

Fatigue Strength of S275 Mild Steel under Cyclic Loading

T. Aldeeb, M. Abdueilmula

Abstract—This study examines the fatigue life of S275 mild steel at room temperature. Mechanical components can fail under cyclic loading during period of time, known as the fatigue phenomenon. In order to prevent fatigue induced failures, material behavior should be investigated to determine the endurance limit of the material for safe design and infinite life, thus leading to reducing the economic cost and loss in human lives. The fatigue behavior of S275 mild steel was studied and investigated. Specimens were prepared in accordance with ASTM E3-11, and fatigue tests of the specimen were conducted in accordance with ASTM E466-07 on a smooth plate, with a continuous radius between ends (hourglass-shaped plate). The method of fatigue testing was applied with constant load amplitude and constant frequency of 4 Hz with load ratio (Fully Reversal $R = -1$). Surface fractures of specimens were investigated using Scanning Electron Microscope (SEM). The experimental results were compared with the results of a Finite Element Analysis (FEA), using simulation software. The experiment results indicated that the endurance fatigue limit of S275 mild steel was 195.47 MPa.

Keywords—Fatigue life, fatigue strength, finite element analysis, S275 mild steel, scanning electron microscope.

I. INTRODUCTION

THE mechanical parts of a machine can fail under cyclic loading during the lifetime of the machine. Fatigue is observed to be the major cause of failure in metal structures and components, and is expected to be responsible for approximately 90% of all metallic failure [1]. Researchers have assumed that as long as the behavior of the material does not exceed the yield point, the material will not fail, but this argument is not always correct [2]. During the service procedure, stresses can lead to a small crack on the surface of the mechanical component. This phase is called the initiation of the crack and is known as “stage one”, where the stresses are the highest. The crack then starts to propagate and grow throughout the surface of the material with the application of repeated stress. This is referred to as “stage two”. At some point, the crack can reach a critical stage and cause catastrophic failure in the material, which could cause major loss in human lives and have a significant economic impact. This failure stage is known as “stage three” and this phenomenon is known as Fatigue. For this reason, engineers during the mid-19th century started to investigate the behavior of materials by conducting analytical, experimental and

numerical analysis, deploying techniques that have been developed over the past 170 years in order to investigate the effect of stresses and load variation on fatigue strength and crack growth [2]-[4]. On the basis of reputedly published papers, the nature of fatigue mechanisms and the factors that influence fatigue must be taken into consideration in manufacturing design [5]. To better understand the fatigue behavior of material, standard force-controlled high cycle fatigue experiment tests must be conducted on smooth, flat, or cylindrical specimen under loading conditions, in order to assess the fatigue life of the component

Structural S275 mild steel plates are commonly used in most industrial construction, such as bridges, railways and ships etc. Consequently, it is crucial for industrial construction to establish the fatigue strength of material, in terms of stress and the number of cycles needed to fail, known as the S-N curve, for better design and to avoid unexpected failure in the material. Basquin equations [6] are employed to calculate the fatigue design parameters from conducted experimental data and to further determine the fatigue life of structure for unknown loading. However, industrial companies demand fatigue data for material design and selection and request such information from universities or specialist laboratories. Therefore, the present study is focused on fatigue strength of a smooth plate with a continuous radius between ends (hourglass-shaped plate) of S275, composed of mild steel at room temperature, and subject to a varying loading.

II. MATERIAL AND EXPERIMENT DETAILS

A. Specimen Geometry and Preparation

The S275 mild steel is considered in this study to determine the fatigue strength at room temperature. The material was provided by a local supplier as flat bars and the continuous radius between ends was fabricated carefully at Northumbria university laboratory using Mazak CNC with coolant, so the microstructure of material was not affected by the heat generated by the machine. The geometry of the specimens was designed in accordance with ASTM E466-07 [7]. The dimensions of a specimen are shown in Fig. 1.

