A R C H I W U M   I N S T Y T U T U   I N Ż Y N I E R I I   L Ą D O W E J
Nr 12 ARCHIVES OF INSTITUTE OF CIVIL ENGINEERING 2012

INVESTIGATION ON FATIGUE STRENGTH OF CORRUGATED STEEL PLATES BOLTED LAP JOINTS UNDER FLEXURE

Hesham MOHAMMED*, John B. KENNEDY**,
*) Professor, Dept. of Structural Engineering, Univ. of Cairo, Cairo, Egypt.
**) Univ. And Emeritus Professor, Dept. of Civil and Environmental Engineering, Univ. of Windsor, Windsor ON, Canada

Abstract

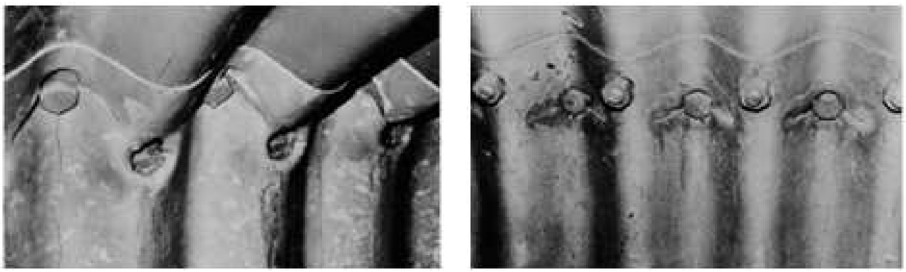
Soil-steel structures have been used successfully in constructing underground conduits of medium and short spans. In the recent years, manufacturers of these structures in United States and Canada ventured into using this economic type of construction to replace old and deteriorated short-span concrete bridges. Under conditions of long span and shallow soil cover conditions, the surrounding soil may not be able to provide the required support for the steel structure. As the result, the steel structure tends to deform more freely, leading to a considerable increase in its bending moment under both construction and live loads. The lap joints used in constructing the steel structure become susceptible to premature fatigue failure. In this paper, the effects of bolt arrangement, steel sheet thickness and initial misalignments on the fatigue strength are investigated. As a result of the study a group of (S-N) curves is recommended for the design of the lap joints under cyclic loading.

Key words: Short Span Bridges; Lap Joints, Finite Element Analysis, Corrugated Steel Sheets; Fatigue Strength of Bolted Joints.

1. INTRODUCTION

A soil-steel structure drives its load carrying capacity from the interaction of a highly flexible steel structure with the surrounding engineered soil. Over the last five decades, soil-steel structures have been used successfully in constructing underground conduits of medium and short spans. These structures are built with different shapes (circular pipes, ellipses, pipe arches, arches, and reentrant arches) and under different depth of soil cover (shallow and deep). They are constructed from corrugated steel sheets lapped together using bolted joints to form the required shape. In recent years, manufacturers of these structures in the United States and Canada ventured into using this economic type of construction to replace old and deteriorated short-span concrete bridges. The economic viability in using them for relatively long spans is mainly dependent on the required minimum depth of soil cover, since any increase in the soil cover will directly affect the construction cost associated with the amount of backfill needed for longer ramps. For this reason, attempts are made to build these structures under the shallowest possible depth of cover for economy. The Cheese Factory Bridge, Located in Wellington County Ontario, Canada was built under such conditions. The bridge was built in 1984, with a depth of soil cover of 2 m (Mohammed, Kennedy and Smith 2002).

