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A Review on Wind Induced Fatigue Analysis for High-Mast Lighting Towers

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***Abstract*— Recent developments on high-mast arm structures have increased awareness of the fatigue behavior associated with these structures. Mast arm structures that are subjected to cyclic loading conditions tend to fail due to fatigue failure. Size and thickness of base plate, geometry and thickness of mast arm, welding thickness and numbers of anchor bolts are highly influencing on the fatigue performance of a high-mast lighting tower system. It was found that, dynamic characteristics and damping ratio of the mast arm also has the most significant effect on the hotspot stress of the mass arm wall system. Palmgren Miner theory of cumulative damage method, Weibull wind distribution and S-N Curves are widely used to estimate the fatigue life of the structures. Since, there are no redundancy built into this high-mast arm structures, failure of these structures would be very hazardous. Generally, failures are observed around the man access hole, base connection and anchor bolt location due to high stress concentration at these locations. Furthermore, lock-in conditions in the second mode must be investigated as this mode is more critical for bending response. So, fatigue study of high-mast arm structures should be performed against excessive stress developed due to resonant vibration of periodic or random oscillation depending upon the flow regime.**

Keywords—Hotspot, high-mast arm, damage, fatigue

I. INTRODUCTION

High-mast arm structures are widely used to illuminate the lights for the sports complex, highway interchanges, airports and some industrial yards. There is significant effect on the mast-arm structures from two types of wind action, these are; (1) Along-wind action: -buffeting by atmospheric turbulence, (2) Cross-wind action: - mainly due to vortex shedding action, which acts perpendicular to along wind direction as shown in Fig. 1.

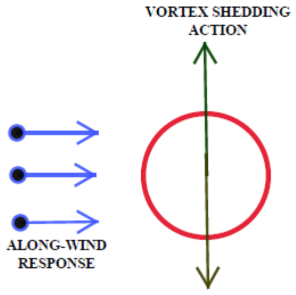

Fig. 1. Vortex shedding action over the cylinder

Spectral method (Hansen method) and vortex resonance method are widely used to estimate the vortex shedding induced forces on slender steel structures [1]. These methods are based on the assumption that, the vortex shedding creates sinusoidal forces of harmonic nature that are perpendicular to along wind direction. Geometry of mast arm, man access hole, base connection and free-standing length of the pole are important parameters, because these are highly influencing on the fatigue performance of the mast arm structures under cyclic wind action [2]. Wind forces acting on these wind sensitive structures are mainly depending on basic wind speed, terrain category and dynamic response [3]. Generally, vortex shedding concept generates sinusoidal excitation model on circular cylindrical mast arm and negative aerodynamic damping is developed due to this excitation forces. Nominal stress approach and hotspot stress approach are widely used to estimate the fatigue life of mast arm structures under stress cycles which are developed by wind action. Equivalent structural stress method also is one of the best techniques available to estimate the fatigue life with advantage of mesh insensitive quality and capability of unifying different S-N Curves [4]. S-N curves are used to estimate the number of load cycles under hotspot stress with reference value of two million load cycles as shown in Fig. 2.

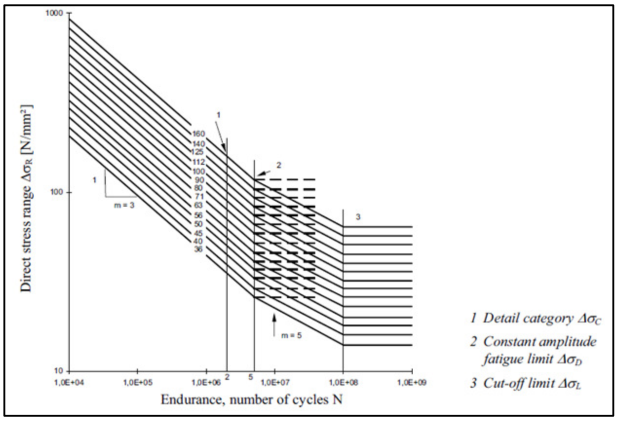

Fig. 2. S-N Curves with suitable category [14]

In mast arm structures, most of the fatigue failures are occurring due to large number of stress cycles which are generated due to large vibration with lock in condition [5]. There are many variables are involved in the hotspot stress variation of mast-arm structures. The major variables are; mean wind profile, damping, mode shapes, natural frequency at each mode, flow characteristics, Reynolds number, surface toughness and mass distribution of structures [6]. Finite element model is used to estimate the hotspot stress due to along and vortex shedding wind action and fatigue life could be estimated by accumulating the fatigue damage with consideration of dynamic response [7]. Wind induced fatigue damage can be mitigated by following methods;

(1) By altering the geometry of mast arm structures before and after installation.

