tsang, 2001, French et al., 2004, Abendroth and Greimann, 2005, Breña et al., 2007).

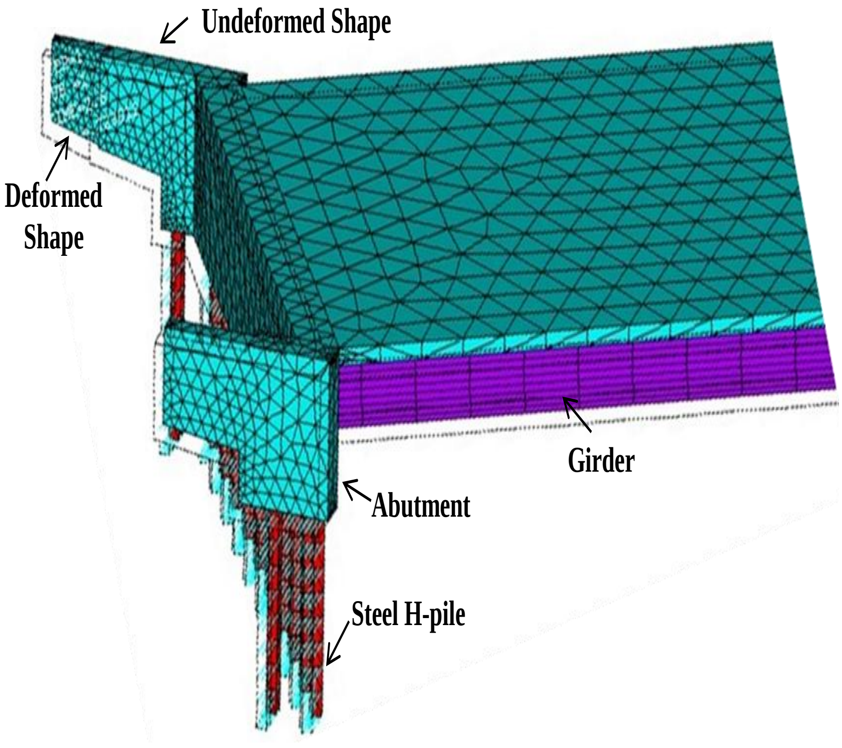


Figure 2. Pile displacement due to thermal changes.

The mean or the effective bridge temperature across the bridge deck is primarily responsible for the expansion and contraction of a bridge (Arsoy, 2008, Emerson, 1977, Black and Emerson, 1976). In this research, the thermal induced response of integral bridge piles is studied by observing the field measurement data of several integral bridges available in the literature.

Field studies performed by Girton et al.1991, on the Boone River bridge and the Maple River bridge in Iowa, USA showed that both bridges exhibited one large strain cycle per year due to seasonal temperature changes and about 52 small strain cycles per year due to more frequent (e.g. weekly) temperature fluctuations as shown in Fig.3. Another field test performed by French et al.[6] on a reinforced-concrete integral bridge in Minnesota, USA also demonstrated one large strain cycle per year due to seasonal temperature changes and about 120 small strain cycles per year due to more frequent temperature fluctuations. According to another research study performed by Abendroth et al. 2007, the Tama county bridge in Iowa, USA exhibited one large strain cycle per year due to seasonal temperature changes and about 81 small strain cycles per year due to more frequent temperature fluctuations. Moreover, all the available field test records demonstrate that the amplitude of the small strain cycles in the piles supporting the abutments fall within 20% to 40% range of the amplitude from the large strain cycles. Similar findings were reported by Lawyer et al. [3] and Dicleli and Albhaisi, 2003. Further examination of the recorded flexural strain cycles in steel H-piles revealed that the small strain cycles may be divided into two types as primary and secondary. The primary cycle is defined as a cycle that crosses the backbone of the large amplitude cycle and the secondary cycle is a smaller amplitude cycle that does not cross the backbone of the large amplitude cycle as shown in Figs. 4 and 5.

