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FATIGUE LIFE OF BOLT SUBJECTED TO FATIGUE LOADING CONDITIONS

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ABSTRACT

With the aim to create awareness amongst designers and to establish database on fatigue life of bolt, this experimental study was conducted. Two sizes of High Strength Friction Grip (HSGF) bolt were chosen and they were subjected to low and high cycle constant amplitude loading condition. Each of them undergone 4 different stress ranges and at 3 means stress level. Three bolts from each size were tested under static loading in order to obtain their mechanical properties. Unlike for high cycle fatigue, the low cycle fatigue where S_{max}/σ_Y *is more than 50%, the fatigue life of bolt is not significantly influenced by the mean stress and the stress range. The reduction in fatigue life is quite alarming. The average slope of S-N curve in which indicates the rate of crack growth is in the range of 2 to 3 which is within the range of welded members. This work also suggests an alternative terminology of stress and the important of establishing S-N curve for designing of bolt against fatigue.*

Key words: *Bolt, Fatigue Life, Constant Amplitude Loading, S-N Curve, Low-High Cycle Fatigue*

INTRODUCTION

Concrete and steel are the most common materials used in civil engineering structures. Its selection is dictated by various factors like structural efficiency and integrity, constructability, skill manpower, overall cost and availability of the materials. Structural steel or steel-concrete elements are connected together either by welding or bolting or a combination of both. Hence, type of connection uses together with service loading that varies with time will be an encouraging factor to influence fatigue life of the joint. In any joint detailing, there are three features allow for high stress intensity that may lead to failure. They are the bolt configuration, holes to sit the bolt and weld. For bolt, there are at least three potential locations that prone to high stress gradient [1] i.e. at the head fillet, thread runout and first thread to engage nut. All of them exhibit a reduction in cross section in which potential to promote failure.

In the current design practice for steel structures against fatigue loading, normally designer focuses on designing main structural elements and leave to fabricator to design the joints. The presumption is such that fatigue failure is not likely to happen, thinking that bolt is not playing a major role to resist loading. Besides many tragedies, the recent collapse of Ramsgate Walkway in England in 1994 where six people were killed and seven injured proved otherwise [2,3,4]. From an enquiry [3 and 4], it was concluded that the bearing was not given enough fatigue resistance. Record showed there are 11 other similar serious collapses apart from Ramsgate in recent times but fortunately they did not take life. Often design of bolt under repeated loading e.g. steel bridge is simplified as equivalent to design against static load condition. The attitude towards such failure leads to lack of fatigue data for bolt.

Normally, S-N curve (i.e. applied stress versus number of stress cycles) is used to assess the fatigue resistance of steel structural members. For welded connection, the S-N curve has been established although it is only based on weld classifications [5]. No such data has been established for bolt connection. The S-N curve is obtained from experimental data where the structure is tested at various stress ranges under constant amplitude loading until failure. Then this information is used to predict the fatigue life of a structure subjected to load of variable amplitude by the use of Miner's Cumulative Damage Rule [6].

The Miner's cumulative damage theory assumes the damage caused by a cycle in a variable amplitude load is equal to that of a cycle of the same stress under constant amplitude loading. Therefore, damage 'D' during one cycle is defined by the reciprocal 1/N obtained from the S-N curve of the component and failure occurs when the accumulated damage reached a critical value; D = 1.

$$D = \frac{n_1}{N_1} + \frac{n_2}{N_2} + \frac{n_3}{N_3} = \sum_{i=1}^{j} \frac{n_i}{N_i} \qquad \text{Eqn. 1}$$