Under the conditions of long span and shallow soil cover, the surrounding soil may not be able to provide the required support for the structure. As the result, the conduit tends to deform more freely, giving rise to a considerable increase in the bending moment under both the construction and live loads. Traditionally, the design of soil steel structures is based on compression theory, in which it is assumed that the corrugated steel sheets are subjected only to compression. This assumption is considered to be accurate for structures having a high ratio of depth of cover to conduit radius, and with a circular cross-section and backfilled carefully with well compacted engineered soil. To account for the bending moment due to the conditions mentioned above, The Federal Highway Administration in USA developed the computer package Culvert Analysis and Design CANDE (Musser 1989). This package uses the finite element method in calculating the bending moment in the corrugated steel and hence in the design of the structure. However, in designing the corrugated steel sheet no account is made for the effect of the lap joint in reducing the fatigue strength of the connection. As a result several cases of distress have been observed in these structures (Bakht and Agarwal 1987). Furthermore, the effect of the bolt arrangement on the lap joint moment capacity has been studied experimentally and the correct and incorrect lap joint was identified (Lee and Kennedy 1988). The correct lap joints were those where the bolts in the row closer to the visible edge of the corrugated sheet are placed in the valleys, and those in the other row on the ridges. Figure 1 show the distress in the structure due to the bending moment in both the correct and incorrect lap joints.



(a) Correct Lap (b) Incorrect Lap

Figure 1: Observed Joint Cracks in Corrugated Steel Structures

In this work, the fatigue resistance of the lap joint of the corrugated steel sheet is evaluated experimentally as well as using finite element analysis. Different cases of sheet thicknesses, bolt configurations and initial misalignments are investigated.

2. FATIGUE TEST SETUP

Corrugated steel lap joints were tested using an INSTRON Machine. A typical test setup is shown in Figure 2, showing the loading frame with the actuator. A second steel frame was built to connect the tested specimen to the loading frame. The specimen was connected to the loading frame using bolted joints on either sides of the specimen and was loaded by two-line loads. To prevent any load concentration on the specimen surface, the surface of the line loads was of the same shape as that of the corrugation of the steel sheet surface and using a rubber interface element between the line loads and the specimen.

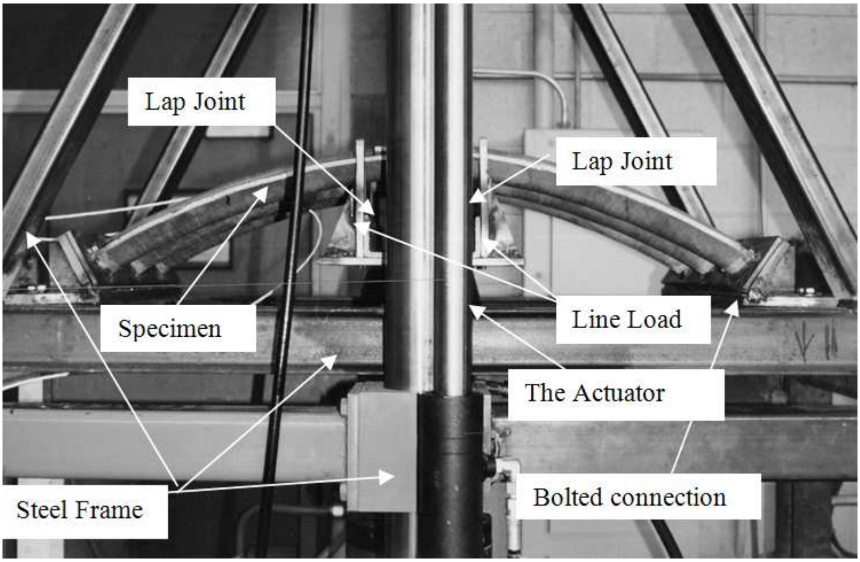


Figure 2: Lap Joint under Test and Loading Device

A total of 18 full-scale correct lap joints were tested. The tested joints were 3, 4 and 5 mm thick. The specimens were curved to 750 mm radius, with an overall length of 995 mm. All specimens were 457.2 mm wide, with three complete corrugations. Each joint was assembled using eighteen 19-mm bolts, with 6 bolts used for the lap joint and the remaining 12 bolts for connecting the specimen to the loading frame. The bolts had edge distances of 35 mm and 86 mm for those at the crown and at the valley, respectively. These edge distances are the industrial edge distance standard for corrugated lap joints. A torque wrench was used to tighten the bolts to 250 N.mm, as recommended by Ontario Highway Bridge Design Code (MTO 1991). Figure 3 shows a typical tested lap joint specimen, with cracks at the bolt holes, shown in Figure 4. The test results of the 18 tested lap joints are summarized in table 1.