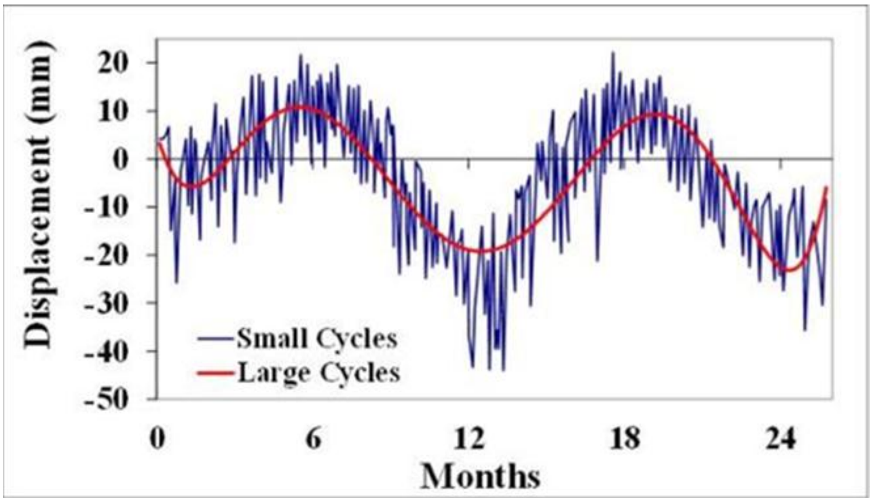


Figure 3. Measured pile displacements by Girton et al. (1991).

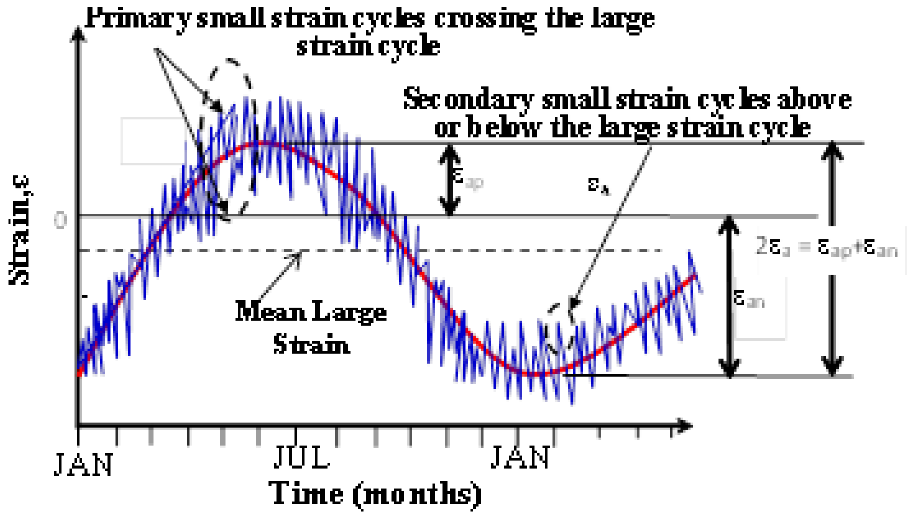


Figure 4. General flexural strain versus time record for integral bridge piles (Dicleli and Albhaisi (2004)).