(2) By reducing the movement of mast arm by adding aerodynamics devices to disturb the vortex streets.

(3) By adding mechanical devices to reduce the vibration.

The aim of the study of the mast arm structure is to identify the factors are influencing on the fatigue performance of the system under wind action.

II. THEORETICAL STUDY

The vortex shedding induced forces are mainly depends on Reynolds number Re at the critical wind velocity (Vcrit) as given in Eq. (1).

$$Re = D * V_{crit} / \upsilon \qquad (1)$$

Where; D is frontal width / diameter of mast arm wall and υ is kinematic viscosity of air ($15*10^{-6} m^2/s$). The calculation of vortex shedding induced force, presented in EN 1991-1-4:2005 [8] is directly correlated with deflection ($y_{F,max}$) of mast arm structures as given in Eq. (2).

$$y_{F,max}/b = (1/St^2). (1/Sc). K. Kw. Clat \qquad (2)$$

where; St is Strouhal number (0.18), Sc is Scruton number, Clat is the lateral force coefficient, Lj is the effective correlation length, K is the mode shape factor and Kw, is the effective correlation length factor. Ruscheweyh has modified the basic sinusoidal model by the use of "effective correlation length". This term allows to apply the vortex shedding induced forces over a height range less than total height of mast-arm structures [6]. The assumed vortex shedding induced forces on the high-mast lighting tower system (Fw) can be calculated using Eq. (3), which is given in EN 1991-1-4:2005.

$$F_w = m(s). (2\pi n_{i,y})^2 \Phi i,y(s)\ y_{F,max} \qquad (3)$$

where; m(s) is the vibrating mass of the structure per unit length (kg/m), $\Phi_{i,y}$ is the mode shape of the structures normalized to 1, y_{max} is the maximum displacement over time of the point with $\varphi_{i,y}$ (s) equal to 1 and $n_{i,y}$ is the natural frequency of the system. Modal analysis should be performed to obtain the natural frequency of mast arm structures at 1st and 2nd modes as shown in Fig. 3.

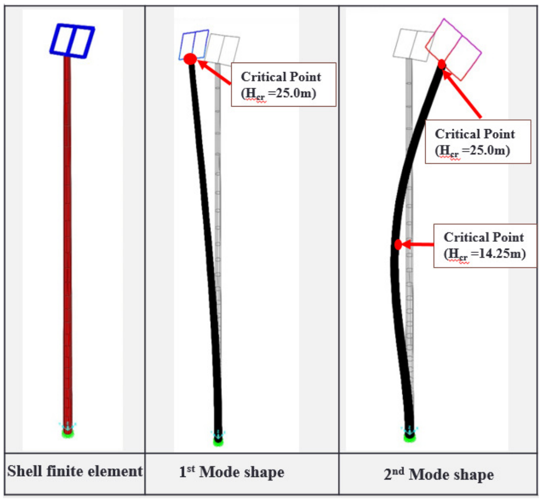

Fig. 3. Modal analysis output for 1st and 2nd mode

Cumulative fatigue damage is generally estimated using Palmgren -Miner rule as shown in Eq. (4).

$$D = \Sigma \{ni(\Delta\sigma)/Ni(\Delta\sigma)\} \qquad (4)$$

where; ni(Δσ) is the number of cycles of stress load for a specified stress range for which Ni(Δσ) is the cycles of load which is expected before the structure suffers damage [9]. Number of cycles for the particular stress is obtained using S-N curves with consideration of suitable detail category for each structural element. Generally, following detail category should be used for each structural element of mast arm structures [3].

(1) Category 140 is used for the mast arm wall.

(2) Category 80 is used for the base connection with fillet weld.

(3) Category 71 is used for the base connection with butt welds.

Number of Load cycles caused by vortex excitation can be calculated using the mean and critical wind velocity profile and the natural frequency of the cross-wind mode as given in EN1991-1-4:2005 (E10). Also, natural frequency of high-mast arm structures at each mode should be obtained using modal analysis. It is generally assumed that, critical location of vortex shedding induced forces is at antinodes point of mast arm structures as shown in Fig. 4.