Table 1: Fatigue Data of for Corrugated Steel Lap Joint

Specimen	Lap Connection Type	Plate Thickness (mm)	Stress Range (MPa)	N (Cycle)
CORR-31	Correct	3	110	2320000
CORR-32	Correct	3	135	500000
CORR-33	Correct	3	151	920000
CORR-41	Correct	4	112	1240000
CORR-42	Correct	4	146	470000
CORR-43	Correct	4	162	165000
CORR-51	Correct	5	136	530000
CORR-52	Correct	5	147	330000
CORR-53	Correct	5	170	100000
UNCORR-31	Incorrect	3	43	335619
UNCORR-32	Incorrect	3	73	27485
UNCORR-33	Incorrect	3	92	11545
UNCORR-41	Incorrect	4	35	1300000
UNCORR-42	Incorrect	4	55.5	120000
UNCORR-43	Incorrect	4	75	31875
UNCORR-51	Incorrect	5	37	977677
UNCORR-52	Incorrect	5	50	165400
UNCORR-53	Incorrect	5	91	12200

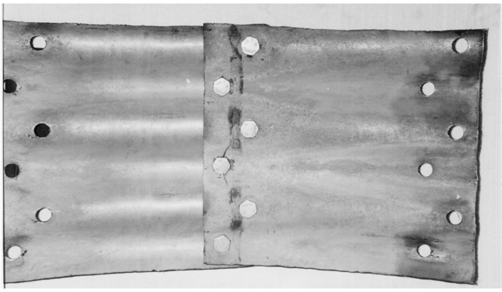


Figure 3: Top View of Tested Joint (Correct Lap)

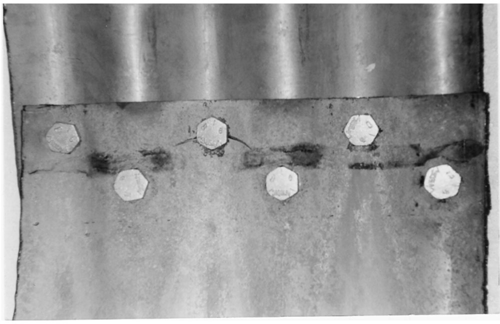


Figure 4: Observed Cracks in the Tested Joint (Correct Lap)

3. FINITE ELEMENT MODEL

The multi-purpose finite element package ANSYS was used to analyze the corrugated steel lap joints under load. A 4-nodded shell element was assumed to model the steel corrugated sheet and the bolts were modeled as a three dimension beam element. The bolt shaft was modeled using 8-link members connecting 8 nodes on the periphery of the bolt holes on one sheet to the respective nodes on the other sheet. The total cross-sectional areas of the 8 links were equivalent to the shaft cross-section area. Both the bolt head and nut were modeled using beam elements connecting the nodes on the bolt holes periphery. Initial pre-tension was applied on the link members, representing bolt tightening. The overlap surfaces between the two corrugated steel sheets were covered with interface elements which allowed the separation between the two surfaces, when subjected to tension. The lap joints were loaded using two line loads, 298 mm apart. The load was applied using a displacement control technique to allow for more stable analysis during the post peak loading stage. Figure 5 shows the lap joint statical system and dimensions.