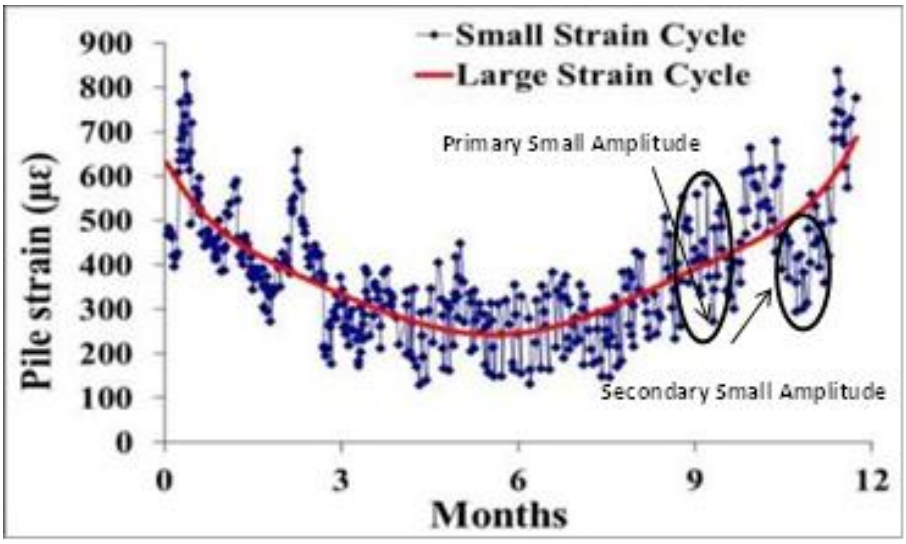


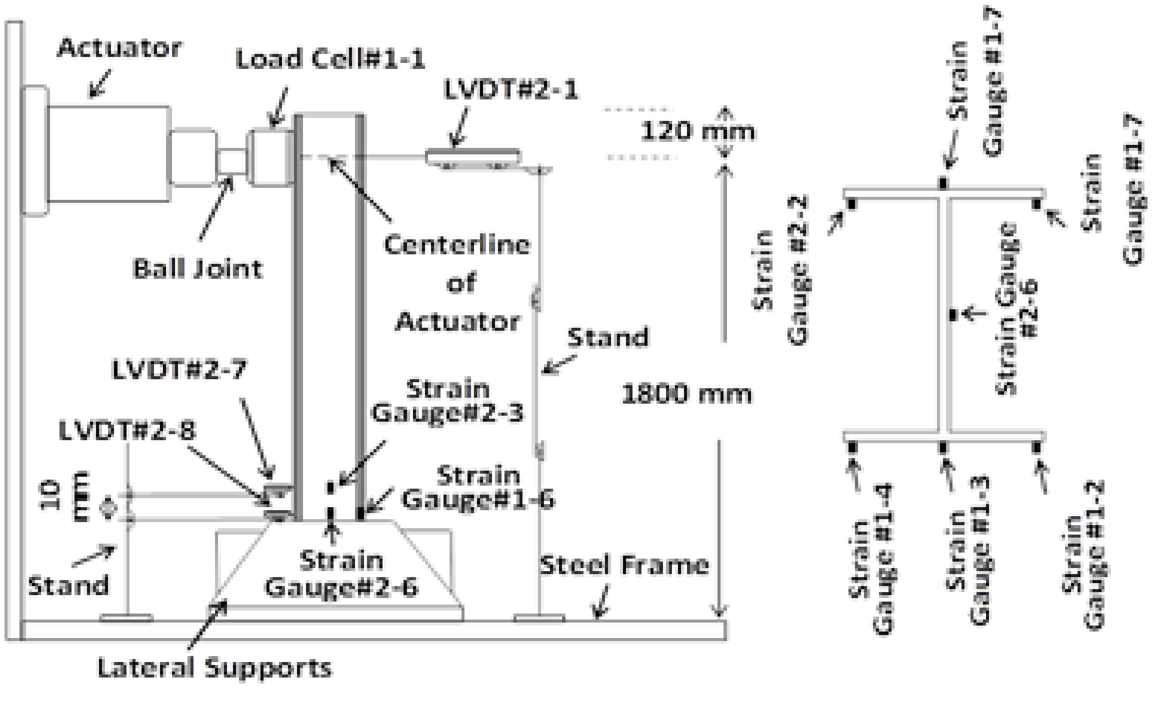
Figure 5. (a) Experimental bridge displacement versus time record for Bridge #55555 and the demonstration of primary and secondary small strain cycles.

It is worth mentioning that the net difference between the seasonal and construction temperatures may be disparate in the summer and winter times based on the climatic conditions of the area where the bridge is located. Therefore, the amplitudes of the positive (ε_{ap}) and negative (ε_{an}) strain cycles corresponding to the summer and winter time may not be equal as observed from Fig.4. However, as the range of strain amplitudes rather than the strain amplitude itself defines the extent of fatigue damage in steel H-piles, the positive and negative strain amplitudes may be assumed to be equal (equal to half of the strain range) (Dicleli and Albhaisi, 2004) when studying the low cycle fatigue life of steel H-piles (i.e. $\varepsilon_{ap} = \varepsilon_{an} = \varepsilon_a$).