Where n_i is the number of stress cycles at the i^{th} stress level in the variable amplitude loading spectrum, and N_i is the number of stress cycles to cause failure at the same i^{th} stress level under the constant amplitude load test. The simplicity of Miner rule makes it very convenient for design purposes. Even though most structures are exposed to loading varies with time but fatigue life analysis requires fatigue data from constant amplitude load called the S-N curve. On normal plot the S-N graph shows an exponential shape in the form of;

$$S^m N = C \qquad \text{Eqn. 2}$$

Let C be the constant and S is the applied stress whereas m is the slope of the graph. Current published data on fatigue said that S is in the form of stress range and another school of thought assumed as the mean stress in the constant amplitude load where;

$$\text{Stress range} = S = S_{max} - S_{min} \qquad \text{Eqn 3}$$

S_{max} is the maximum stress and S_{min} is the minimum stress in a cycle and;

$$\text{Mean stress} = S_{mean} = 0.5\,(S_{max} + S_{min}) \qquad \text{Eqn. 4}$$

Next, it will be noted that, the S-N curve is linear on a log stress against log N basis and it can therefore be expressed as;

$$m \log S + \log N = \log C \qquad \text{Eqn. 5}$$

Rearranging equation 5; $\log N = -m \log S + \log C$ Eqn. 6

Equation 6 indicates a linear relationship between S and N with a negative slope and the constant C can be obtained as an inception point to the N-axis. Knowing the C and m, fatigue crack growth rate could be obtained by using Paris's equation [7].

Therefore, this experimental work is aimed to critically determine the influence of various variables listed below on the fatigue life of bolt. They are namely;

a) To study the effect of low and high cycle fatigue loading environment.
b) To examine the dominant effect of mean stress or stress range.
c) To examine an alternative terminology for the applied stress.
d) To establish the S-N curve.

RESEARCH PROGRAM

Two sizes of HSGF bolt were chosen such as 12mm and 25mm diameter with 150mm long. Three bolts from each size were tested under static loading in order to obtain their mechanical properties as a benchmark for fatigue test. The tensile test was tested in accordance to British Standard. Table 1 and 2 give the chemical and mechanical properties of the bolt, respectively. Knowing the yield strength of the bolt, hence the input data for the fatigue test could be ascertained and they are listed in Table 3.

For the fatigue test, the bolt is subjected to cyclic constant amplitude loading under pulsating mode 1 i.e. tensile mode. The load was generated as cyclic sine wave loading running at a frequency between 8 to 10 hertz. The testing machine was put under displacement control. Smaller bolt size was subjected to stresses that near to or greater than its yield strength i.e. more than 50%σ_Y. This condition is known as low cycle fatigue where the number of cycles to failure is small. While the larger bolt is subjected to stresses that is less than 30% of its yield strength and said to be a high cycle fatigue. It requires large number of cycles to cause failure. Each of the bolt size undergone 4 different specified stress ranges and 3 means stress level. The test was conducted until failure or once the number of load cycles hits 2 millions that is supposedly be an endurance limit for steel. On the other hand, the larger bolt was tested till 10 million cycles is reached instead of 2 million. Both bolt sizes experienced the mean stress level which is below their respective yield strength.

RESULTS AND DISCUSSION

Result from the static test showed that the surface of failure is in the form of cup and cone depicting the ductile properties of the bolt. The yield strength is 389 MPa and 635 MPa for bolt size 12 mm diameter and 25 mm respectively. While the Young's modulus for the smaller bolt is 27.71 GPa and 34.70 GPA for the larger bolt. It has been shown in most references for fatigue study the applied stress is referred to the stress range and sometimes as the mean stress. Thus, Figure 1 and Figure 2 show respectively the stress range and mean stress against number of stress cycle on normal linear plot. For the sake of identification, the bolt experienced low cycle fatigue (LCF) is drawn in broken line and the larger bolt subjected to high cycle fatigue (HCF) is in full line. The bolt which did not fail as noted in Table 3 is not included in the plot, except for stress range 66MPa in the smaller bolt. These presentations are not 'good' enough to examine the performance of the bolt under repeated cyclic loading. Therefore, they are transformed into double logarithmic scale as illustrated in Figure 3 and Figure 4.