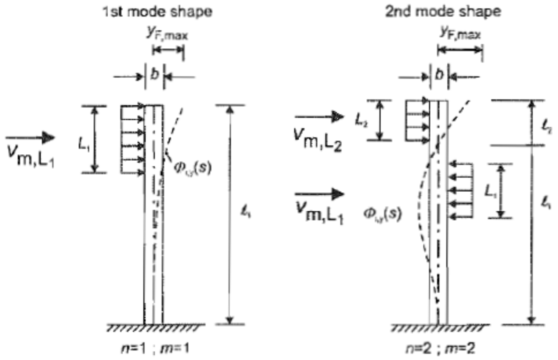

Fig. 4. Effective correlation length for 1st and 2nd mode

III. FACTORS AFFECTING THE FATIGUE PERFORMANCE OF MAST ARM STRUCTURES.

A. *Geometry of mast arm and base connection*

The variation of stress concentration factor (SCF) with base plate thicknesses from three different research study clearly shows that, base plate thicknesses are highly influencing on the fatigue performances of the high-mast lighting tower system as shown in Fig. 5. SCF is decreased with increasing of the base plate thickness of the mast arm structures. Therefore, it can be concluded that, the base plate thickness of the high mast lighting tower system is an important parameter and special concerns should be given at the time fatigue design of high-mast lighting tower system [2],[10], [11].

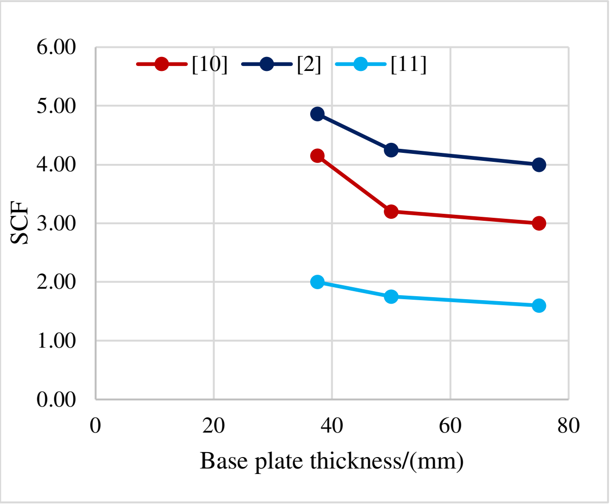

Fig. 5. Variation of SCF with base plate thickness

Increasing the base plate thickness from 37.5mm to 50.0mm for the unstiffened base model of the mast-arm structure, decreases the interface of mast arm wall and base plate SCF by 35%. Therefore, interface of the mast arm wall and the base plate connection was identified as a high stress concentration area and first crack was identified on this particular location of unstiffened base connection, as shown in Fig. 6. Therefore, in order to improve the fatigue life of the high-mast lighting tower system, connection between the base plate and mast arm wall should be designed to withstand the high fatigue loads due to along wind and vortex shedding induced loads [10].

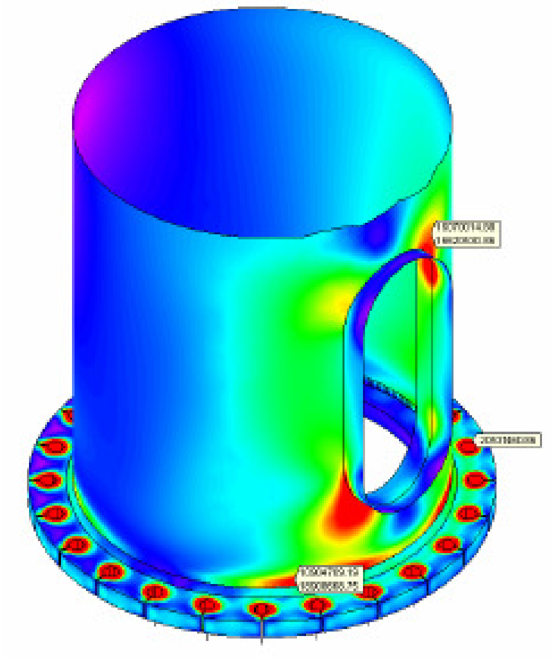

Fig. 6. Location of Fatigue crack [10]

Increasing the base plate thickness provides significant improvement to the fatigue life of the towers by reducing the maximum stress at the base plate to tube wall connection as shown Fig. 7. Therefore, base plate flexibility has a considerable influence on the stress behaviour in the tube wall adjacent to the unstiffened connection of the high mast lighting tower system [2].