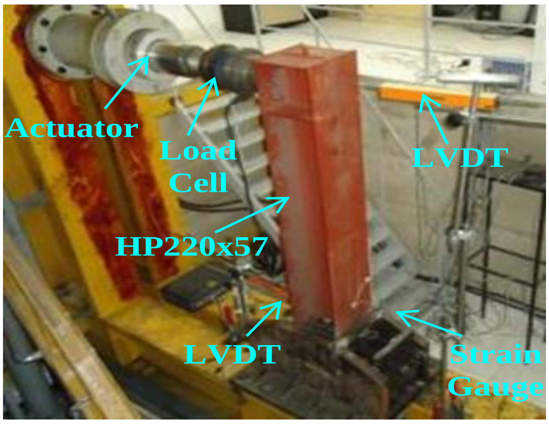
3. TEST SETUP

3.1 Instrumentation and Application of Displacement Controlled Cycles

Three types of measuring devices are used to instrument the steel H-piles as shown in Fig.6. These are, (i) electrical resistant strain gauges for measuring strains on the steel H–piles, (ii) Load cell for measuring the lateral load level and (iii) LVDT (displacement transducer) for measuring the lateral displacement. The pile is instrumented with twelve strain gauges and three displacement transducers. The plan view of the configuration of the strain gauges on the pile cross-section is shown in Fig.6-(a). Strain measurements are required to correlate fatigue life of HP steel section with the cyclic strain amplitudes. Therefore, strain measurement is performed at the critical locations where fatigue failure occurs. Displacements, strains and lateral loads are measured and recorded using a data-logger (TDG-Ai8b). Furthermore, in the test set up, a displacement controlled hydraulic actuator capable of applying ±500 kN lateral load and a stroke of ± 125 mm is used to impose lateral cyclic displacements. A second actuator with a 1000 kN load capacity and capable of keeping the applied load constant is used to exert axial load on the pile specimens (Fig. 6(b)-(c)).



(a)



(b)

(c)

Figure 6. (a) Schematic plot of the test set-up: depicting the location of the strain gauges and LVDT, Photograph of the test set up; (b) without axial load, (c) with axial load

3.2 Material Properties of the Piles Used in the Tests

The HP220x57 piles used in the tests are made of S 320 GP steel according to EN 10204. Standard tensile tests on steel coupons extracted from the HP220x57 section is performed according to American Standards for Testing Materials, (ASTM, 2005). Using the tensile test' results, the average value of the modulus of elasticity of the steel material is determined as 200,000 MPa. In addition, the yield and ultimate tensile strengths are determined as 306 MPa and 421 MPa respectively.

4. LOW CYCLE FATIGUE TESTS AND TEST RESULTS

In this study, three sets of steel HP220x57 pile specimens are tested. The first set of tests (Set #1) is a benchmark test where only large strain cycles with various amplitudes are applied to the pile specimens and the number of cycles to failure are counted. In this set of tests the effect of large strain amplitude on the low cycle fatigue life of steel H-piles is investigated. In the second set of tests (Set #2), consists of piles subjected to large strain cycles in the presence of a typical axial load. The results from this set of tests are compared with those from Set #1 to investigate the effect of axial load on the low cycle fatigue life of steel H-piles. The last set of tests (Set #3) is also performed to investigate the combined effects of large strain cycles, and axial load on the low cycle fatigue life of steel H-piles. In the tests, the amplitude of the large strain cycles is varied while the axial load and the amplitude of large strain cycles are kept constant. The number of cycles to failure are compared with those from, Set #1, Set #2 and Set #3. Detailed discussion of the experimental tests and test results are given in the following sections.