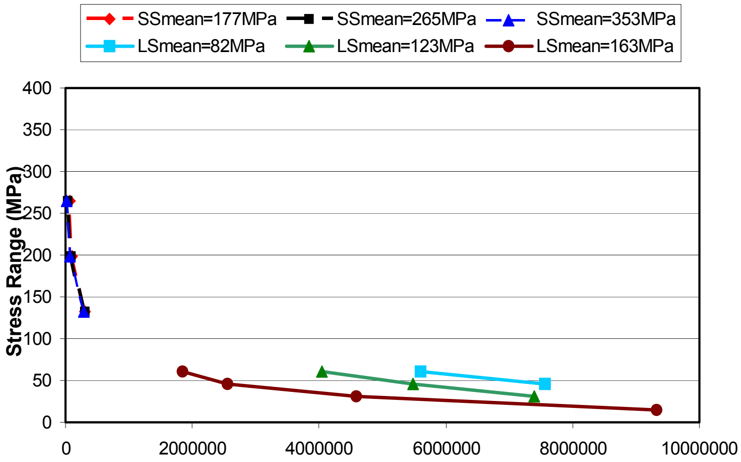

Figure 1: Linear plot of stress range and number of stress cycles

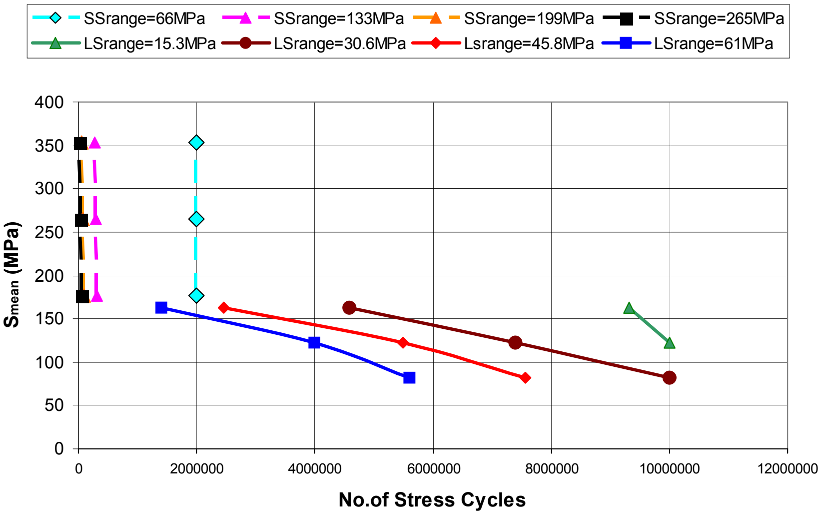

Figure 2: Linear plot of the mean stress and number of stress cycles

Effect of Fatigue Loading Conditions

This discussion is limited to two types of fatigue loading conditions namely low and high cycle fatigue. The S-N curve from Figure 1 and 2 showed that for LCF, the stress range rapidly decreases as the number of cycle increases, but the curve then seems to flatten out. Whereas for HCF, a small decrease in stress causes a large increase in N. Based on equation 6, Figure 3 gives almost a linear relationship between log S and log N for both cases, while in Figure 4 only stress range 66 MPA and 133 MPa are having a straight line and yet others are not. It can be said that under LCF, the stress range and mean stress are not greatly affected the fatigue life but it is not so for HCF.

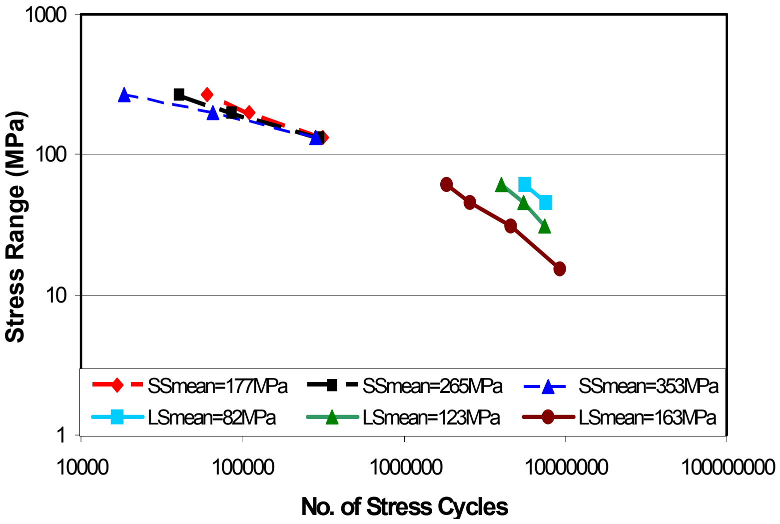

Figure 3: Influence of stress range on fatigue life of bolt subjected to low cycle fatigue loading condition