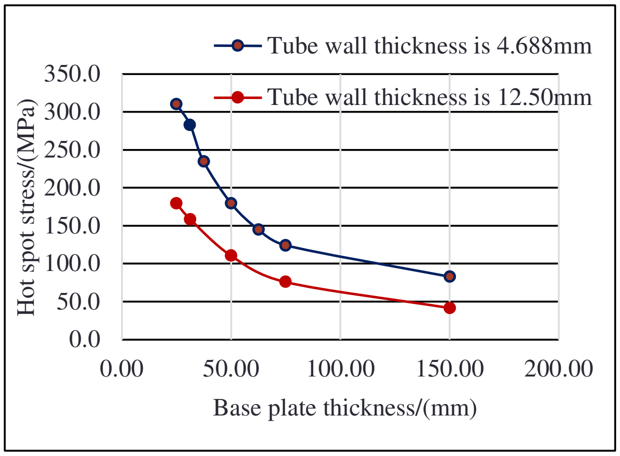

Fig. 7. Variation of hotspot stress with base plate thickness [2].

B. *Numbers of Anchor bolts*

In this Fig. 8, the normalized hotspot stress decreases as the number of anchor rods are increased. Also, it shows that, increasing the base plate thickness does not have any adverse impact on the hotspot stress variation of the high-mast lighting towers. It is found that, four anchor rods or eight anchor rods configurations are adequate and there is no need to use greater number of anchor rods [2].

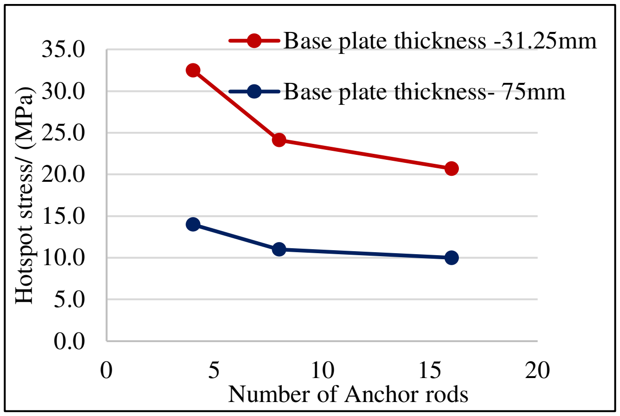

Fig. 8. Variation of hotspot stress with number of Anchor bolts (Mast arm wall thickness -4.68mm) [2].

C. *Geometry of Stiffeners*

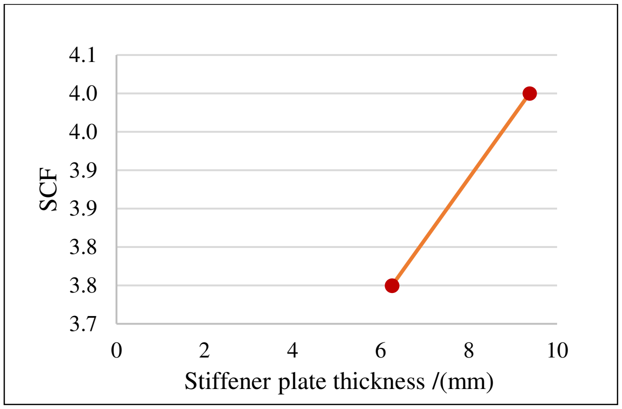

Fig. 9. Variation of SCF with stiffener plate thickness [10]

As shown in Fig. 9, there are no significant effect on SCF at socket weld location due to changing the thickness of the stiffener wall. The stiffener SCF is only increased by 7% when increasing the thickness of the stiffener plate by 50%. Also, it is found that, socket weld SCF for the unstiffened model is greater than the SCF for the stiffened model [10]. It can be concluded that, thicknesses of mast-arm wall and base plate are highly influencing on the SCF and hotspot stress of the mast arm structures compare to number of anchor bolts and geometry of stiffener wall.

IV. FATIGUE STUDY

There are several factors playing an important role to influence the accuracy of estimation of the fatigue life. These are [2];

(1) Errors in numerical model.

(2) Errors in estimation of wind forces.