4.1 Set #1: Pile Specimens Subjected to Large Amplitude Strain Cycles

Set #1 tests employ pile specimens subjected to only large strain cycles. In Set #1-a, the piles are subjected to large flexural strain cycles such that a flexural strain equal to five times the yield strain ($\varepsilon_a=5\varepsilon_y$) is developed in the outermost fibers of the flanges in each cycle. This required the application of a cyclic lateral displacement of ±64 mm at the pile top. Fig.7 shows a typical HP220x57 pile specimen under such a cyclic lateral displacement. In Set #1-b however, the piles are subjected to cyclic flexural strains equal to ten times the yield strain ($\varepsilon_a=10\varepsilon_y$) in the outermost fibers of the flanges. This required the application of a cyclic lateral displacement of ±90 mm at the pile top. During the experimental testing of the piles under constant amplitude cyclic strains in Set #1-a and Set#1-b, the fatigue-induced cracks firstly developed in the intersection of the flanges and the web. The cracks then expanded towards the tips of the flanges under further cycling as shown in Fig.8. In the case of Set #1-a tests, the specimens fractured due to low cycle fatigue when the average number of cycles from the test reached 241. In the case of Set #1-b test however, the specimens fractured due to low cycle fatigue when the average number of cycles reached 154. In both set of tests, local buckling occurred in the flanges.

Figure 7. Application of a cyclic lateral displacement at the pile top (a) push, (b) pull direction.

Figure 8. Step-by-step spread of fracture throughout the pile flange.

4.2 Set #2: Pile Specimens Subjected to Large Amplitude Strain Cycles in the Presence of Axial Load

Set #2 tests employ pile specimens subjected to large amplitude strain cycles in the presence of a typical axial load of 170 kN equal to 7.5% of the yield axial strength ($P=0.075P_y$) of the pile specimen as shown in Fig.9. This series of tests consists of two subsets of pile specimens, Set #2-a and Set #2-b. In Set #2-a, the piles are subjected to large flexural strain cycles such that a flexural strain equal to five times the yield strain ($\varepsilon_a=5\varepsilon_y$) is developed in the outermost fibers of the flanges in each cycle.

This required the application of a cyclic lateral displacement of ±62 mm at the pile top. In Set #2-b however, the piles are subjected cyclic flexural strains equal to ten times the yield strain ($\varepsilon_a=10\varepsilon_y$) in the outermost fibers of the flanges. This required the application of a cyclic lateral displacement of ±91 mm at the pile top. The average number of cycles to failure from the pile specimens of Set #2-b are then compared with that from Set #2-a to determine the effect of the amplitude of large strain in the presence of axial load on the low cycle fatigue life of steel H-piles. In the case of Set #2-a tests, the specimens fractured due to low cycle fatigue when the average number of cycles reached 354. In the case of Set #2-b tests however, the specimens fractured due to low cycle fatigue when the average number of cycles reached 94 as shown in Fig.10.

Figure 9. Application of a cyclic lateral displacement at the pile top (a) pull, (b) push direction

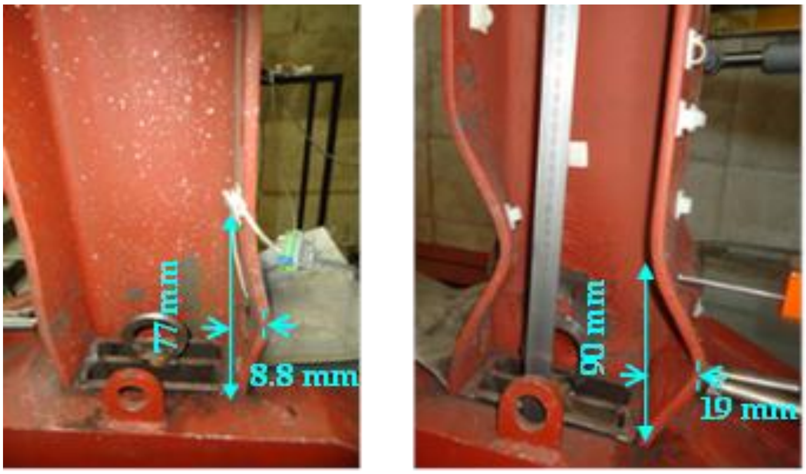


Figure 10. (a) Maximum Strain of $\varepsilon_a=\pm5\varepsilon_y$, (b) Maximum Strain of $\varepsilon_a=\pm10\varepsilon_y$.