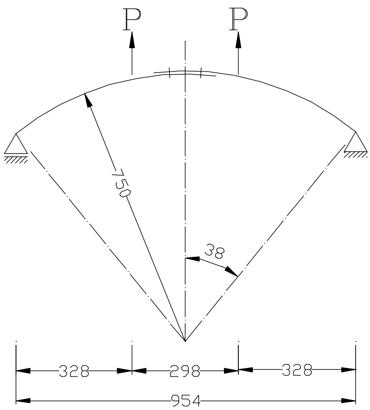


Figure 5: Model Dimensions and Statical System (All Dimensions are in mm)

The corrugated steel was made from steel with an elastic modulus of 200,000 MPa, Poisson's ratio of 0.3 and yield stress of 230 MPa. In the analysis, the steel was modeled as an elastic perfectly plastic material using Von Miss failure criteria. The lap joint was considered simply supported, achieved by assuming hinges at one side of the specimen at mid-height of the corrugation, with rollers at the other side. At the two sides of the lap joints, the rotation and lateral displacement were restrained to represent the continuity of the corrugated metal sheet. The finite element mesh was refined at the location of the bolt hole to capture the high stress variation in this region. Figure 6 shows a typical finite element mesh used in the analysis. The model was loaded incrementally with a maximum increment of 5% of the full load until complete plasticity of the joint occurred. The analysis was continued until the displacement at the load location reached 60 mm.

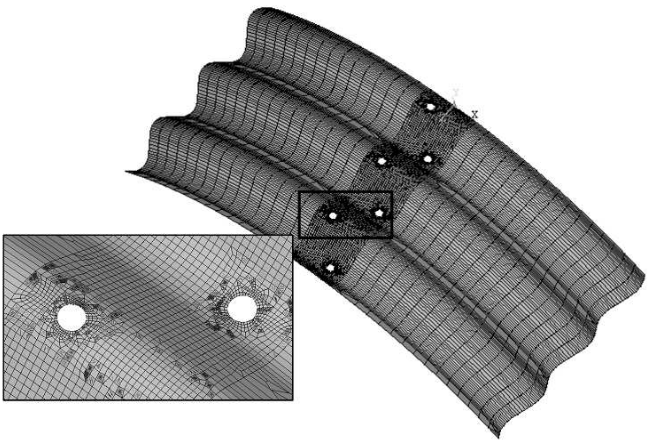
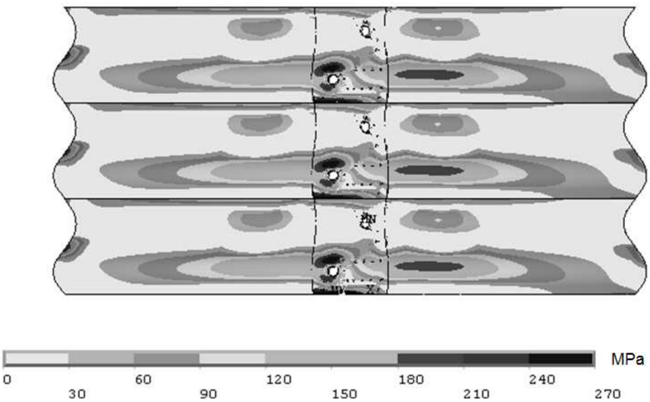


Figure 6: Finite Element Mesh Used in the Analysis

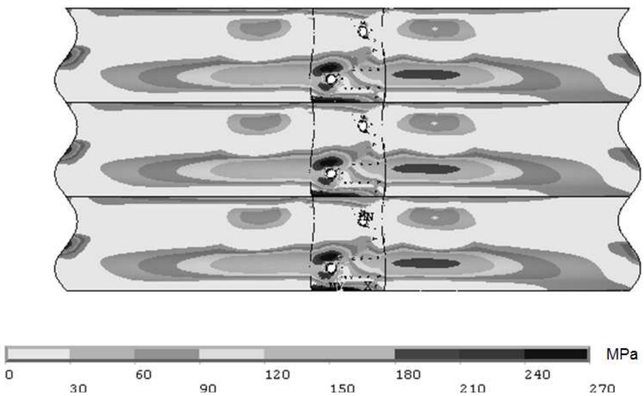
A total of 30 joints were analyzed. Different corrugated sheet thicknesses of 3, 4, 5, 6 and 7mm were analyzed for joints with a correct lap as well as incorrect lap conditions. Furthermore, three conditions were considered: prefect alignment, 2 mm of misalignment, and 4 mm misalignment.