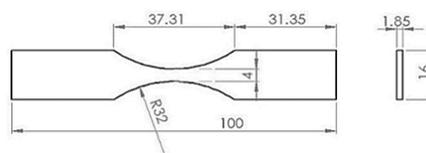


Fig. 1 Dimensions of a specimen used (all dimension in mm)

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B. Tensile Testing

To define baseline data for fatigue testing and analysis, mechanical properties of the material are essential. Two smooth tensile specimens were prepared in accordance with ASTM E8/E8M-09 standard test methods for tension testing of metallic materials [8]. For each specimen, the dimension was sub-size rectangular specimen, with a thickness of 2 mm

and 25 mm gauge length. The specimen was pulled at a crosshead speed of 1mm/min until it fractured, as shown in Fig. 2. The young Modulus, 0.2% yield strength, ultimate tensile strength, and (the percentage of total elongation of material) were calculated. The mechanical properties of S275 is presented in Table I, while the chemical composition of material is shown in Table II.

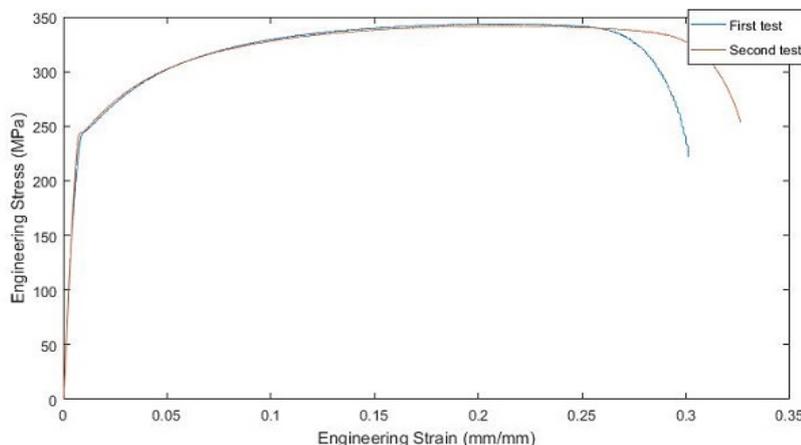


Fig. 2 Monotonic tensile test of S275 mild steel

TABLE I
MECHANICAL PROPERTIES OF S275 MILD STEEL

Mechanical Properties	S275 Mild Steel
Yield strength (MPa)	275
Modulus of elasticity (GPa)	40
Average Tensile strength (MPa)	344
Average Strength at break (MPa)	312
Elongation at break (mm)	11

TABLE II
CHEMICAL COMPOSITION OF S275 MILD STEEL % [9]

C	Si	Mn	P	S	Cr	Mo	Ni	Cu	N
.14	.010	.80	.012	.016	.030	.005	.020	.030	.003

C. Grinding

Specimens were grinded in accordance with ASTM E3-11 [10]. The method of grinding the specimen was manually, due to the thinness of the specimen and also due to financial consideration. In the hand-held grinding procedure, the specimen was held by hand and moved back and forth across a piece of paper on top of a flat and rigid piece of glass, which was balanced to have a flat area. The time of grinding was in the range of 15-45 seconds for each step, with consideration to have an identical time. Additionally, during each step of grinding, the specimen was rotated 90°. At the end of grinding, on each paper the specimen was cleaned in one direction with a piece of tissue, to prevent any contamination on the surface of the specimen. Finally, after grinding was complete, the specimen was cleaned thoroughly using acetone solution to remove any debris on the surface of the specimen. Silicon carbide papers with grit grade of 240, 400, 800, 1200, 2000, and 2500 were used for fine grinding. The reason for grinding of specimens is to obtain requirements, such as

uniformity, flatness and level the mount surface.

D. Experiment Procedures

The Experiments were carried out under axial constant amplitude to determine the S-N curve. The fatigue test was conducted at Northumbria University using Instron E3000 fatigue testing machine, of 3 KN load capacity. The jaws of the machine are driven by an electric-magnetic engine, which pushes the center of the specimen up and down with respect to vertical axis of the load. The wave form of the fatigue test was sinusoidal, and all fatigue tests were performed under constant frequency of 4 Hz, and constant load amplitude, with load ratio of (R=-1 Fully Reversed). The load applied during the fatigue test was less than the yield stress by a factor of 0.9, in order to reach the failure points for high cycle fatigue, then the load was reduced by a factor of 0.1 for each test. The specimen undergoing the fatigue test is illustrated in Fig. 3. To obtain the S-N curve for Fatigue testing, 8 points are required, as recommended by ASTM E606-92 [11]. The S-N curve is the plot of stress versus the number of cycles needed to fail.