5. CONCLUSIONS AND RECOMMENDATIONS

This research study provides a new insight into the behavior of integral bridge steel H-piles under seasonal large flexural strain cycles including the effect of axial load on the pile due to the self-weight of the structure. Accordingly, in this research study, individual and combined effects of largel flexural strain cycles and axial load on the low cycle fatigue life of uncompact steel H-piles at the abutments of integral bridges is investigated as a function of the amplitude of large strain cycles associated with seasonal temperature fluctuations. For this purpose, a series of parametric full scale experimental tests are conducted on HP220x57 steel H-pile specimens. It is observed that, as expected, number of cycles to failure is inversely proportional to the strain amplitude. Furthermore, the effect of axial load is observed to have a significant effect on the low cycle fatigue performance of steel H-piles in two ways: (i) when the pile is subjected to moderate strain amplitudes (five times the yield strain), the presence of axial load is observed to enhance the low cycle fatigue life of the pile. This mainly due to the fact that, the presence of axial load decreases the amplitude of the tensile strain that results in cracking of the material (it delays the initiation of the crack), (ii) when the pile is subjected to larger strain amplitudes (10 times the yield strain), the presence of axial load is observed to decrease the low cycle fatigue life of the pile. This is mainly due to local buckling of the flange under the effect of compressive stresses from the axial load and high compressive strains due to the effect of bending. Local buckling increases the local curvature and strains. This locally accelerates the cracking of the material.

REFERENCES

Dicleli M, Albhaisi SM., Effect of Cyclic Thermal Loading on the Performance of Steel H-Piles in Integral Bridges with Stub-Abutments, Journal of Constructional Steel Research; 60(2):161-182, , 2004.

Girton D.D., Hawkinson T.R., Greinmann L.F., J, Validation of Design Recommendations for Integral-Abutment Piles, Journal of Structural Engineering, v117, n 7, p 2117-2134, 1991.

A. Lawyer, C. French, C.K. Shield. Field performance of integral abutment bridge. Transportation Research Record, 1740 (2000), pp. 108–117.

Arsoy S., Duncan J.M., Barker R.M., Behavior of a Semi-integral Bridge Abutment under Static and Temperature-Induced Cyclic Loading, Journal of Bridge Engineering, Vol.9, No.2, 2004.

Dicleli M, Albhais SM., Maximum Length of Integral Bridges Supported on Steel H-Piles Driven in Sand. Department of Civil Engineering and Construction, Bradley University, Peoria, IL, 2003.

French C., Huang J., Shield C., Behavior of Concrete Integral Abutment Bridges, Final Report, 2004.

Hällmark R., Low Cycle Fatigue of Steel Piles in Integral Abutment Bridges, Master Thesis, 2006.

Pétursson, H., Collin, P., Veljkovic, M., and Andersson, J. Monitoring of a Swedish integral abutment bridge. Structural Engineering International, 2011-21, 175–180.

Razmi J., Ladani L., Aggour M.S. Fatigue Crack Initiation and Propagation in Piles of Integral Abutment Bridges. Computer-Aided Civil and Infrastructure Engineering 2013-28, 389-402.

England, G.L. and N. Tsang, 2001. Towards the design of soil loading for integral bridges.

Abendroth R.E., Greimann L.F., Field Testing of Integral Abutments, Iowa DOT Project HR-399, Iowa State University and Iowa Department of Transportation, Iowa, 2005.

Breña S.F., Bonczar C.H., Civjan S.A., DeJong J.T., and Crovo D.S., Evaluation of Seasonal and Yearly Behavior of an Integral Abutment Bridge, Journal of Bridge Engineering, ASCE, Vol. 12 (3), May-June 2007, pp. 296-305.

Arsoy, S., Proposed Mathematical Model For Daily and Seasonal Thermal Bridge Dislacements, Transportation Research Record 2008;2050:3-12.

Emerson, M., Temperature Differences in Bridges: Basis of Design Requirements. Transport and Road Research Laboratory (TRRL) Report 765, Crowthorne, Berkshire, U.K., 1977.

Black, W., and Emerson, M. Bridge Temperatures Derived from the Measurement of Movements. Report 748, Transport and Road Research Laboratory (TRRL), Crowthorn, England 1976; 1–33.

Abendroth R.E., Greimann L.F., An Integral Abutment Bridge with Precast Concrete Piles Final Repor, 2007.

ASTM 2005. Standard Test Methods for Tension Testing of Metallic Materials