Figure 7 shows typical maximum tensile stress distribution in the corrugated steel sheets for both the correct and incorrect lap joints. It can be observed from the results that an incorrect lap joint experiences larger zones of high tensile stresses compared to those in a correct lap joint.

Similar results, not shown here for brevity, were obtained for the maximum plastic strains which influence the fatigue life of the joint. The high tensile stresses areas, shown in Figure 7, at the edges of the specimens can be attributed to the boundary conditions. The finite element analysis results were used in evaluating the maximum stress and the maximum plastic strain around the bolt holes at every load step. The results from the analysis led to predict the fatigue life of the specimens under different load levels, using the low-cycle fatigue concept.



(a) Joint with a Correct Lap



(b) Joint with a Correct Lap

Figure 7: Stress Distribution in a Lap Joint

The fatigue resistance of a specimen subjected to completely reversed cyclic loading can be characterized by the following Eqs. (1) and (2) and four material parameters which relate to the stress amplitude $(\frac{\Delta\sigma}{2})$ and to the fatigue life $(2N_f)$ (Morrow 1965),

$$\frac{\Delta\sigma}{2} = \sigma_f^{/} \, (2N_f)^b \tag{1}$$

and

$$\frac{\Delta\varepsilon}{2} = \frac{\sigma_f^{/}}{E}(2N_f)^b + \varepsilon_f^{/} \, (2N_f)^c \tag{2}$$

Where:

E = the elastic modulus

$\sigma_f^{/}$ and b = the fatigue strength coefficient and exponent

$\varepsilon_f^{/}$ and c = the fatigue ductility coefficient and exponent

$2N_f$ = the fatigue life of the smooth specimen

For steel ASTM A-36 mild steel the values of the parameters are, $\sigma_f^{/}$ = = 1,016 MPa; b = -0.132; $\varepsilon_f^{/}$ = 0.27 and c = - 0.451 (Rolfe and Barsom, 1977; Mattos and Lawrence, 1975). In the presence of a mean stress (σ_o), Eq. (1) and (2) can be modified by introducing a mean stress term to account for the mean stress effect on the stress/strain-life relationships (Morrow, 1968):

$$\frac{\Delta\sigma}{2} = (\sigma_f^{/} - \sigma_o) \, (2N_f)^b \tag{3}$$

and

$$\frac{\Delta\varepsilon}{2} = \frac{(\sigma_f^{/} - \sigma_o)}{E}(2N_f)^b + \varepsilon_f^{/} \, (2N_f)^c \tag{4}$$

4. DISCUSSION OF RESULTS

The Experimental results were used to construct the S-N curve and to verify the finite element results for the cases of correct and incorrect lap joints with no misalignment conditions as well as with 4 mm misalignment.

The definition of the design S-N curves given in the department of Energy Guidelines was adopted in the analysis (Department of Energy 1990). For a normally distributed population of given mean (μ) and a standard deviation (σ), the $(\mu + 2\sigma)$ contains about 95% of the population (Little and Jebe 1975). Thus, the design S-N curves were determined for the case when log N is the dependant variable for the linear model:

$$\log N = A + B \, \mathrm{Log}\, S \qquad (5)$$

The design S-N curve is then given by

$$\log N = A + B \, \mathrm{Log}\, S - 2\,\sigma_{\log N} \qquad (6)$$

The analysis of the fatigue test data were carried out using the least-squares method. Figures 8 and 9 show the S-N curves for the cases of correct and incorrect lap joints respectively. The design S-N curves are plotted as well as those from the finite element analysis. From the results shown, it is clear that the results from the finite element analysis correlate well with the mean S-N curve obtained from the experimental results. Moreover, the effect of using incorrect lap joints in reducing the design stress range is clearly demonstrated. At 2,000,000 cycles, the design stress range reduces from 90 MPa to only 20 MPa due to the use of the incorrect lap joints.