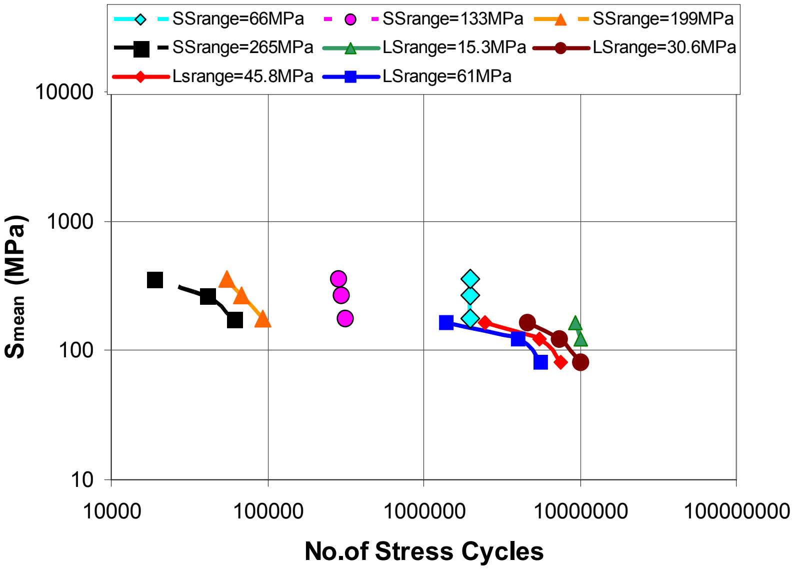

Figure 4: Effect of the mean stress on fatigue life of bolt

The larger bolt size which undergone HCF in this study is having a steeper slope and scattered plot, contrarily to smaller bolt under LCF, see Figure 4. Importantly, both bolt sizes and fatigue loading conditions suggested that the slope or the constant m is in the range of 2 to 3 which is said to be between 2 to 4 for steel [8]. An exception to HCF with S_{mean} = 81.5 MPa gives 4.6. This value is not valid due to bias data since it is obtained from only 2 points. For bolt experienced maximum load close to or above the yield strength; in this case LCF, the value is in the range of 2.02 to 2.6 and they would give almost the same constant m irrespective of the mean stress being applied.

This strong influenced of stress range and mean stress for HCF can be explained as the applied stress is far below the yield strength i.e. less than $30\%\sigma_Y$, major part of the material behaves elastically. Thus, plastic zone and strains developed at the fracture region is so small where small scale yielding is valid. Since stress is proportional to strain, therefore the difference between fatigue and static test is very minimal. So philosophically, design consideration for fatigue is equivalent to static may be valid in this region. But in reality, most structures are not subjected to this low level of stress due to the existence of residual stress, stress riser and loading is variable in nature that will elevate the stress level at the location above 50% of the yield strength.

However for LCF, the applied stress is high enough to develop a considerable size of plastic zone. Here, the stress is no longer proportional to strain, in fact the fracture region behaves as semi-plastic strain characterize by cyclic strain and called as a hysteresis loop [9], i.e. $\varepsilon_p N$ = constant. On the basis of limited fatigue data, Manson [10] suggested $\varepsilon_p N^m$ = constant. Further increases of applied stress beyond the yield strength causes fully plastic strain behaviour; for example sample SC2, SD2, SB3, SC3 and SD3. For this situation, large scale yielding criterion is applicable.