The microstructure of material and surface feature analysis were carried out on SEM (Mira3 Tescan) in order to identify the three modes of fatigue failures that occur on the surface of the material under cyclic loading. Since the type of material is S275 mild steel, and also electrically conductive, there is no need to polish and etch the surface while using SEM. Magnification, ranging from 10 up to 50,000 diameters, is possible and has a great depth-of-field for even very small samples [12].

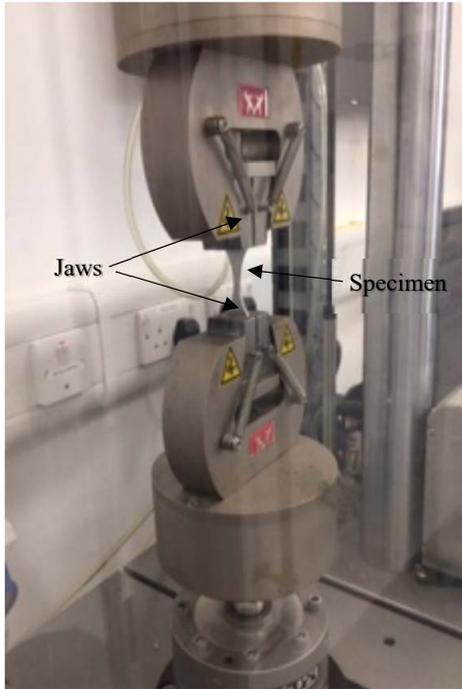


Fig. 3 Specimen undergoing fatigue testing

III. FINITE ELEMENT ANALYSIS

The static and fatigue analysis was carried out using Ansys software with one full tensile test at one end and the other end fixed. The geometry of the specimen was modelled using Solidworks, based on the specimen used in the experiment study. The 3-D geometric design of the tested specimen is shown in Fig. 4. Fig. 5 illustrates the 3-D solid FE-mesh of the specimen with mesh characteristics.

IV. RESULTS AND DISCUSSION

Experimental fatigue data of axial fatigue testing, with load ratio of $R = -1$, and frequency of 4 Hz, were conducted on S275 mild steel specimen. The S-N curve and Data results are presented in Fig. 6 and Table III respectively. Based on the results obtained from the experiment, maximum stress amplitude versus fatigue life is plotted on Semi-Log scale, to view the Significance of fatigue strength at higher stress, compared to lower stress. From the graph, the fatigue strength is decreasing as the maximum stress decreases on the specimen until rupture. The tensile test on the S275 mild steel also proved that the material has high ductility, with approximately 11% higher malleability. The reason for higher ductility is because the S275 mild still contains a carbon element of 0.14% [12].