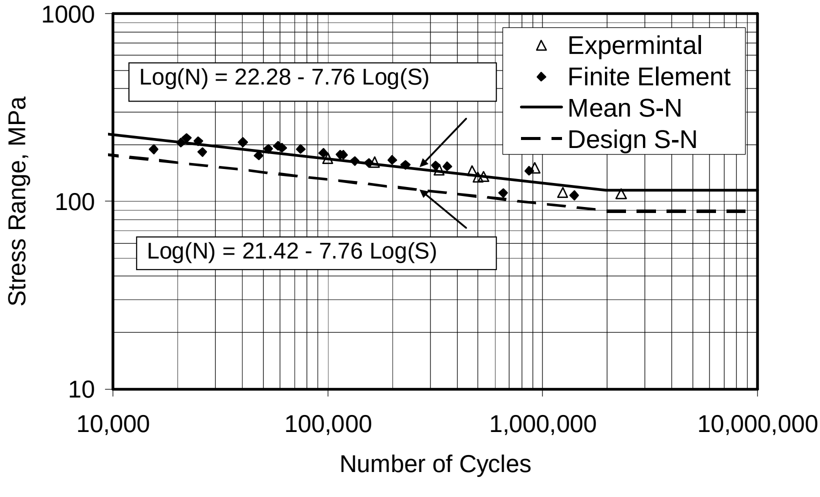


Figure 8: S-N Curve for Correct Lap Joint (No Misalignment)

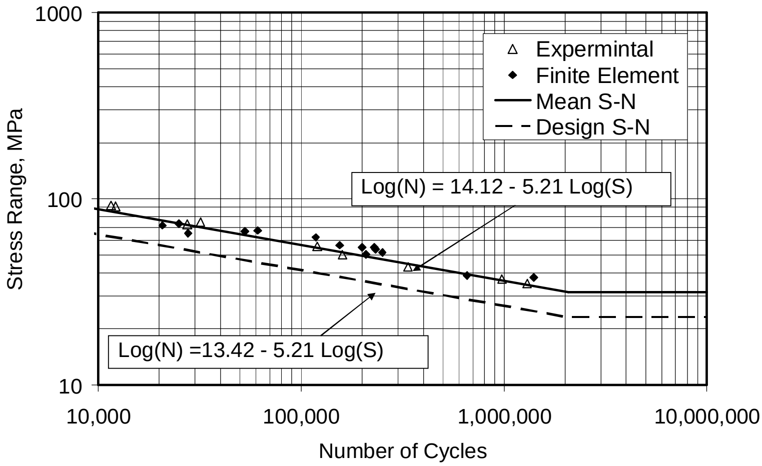


Figure 9: S-N Curve for Incorrect Lap Joint (No Misalignment)

The finite element method was used to analyze the correct and incorrect lap joints with a 4 mm misalignment. Based on the results, the S-N curves were constructed as shown in Figures 10 and 11. The design S-N curves are also plotted as shown. From the figure, it is clear that the joint misalignment is having a major effect on the design stress range for the correct lap joints. The design stress range at 2,000,000 cycle is reduced from 90 MPa to 22 MPa for the correct lap joint while for the incorrect lap it is reduced from 23 MPa to 15 MPa.

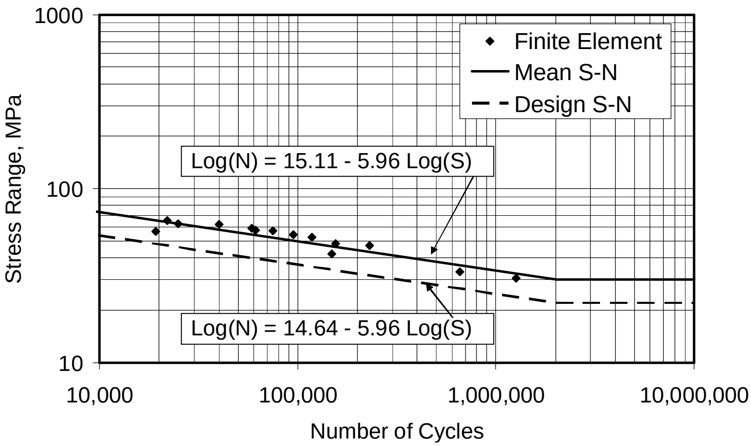


Figure 10: S-N Curve for Correct Lap Joint (4 mm Misalignment)