(3) Approximations on stress estimation using S-N Curves.

S –N curve is used for the fatigue assessment with particular detail category for the each structural elements of the structural system. The detail category takes into consideration the local stress concentrations at the detail, the shape and size of the maximum acceptable discontinuity, the loading condition, metallurgical effects, residual stresses, welding and any post weld improvement [3]. Weibull distribution method is used to estimate the number of cycles of stress load for a specified stress range as shown in Fig. 10. Fatigue damage for the narrow-band vibration for the all-mean wind speed can be obtained by using Weibull distribution and Rayleigh distribution. Total damage caused by along wind action is generally could be ignored, but fatigue damage from vortex shedding action will be significant [12].

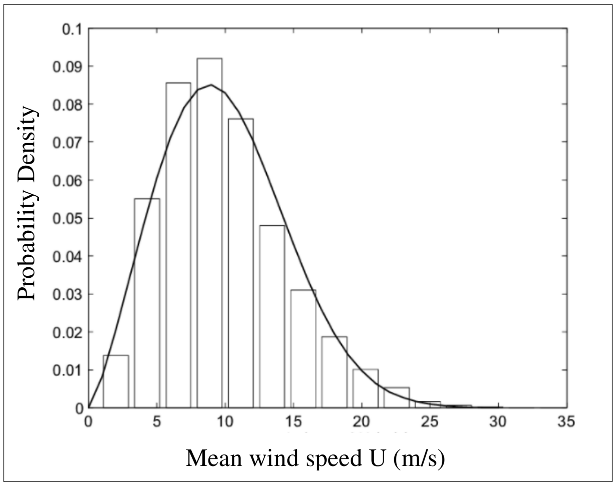

Fig. 10. Weibull wind distribution

It is found that, fatigue life calculated by equivalent structural stress method is 15% higher than that calculated by hotspot stress method as shown in Fig. 11. Also, it can be concluded that, estimation of fatigue damage and fatigue life using equivalent stress method is more conservative and safer than hotspot stress method. But nominal stress method is widely used in the field of civil engineering.

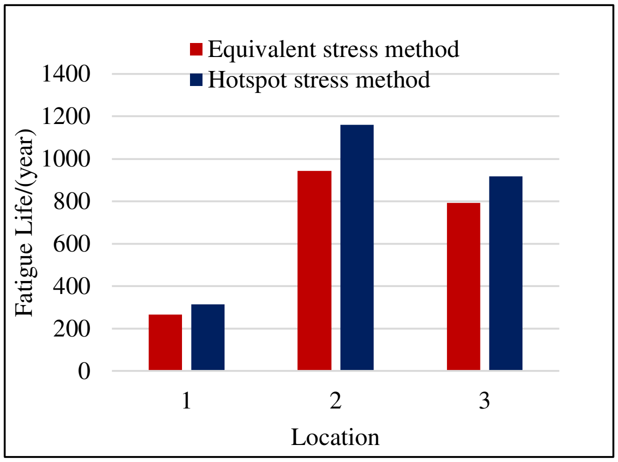

Fig.11. Estimation of fatigue life using equivalent stress method and hotspot stress method.

Cumulative damage variation along with mast arm height helps to identify the critical location due to wind action. Based on literature, fatigue damage is relatively high on base connection area and middle antinode point of mast arm structures compare to other part of mast arm wall as tabulated in Table. I [1].

TABLE I. DAMAGE VARIATION WIITH MAST ARM LENGTH

Z/ (m)	**Damage**
29.5	0.989
19.22	0.008
9.3	0.000
0	0.584

It is found that, nominal stress method is recommended to be used in the estimation of fatigue life of large scale complex structures and suitable due to consideration of critical components regarding fatigue failures of structures [13]. Generally speaking, fatigue damage estimation of mast arm structures are mainly depending on geometry of whole structural system, base connection and assessment method.

Due to lack of detailed research study on the pole connection, future research study should address detailed study for the pole connection with consideration of all factors which are influencing on the fatigue performance of the system [16].

V. CONCLUSION

Fatigue assessment for the free-standing steel structures is important, due to possibility of sudden failures when the vortices are in lock-in condition. Also, number of factors are influencing in the fatigue performance of the mast-arm structures and also these factors are depending on the assessment method of fatigue damage.

From the review of literatures, following conclusions can be made.