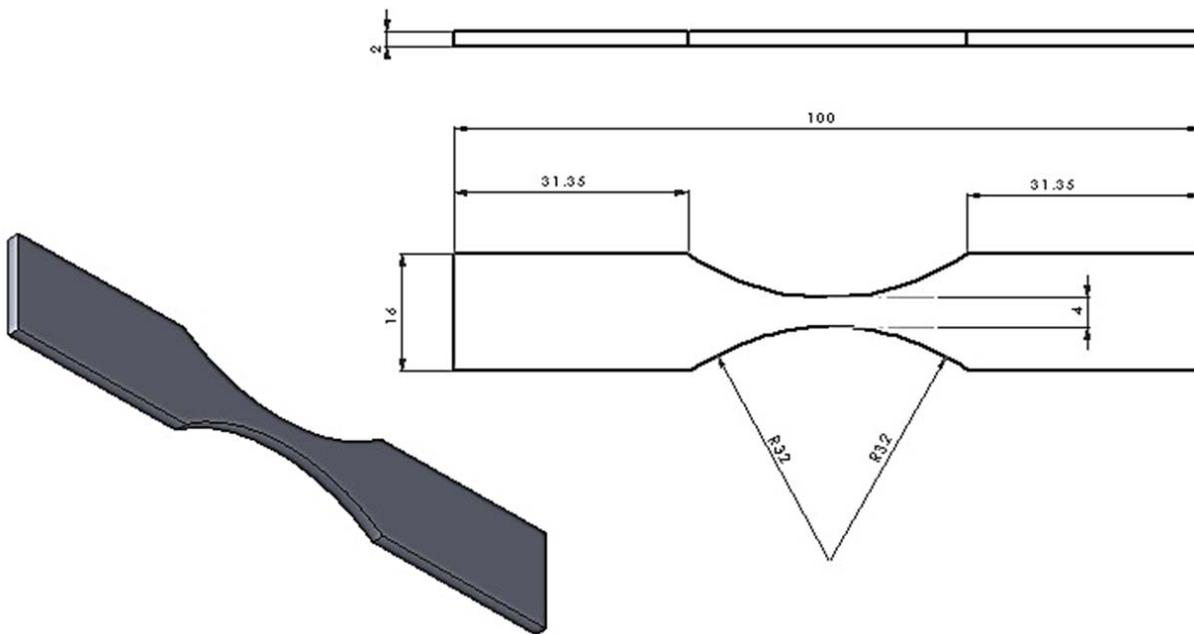


Fig. 4 3-D Design of specimen

The collected data from the experiment have been fitted by power law equation, in order to define the material fatigue behavior. The power law equation is referred to as the Basquin Equation, and typically describes S-N curve. It is given by:

$$\sigma = aN^b \tag{1}$$

where σ is maximum stress amplitude, a is the fatigue strength

coefficient and b is the fatigue strength exponent. a and b can be determined experimentally. Therefore, the Basquin equation of S275 mild steel, based on the least square regression line, can be rewritten as follows:

$$\sigma = 413.69N^{-0.069} \tag{2}$$

It can be observed from Table II that the number of cycles

decreases as the applied load decreases, until the endurance limit of the material is reached, where the area or zone below the endurance limit of the material cannot fail. The endurance limit of S275 mild steel was found to be 159.47 MPa at 1×10^6 . Fatigue tests below 1000 cycles is known as Low Cycle Fatigue LCF, whereas fatigue tests above 1000 cycles is known as High Cycles Fatigue HCF [13]. In the graph, the arrows indicate that two specimens did not fail, which means any kind of load applied below the endurance limit of S275 mild steel will not fail. Industrial companies pay considerable amounts of money to design their components for better and safer design in order to avoid a sudden failure. Additionally, the study indicates that the behavior of fatigue strength on S275 mild steel was less hardening at surrounding conditions [14]. In this study, it can be concluded that the fatigue strength of S275 Mild steel was successfully investigated.

In terms of SEM, the advantage of using (SEM) is that it can examine the microstructure of material at the fracture surface [15]. Fatigue failure can be identified by three stages; initiation propagation and final rupture. Additionally, benchmark, voids and striation can be seen on the fracture surface of the material using (SEM). At a higher amplitude loading, between (250-190 MPa), the failed specimens have a behavior of ductile fracture mechanism, a “cup and cone” pattern, which is caused by micro-void coalescence and characteristics as one of ductile fracture behavior [16] as show in Fig. 7.

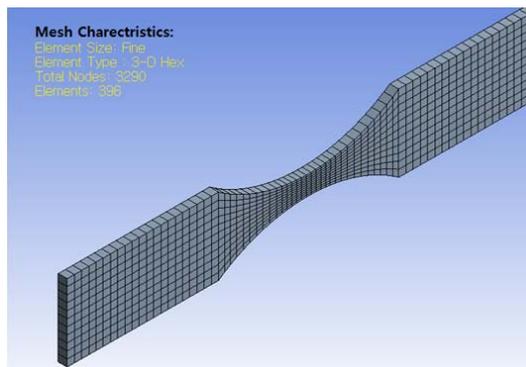


Fig. 5 The FE-mesh of specimen with mesh characteristics

TABLE III
EXPERIMENT DATA OF S275 MILD STEEL

Load (KN)	Area (mm ²)	Stress (MPa)	N (Cycles)
1.9	1.85*4	266.51	770.5
1.7	1.85*4	238.46	2669.5
1.6	1.84*4	225.65	4810.5
1.5	1.85*4	210.41	16343.5
1.4	1.86*4	195.32	65878.5
1.3	1.85*4	182.35	186920.5
1.25	1.85*4	175.34	145210.5
1.2	1.85*4	168.32	512399.5
1.1	1.85*4	154.30	2286875
1.1	1.84*4	155.14	2000000