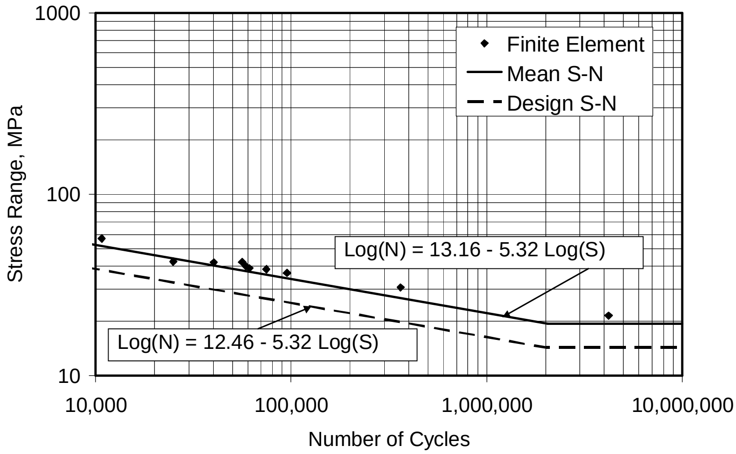


Figure 11: S-N Curve for Incorrect Lap Joint (4 mm Misalignment)

To conduct a comparison between the behaviors of different lap joints, the design S-N curves for all the four cases are shown in Figure 12. From the figure, it can be observed that the correct lap joint with no misalignment exhibits superior fatigue strength when compared to the other three other connections. Furthermore, it can be observed also that the use of an incorrect lap, even with no misalignment, causes a significant reduction in the joint fatigue strength. The effect of misalignment in reducing the fatigue strength of the lap joint is also observed. This is contrary to the reported lap joint behavior under static loading (Lee, R.W.S, and Kennedy, D.J., 1988) showing that joint misalignment and the use of incorrect lap has no effect on the ultimate moment capacity of the joint.

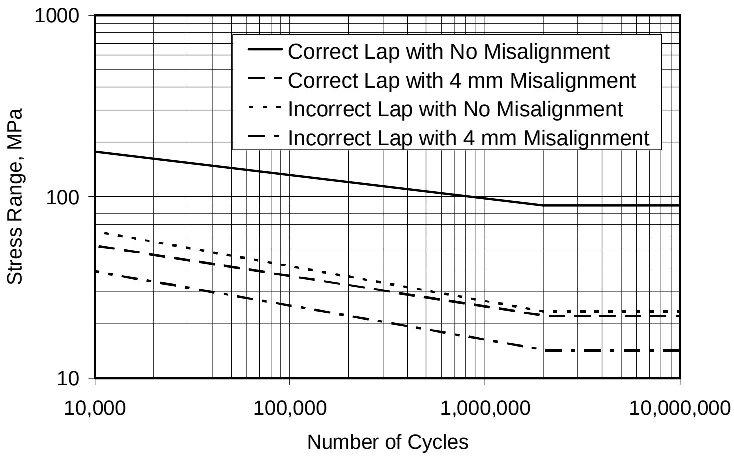


Figure 12: Comparison between S-N Curves for Different Lap Joints Configurations

5. CONCLUSIONS

Fatigue tests on full scale 18 corrugated steel lap joints were conducted, including correct, incorrect and misaligned lap joints. Based on the results from the tests, verified by the finite element analysis, the following conclusions can be made:

1. A correct lap joint with no misalignment has superior fatigue strength in comparison with an incorrect lap joint.
2. Lap joint misalignment causes a considerable reduction in the fatigue strength of the joint.
3. The fatigue strength of lap joints used in soil steel structures, need to be considered in their design when under shallow soil cover condition, as well as in soil steel structures with variable curvature such as in pipe and reentrant arches.