- Maximum hotspot stress at the base of the high-mast lighting tower decreases with increasing of mast arm wall thicknesses.

- Maximum SCF decreases with increasing of base plate thicknesses of the high-mast arm structures.

- Assessment of fatigue damage using equivalent stress method is better than the hotspot stress method. But nominal stress method is widely used in design stage of civil engineering applications.

- Fatigue life of high-mast arm structures increases with increasing of mast arm wall thickness, base plate thickness and number of anchor rods.

- Generally cumulative damage is high at middle antinode point of mast arm structures compare to other locations.

- Maximum hotspot stress is identified around the man access hole, welding location and anchor bolt location of mast-arm structures.

Addition to that, detailed finite element analysis and estimation of vortex shedding induced forces are highly recommended to obtain a more accurate fatigue life of mast arm structures.

REFERENCES

[1] Marina Rakocevic and Svetislav Popovic, "Calculation procedure for determining wind action from vortex-induced vibration with verification of fatigue strength of steel structures," GRADEVINAR 70(2018), Page 793-809.

[2] Margaret K. Warpinski, "The effect of base connection geometry on the fatigue performance of welded socket connections in multi-sided high mast lighting towers," Theses and Dissertations, paper 940, 2006.

[3] Priyan Mendis, Shiromal Fernando, John Holmes, Tharaka Gunawardena, Yousef AbuZidan and Priyan Dias,"Wind Induced analysis of Lotus Tower Mast," Nineteenth Australian Wind Engineering Society Workshop. Fatigue, 2018.

[4] Zhao fang, Aiqun Li, Wanrun Li, and Sheng shen, "Wind-induced fatigue analysis of high-rise steel structures using equivalent stress method" Article of Applied Sciences, January 2017.

[5] I.Giosan, P.Eng., " Vortex Shedding Induced Loads on Free Standing Structures" 2005.

[6] John D.Holmes, " Response of Cylindrical structures to vortex shedding in the natural wind," 13th Australian fluid mechanics conference, 1998.

[7] Li-wei Tsai, Alice Alipour, "Assessment of fatigue life and reliability of high-mast luminaire structures," Journal of constructional steel research 170, 2020.

[8] EN 1991-1-4:2005, "Action on structures (Part 1-4: General Actions – Wind actions)".

[9] Johan Maljaars, Mladen Lukic and Frans Soetens, "Comparision between the Eurocode for fatigue of steel structures, EN 1993-1-9, and the Eurocode for fatigue of Aluminium structures EN1993-1," 5TH Fatigue Design Conference, 2013.

[10] Mark T.Koenigs, Tamer A. Botros, Dylan Freytag and Karl H.Frank.,"Fatigue strength of signal mast arm connections," Research report (9/99-8/01), 2003.

[11] Andrew Stam, Nicholas Richman, Charles Pool, Craig Rios, Thomas Anderson and Karl Frank, "Fatigue Life Steel Base plate to Pole connection for Traffic Structures,"Technical report – 9-1526, 2011.

[12] Byungik chang, Brent M. Phares, Partha P. Sarkar, and Terry J. Wipf, " Development of a procedure for fatigue design of slender structures subjected to wind-induced vibration," Journal of the transportation research board, pp 22-33, 2009.

[13] Rayn J. Serman and Robert J. Conner, "Development of a fatigue design load for high-mast lighting towers," J.Struct Eng, 2019.

[14] EN 1993-1-9:2005, "Design of steel structures (Part 1-9: Fatigue)".

[15] Jay Puckett, Rebecca Johnson and Michael Barker, "Study of the effects of wind power and vortex induced vibrations to establish the fatigue design criteria for High-mast poles," Civil and Architectural Engineering, University of Wyoming, 2011.

[16] Christopher M. Foley, Baolin Wan, Mathew Weglarz, Matthew Hellenthal, Jordan Komp, Andrew Smith and Joseph P. Schmidt, "Fatigue risks in the connections of Sign Support Structures – Phase 1," Department of Civil & Environmental Engineering, Marquette University, 2008.

[17] Karl H. Halse, "On Vortex Shedding and Prediction of Vortex – Induced Vibrations of Circular cylinders," Department of Marine structures, Norweign University of Science and Technology, 1997.

[18] Mustafa Aygul, "Fatigue analysis for the welded structures using the finite element method," Department of Civil and Environmental Engineering, Chalmers University of Technology, 2012.