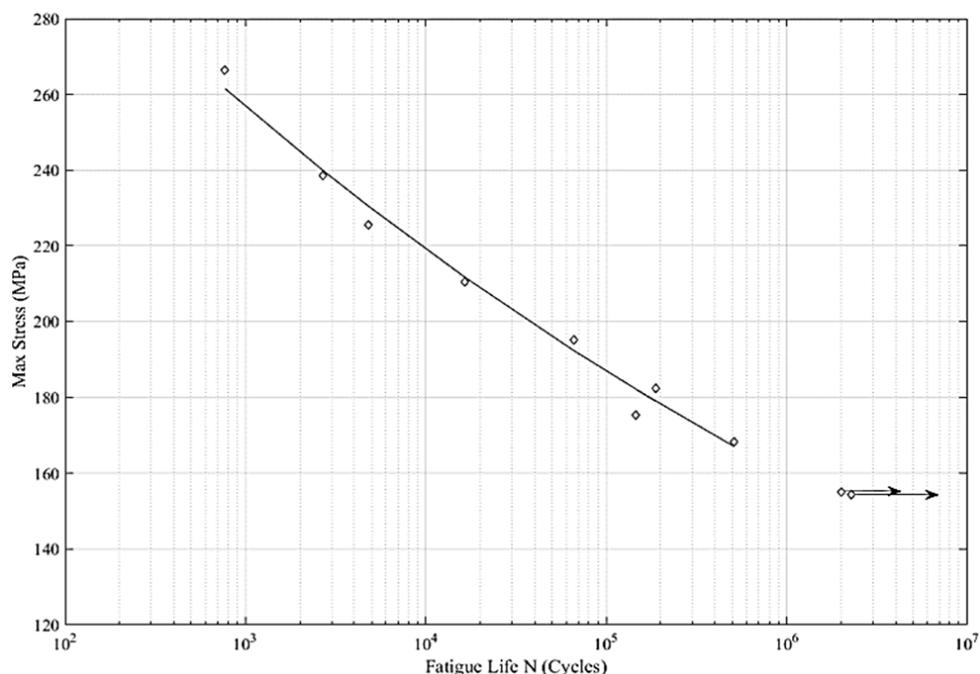


Fig. 6 S-N curve of s275 mild steel under load ratio of -1

Fracture surface was investigated at a lower amplitude loading, between (190 – fatigue limit MPa). The crack was initiated at the corner of the specimen and started to striate in until it reaches the ductile transition area from propagation to

final rupture. Fig. 8 illustrates three distinct modes of fatigue failure. As a result of (SEM), the surface fracture of the specimen observed showed evidence of failure due to fatigue, such as voids and striation. Meanwhile, these mechanisms are

characterized as ductile fractures [17].

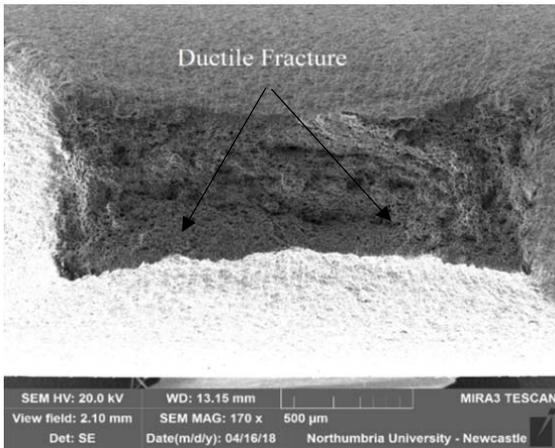


Fig. 7 Fracture surface of material at higher amplitude loading

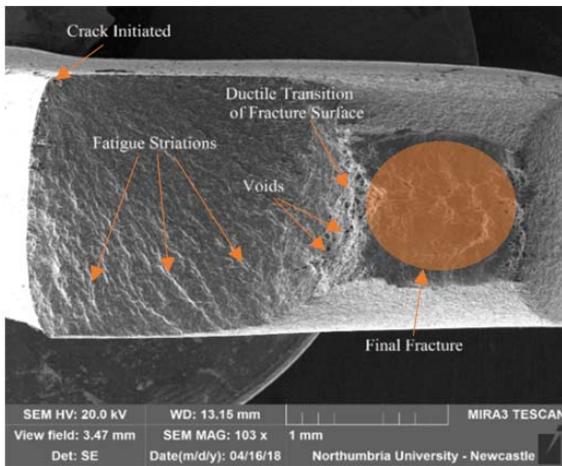


Fig. 8 Fracture surface of material at lower amplitude load

Finally, the outcome of the results obtained from the FE-simulation is compared with the experimental results in Fig. 9

and tabulated in Table IV. The results of FE analysis show a good agreement with the experiment results. The use of FE analysis nowadays is beneficial and powerful in predicating the fatigue life, saving time and cost. In the same way, engineers use the FE analysis in industrial work for safe design and to prevent failures that could lead to catastrophic disasters [18].