6. ACKNOWLEDGEMENT

This research was sponsored by the national Science and Engineering Research Council of Canada under grant A-1896

REFERENCES

1. Bakht, B., and Agarwal, A. (1987): On Distress in Pipe Arches, Ministry of Transportation, Ontario, Downsview, Ont.
2. Department of Energy, (1990): Offshore Installation: Guidance on Design, Construction and Certification, 4th Ed. HMSO, London, UK
3. Lee, R.W.S, and Kennedy, D.J., (1988): Behavior of Bolted Joints of Corrugated Steel Plates, Structural Engineering Report 155, Department of Civil Engineering, University of Alberta, Edmonton.
4. Little, R.E., and Jebe, E. H. (1975): Statistical design of Fatigue Experiments, Applied Since, Essex, U.K.
5. Mattos, R. J. and Lawrence, F. V., Jr., (1975): Estimation of the Fatigue Crack Initiation Life in Welds using Low Cycle Fatigue Concepts, FCP Report No. 19, College of Engineering, University of Illinois, Urbana, IL.
6. Mohammed, H., Kennedy, J.B., and Smith, P., (2002): Improving the Response of Soil-Metal Structures During Construction, ASCE Journal of Bridge Engineering Div., 6-13.
7. Morrow, JoDean, 1965, “Cyclic Plastic Strain Energy and Fatigue of Material”, ASTM STP 378, American Society for Testing and Materials.
8. Morrow, JoDean, 1968, “Fatigue Properties of Material”, SAE Fatigue Design Handbook.
9. MTO, (1991): Ontario Highway Bridge Design Code, 3rd edition. Ministry of Transportation, Ontario, Downsview, Ont.

10. Musser, S.C.G (1989): CANDE-89 culvert analysis and design computer program user manual, Rep. No. FHWA-RD-89-169, Federal Highway Administration, Washington, D.C.
11. Rolfe, S. T. and Barsom, J. M., (1977): Fatigue Control in Structures – Applications of Fracture Mechanics, Prentic_hall, Inc., Englewood Cliffs, New Jersey.

Streszczenie

Konstrukcje stalowo-ziemne są z powodzeniem stosowane do budowy przepustów podziemnych o średniej i krótkiej rozpiętości. W ostatnich latach producenci takich konstrukcji w USA i Kanadzie rozpoczęli zastępować tymi oszczędnymi konstrukcjami stare i zniszczone mosty betonowe o małej rozpiętości. W warunkach dużej rozpiętości i płytkiego naziomu gruntowego, otaczający grunt może nie być w stanie zapewnić wymaganego podparcia konstrukcji stalowej. W rezultacie, stalowa konstrukcja ma tendencję do łatwiejszego odkształcania się, co prowadzi do znacznego wzrostu momentu zginającego przy obciążeniu podczas budowy oraz obciążeniu zmiennym podczas użytkowania. Połączenia zakładkowe stosowane do budowy konstrukcji stalowej zostają w rezultacie narażone na przedwczesne pękanie zmęczeniowe. W tej pracy przedstawiono wyniki badań wpływu rozmieszczenia śrub, grubości blachy stalowej oraz wstępnego niedopasowania na wytrzymałość zmęczeniową. W rezultacie badań zalecono grupę krzywych (S-N) do projektowania połączeń śrubowych na zakładkę podlegającym obciążeniom cyklicznym.

Słowa kluczowe: mosty o małej rozpiętości; połączenia na zakładkę, analiza elementów skończonych, blachy faliste; wytrzymałość zmęczeniowa połączeń śrubowych.