Proposed Alternatives Parameters to Influence Fatigue Life

Published information showed that structures experiencing stresses lesser than its yield strength but occurs in a repeating manner may also failed, unlike under static load. Therefore, under in-service condition the 'landmark' for stress level is the yield strength. Thus, this study is suggesting instead of looking at the stress range and mean stress, the stress level may be examined in terms of maximum stress in a cycle with respect to the yield strength of the material (S_{max}/Yield strength). It is shown in Figure 5 for linear plot and Figure 6 on double logarithmic scale. The presentation is slightly better compared to the one in term of stress range and mean stress; Figure 1 and Figure 3.

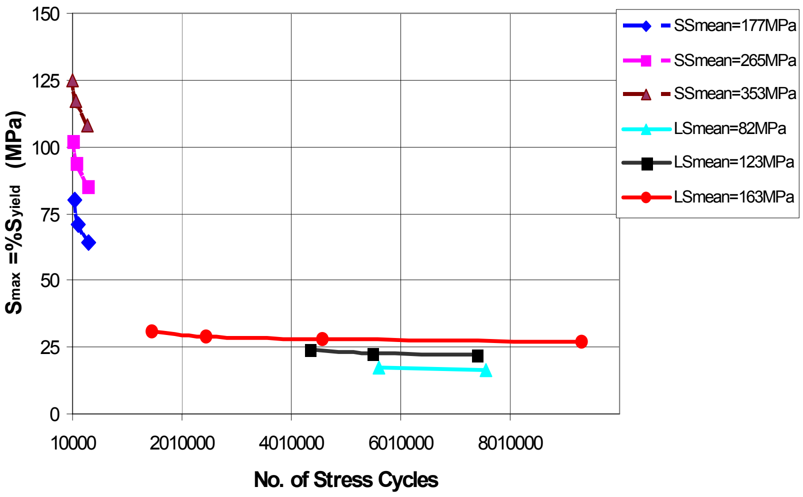

Figure 5: Linear plot of S_{max}/Yield strength under fatigue loading conditions

As before, Figure 5 shows an exponential behaviour of fatigue life but with clearer picture on contribution of the mean stress particularly for LCF. Here, a big increase in stress level would rapidly reduce the fatigue life whereas for the HCF the small increase in stress level would tremendously shorten the life. It can be read directly from Figure 6 that the rate of reducing life is almost constant for both cases irrespective of the mean stress. The higher position of stress level to the yield stress will give direct information on the shortening of the life.

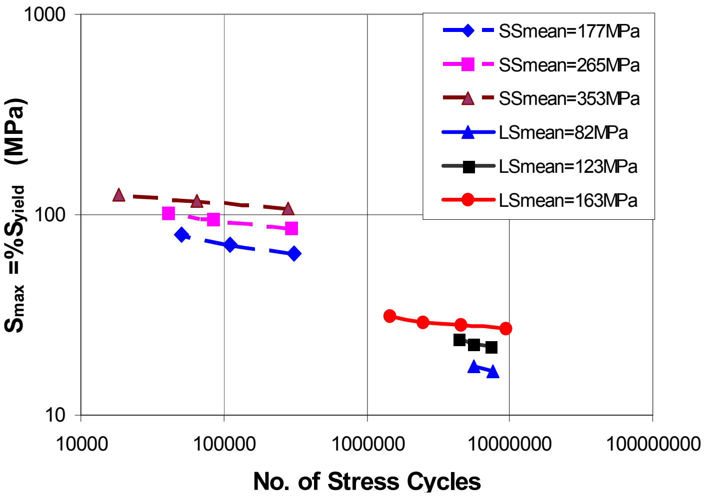

Figure 6: Effect of relative position of stress level to Yield strength on fatigue life

Endurance Limit

Figure 1, 3 and 5 showed that for small stress at HCF the graph almost parallel to horizontal axis. It seems that the bolt is having an infinite life for small applied stress which is not a realistic. It can be said that the material may possess a limiting stress below which the fatigue failure will not to occur. This limiting stress is also known as an endurance limit. The question of whether there is or not the endurance limit for a material is just an academic concern. The reason behind is that in an actual environment most structural element contains features of stress riser where the applied stress being rise up to much higher level nearer towards the yield strength. It is uneconomical to conduct a test at a very low stress under HCF since it is time consuming; may take many days or weeks for one specimen. So, this experimental work used the published data on endurance limit (2 million cycles for LCF and 10 millions for HCF) during laboratory test as mentioned in the earlier section.