The maximum stress that was observed on the specimen are demonstrated in Fig. 10, while applying a load of 1900 N using Ansys Software. It found the maximum stress while applying a load of 1900 N to be 266.93 MPa, in Fig. 10 (a), and occurred at the Centre of the specimen, where the smallest area is located. Consequently, in the fatigue analysis in Fig. 10 (b) showed where the failure occurred on the edge of the smallest area where the maximum stress acted and the fatigue life of applied load of 1900 N was found to be 572.17 cycles, which is very close to the fatigue life by the experiment study and has a value of 770.5. alternatively, the factor of safety is found to be 0.597 at load of 1900 N, in Fig. 10 (c), and the fatigue damage has value of 1.747×10^{-3} , in Fig. 10 (d). Therefore, the FE-analysis can successfully predict the fatigue life and the results agreed with the experiment study.

Finally, The S275 mild steel specimen, used in the fatigue analysis, is considered to be a smooth plate, but interestingly, the FE analysis predicted the value of stress concentration around the smallest area where the failure occurs at the edge, due to the rising stress concentration when applying a load. The stress concentration factor (Kt) was found to be 1.038.

TABLE IV
RESULTS OF FE-ANALYSIS WITH THE EXPERIMENT DATA OF S275 MILD STEEL

$S_n \text{ exp(MPa)}$	$S_n \text{ (MPa) FEA}$	$N \text{ FEA(cycles)}$	$N \text{ exp(cycles)}$
266.51	266.93	572.17	770.5
238.46	238.84	2868.2	2669.5
225.65	226.01	6383.7	4810.5
210.41	210.74	17595	16343.5
195.32	195.63	51711	65878.5
182.35	182.64	139990	186920.5
175.34	175.61	247150	145210.5
168.32	168.59	446570	512399.5

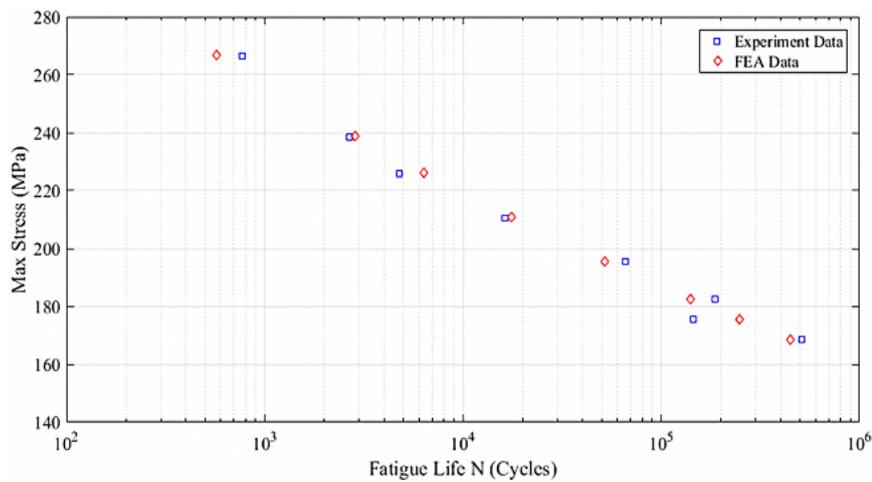
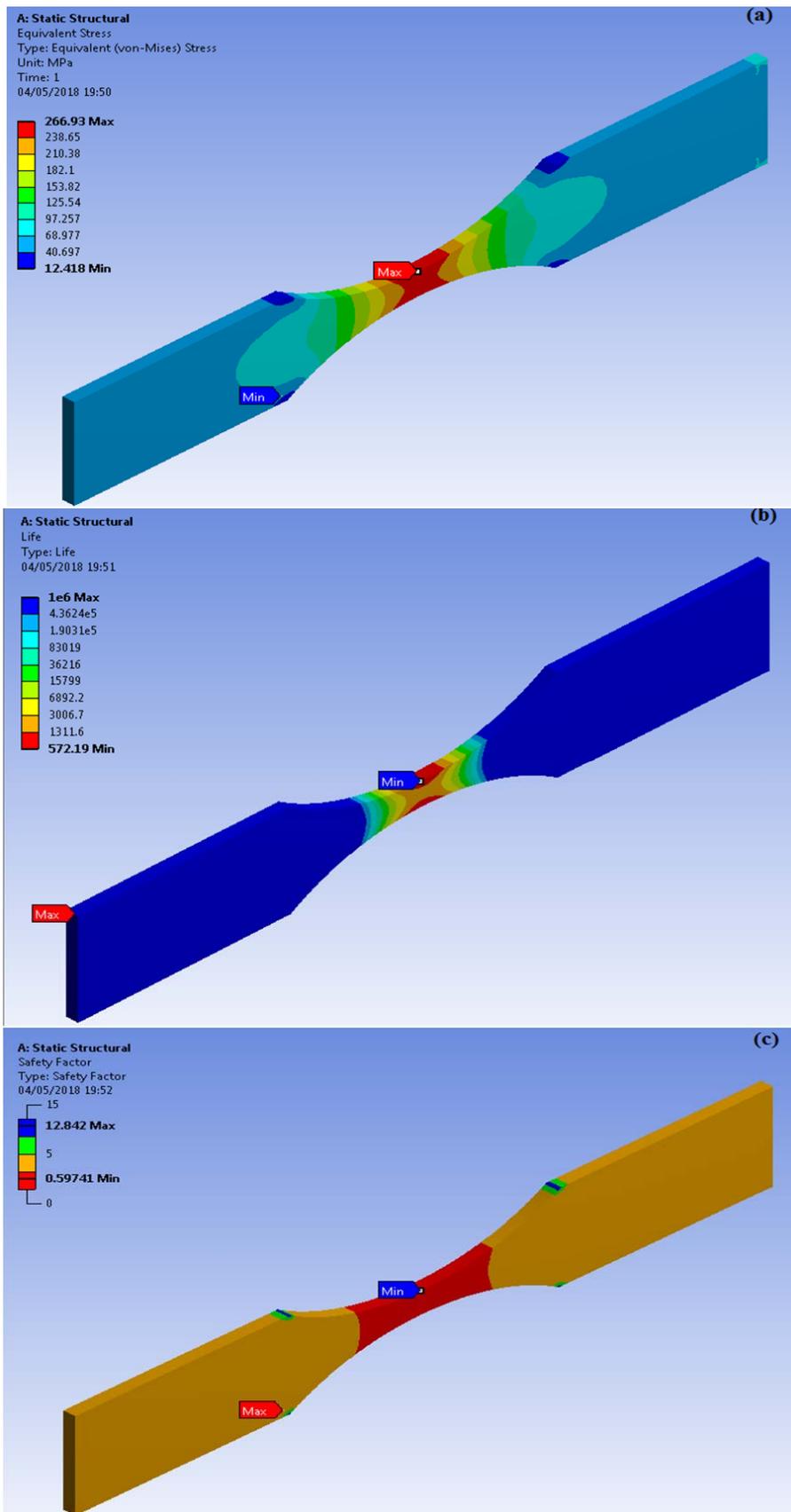