CONCLUSION

Within the scope of this work, it can be concluded that;

a) Structures undergoes low cycle fatigue loading condition will have a very much shorter life than the one under high cycle fatigue.
b) The constant m is independent of bolt size and fatigue loading conditions. It seems to be material constant as found by others for welded joint.
c) Based on existing acceptable terminology of applied stress shows that the influence of the stress range and the mean stress is dominant for structures subjected to high cycle fatigue loading condition.
d) It is also noted that the suggested stress level terminology i.e. S_{max}/σ_Y will improved the understanding on the performance of bolt subjected to fatigue loading.
e) Establishing the S-N curve for bolt is recommended but a compromise between cost and degree of accuracy is desirable.

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APPENDIX

Table 1: Chemical Properties of Bolts

Bolt Size (mm)	C (100%)	Mn (100%)	P (1000%)	S (1000%)	Si (100%)
12ϕ x 150	42	84	13	8	40
25ϕ x 150	43	80	17	12	22

Table 2: Average Values of Mechanical Properties of Bolts

Bolt Size (mm)	Area of bolt (mm^2)	σ_{ult} (MPa)	σ_{proof} (MPa)	σ_Y (MPa)	ε_Y	δ_Y (mm)	Young's Modulus (GPa)
12ϕ x 150	113.10	712.66	No data	389	1.610%	0.829	27.70733
25ϕ x 150	490.87	993	582	635	1.83%	1.001	34.69945

Table 3: Fatigue Test Data

Sample No.	12 mm Bolt diameter **(S)**				Notes	25 mm Bolt diameter **(L)**				Notes
	S_{mean} (MPa)	ΔS (MP)	S_{max} (MPa)	No. of Cycles		S_{mean} (MPa)	ΔS (MPa)	S_{max} (MPa)	No. of Cycles (x 10^6)	
A1	176.84 Below the yield stress and m=2.6	66	54%σ_Y	2mil.	Not Failed	81.5 Below the yield stress and m=4.6	15.3	14%σ_Y	10	Not Failed
B1		133	64%σ_Y	311963	Failed		30.6	15.2%σ_Y	10	Failed
C1		199	71%σ_Y	92686	Failed		45.8	16.5%σ_Y	7.555	Failed
D1		265	80%σ_Y	60617	Failed		61.1	17.6%σ_Y	5.597	Failed
A2	265.26 Below the yield stress and m=2.22	66	76.7%σ_Y	2mil.	Not Failed	123 Below the yield stress and m=2.27	15.3	20.5%σ_Y	10	Not Failed
B2		133	85%σ_Y	297193	Failed		30.6	22%σ_Y	7.391	Failed
C2		199	93.8%σ_Y	68341	Failed		45.8	22.8%σ_Y	5.485	Failed
D2		265	102%σ_Y	40652	Failed		61.1	24.1%σ_Y	4.012	Failed
A3	353.68 Below the yield stress and m=2.1	66	99.5%σ_Y	2mil.	Not Failed	163 Below the yield stress and m=2.01	15.3	27%σ_Y	9.315	Failed
B3		133	108%σ_Y	283706	Failed		30.6	28%σ_Y	4.577	Failed
C3		199	116.5%σ_Y	55299	Failed		45.8	29%σ_Y	2.459	Failed

D3		265	125%σ_Y	18560	Failed		61.1	31%σ_Y	1.456	Failed
Remark	**Low cycle fatigue** - Bolts are subjected to stresses near to/or above the σ_Y of bolt material					**High cycle fatigue** - Bolts are subjected to stresses far from the σ_Y of bolt material				