Fig. 9 FE data and Experiment Data of S275 mild steel



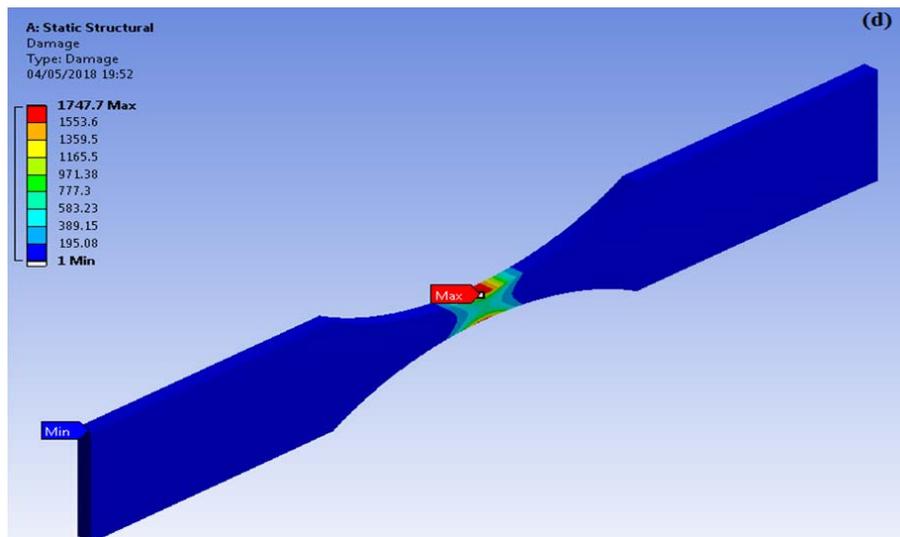


Fig. 10 FE-Results (a) Equivalent Stress at 1900 N. (b) Fatigue life at 1900 N. (c) factor of safety at 1900 N. d: Fatigue damage at 1900 N

V. CONCLUSION

The fatigue strength of S275 mild steel was successfully proposed. The experiment results showed that the fatigue life can fail tremendous fast at higher amplitude loading instead of low amplitude loading. Failed specimens were observed between (770.5 to 512399.5 cycles) and the fatigue endurance limit was obtained to have a value of 159.47 MPa at 1×10^6 due to Basquin equation and machine limitation. A verification of fatigue life of S275 mild steel was conducted by comparing the experiment results with the FEA results. The FE analysis can predict the fatigue life with stress details in better and fast way, leading to save time and cost in industrial construction.

The surface fracture on specimen was observed using SEM such as the initiation stage, propagation stage and the final fracture. The SEM is an appropriate tool to detect the fatigue modes even in very small specimen. Meanwhile, SEM analysis illustrated the surface of specimen failed due to fatigue.

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REFERENCES

- [1] Callister WD, "Materials Science and Engineering: An Introduction", 2nd edn. New York: John Wiley & Sons Inc, 1991.
- [2] Shigley, Joseph E., Charles R. Mischke, and Richard G. Budynas. "Mechanical engineering design". McGraw-Hill, 2011.
- [3] D. Hendrickson, "Fatigue failure due to variable loading, university of Michigan" – Flint.
- [4] Jono, Masahiro. "Fatigue damage and crack growth under variable amplitude loading with reference to the counting methods of stress-strain ranges." *International Journal of Fatigue* 27.8 (2005): 1006-1015.
- [5] Y. Weing: *Int J. Fat.* Vol 15 (1993), p 243.

- [6] Basquin OH, "The exponential law of endurance test". *Pro ASTM*, 1910, 10:625-630.
- [7] American Society for Testing and Materials. Committee E08 on Fatigue and Fracture, "Standard practice for conducting force controlled constant amplitude axial fatigue tests of metallic materials". ASTM. 2007.
- [8] ASTM American Society for Testing and Materials, "Standard test methods for tension testing of metallic materials". ASTM international. 2009.
- [9] EN-10025-2 OR BS EN 10204.
- [10] Standard, A.S.T.M., E3-11, "Standard Guide for Preparation of Metallographic Specimens", ASTM International, West Conshohocken, PA, DOI: 10.1520/E0003-11. 2011.
- [11] Mohammad, Khairul Azhar, et al. "Fatigue Life for Type 316L Stainless Steel under Cyclic Loading." *Advanced Materials Research*. Vol. 701. Trans Tech Publications, 2013.
- [12] Callister, W. D. and Rethwisch, D. G. "Materials science and engineering" (Vol. 5, pp. 344-348). NY: John Wiley & Sons. 2011.
- [13] Vassilopoulos, Anastasios, ed. *Fatigue life prediction of composites and composite structures*. Elsevier, 2010.
- [14] Campbell, J. D. and Duby, J. "The yield behavior of mild steel in dynamic compression". *Proc. R. Soc. Lond. A*, 236.1204 (1956): 24-40.
- [15] Proulx, T., *Conference Proceedings of the Society for Experimental Mechanics Series*.
- [16] Theocaris, P. S. "Yield criteria based on void coalescence mechanisms." *International journal of solids and structures* 22.4 (1986): 445-466.
- [17] Fischmeister, H. E. L. L. M. U. T. F., et al. "Modelling fracture processes in metals and composite materials." *Z. Metallkd.* 80.12 (1989): 839-846.
- [18] Thomas, Daniel J. "Using Finite Element Analysis to Assess and Prevent the Failure of Safety Critical Structures." (2017): 1-3.