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Fatigue Strength Analysis of Fiber Optic Sensor Affected by Temperature Using Finite Element Method

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***Abstract* - Optical fiber is a communication network that the transmission and reception of information signals are using light, an optical source, optical detector, with optical fiber as a transmission medium. Besides as a medium transmission of the information signal, optical fiber can be used as a sensor. Optical fiber sensors can measure temperature, pressure, vibration, displacement, and even rotational motion. In designing optical fiber sensors, industry players must ensure the performance and strength of the product to comply with applicable standards, even with optical fiber sensor fatigue strength standards. Fatigue is a form of failure that occurs in structures subjected to dynamic and fluctuating stresses. This study mainly discussed the strength analysis of fiber optic sensors affected by the temperature change until its fatigued using the finite element method. The fiber optic sensor that received temperature change from the passing train produced thermal stress because of the constraint from both sides of it. Along with time, thermal stress that happens repeatedly produce fatigue failure for fiber optic sensor. From the results of this study, the writer obtained the lowest maximum number of cycles of 294.000 and the highest is 14.570.000 cycles. If the number of cycles is converted to time with existing data, the fastest time that the fiber optic sensor will fail is 3 years and 4 months and the longest time is 166 years and 4 months.**

Keywords: Fiber Optic Sensor, Fatigue, Thermal Stress, Altair Hypermesh, Railway Sensor.

I. INTRODUCTION

As time goes by, the presence of technology is growing fast, especially in the telecommunication aspect. That statement is supported by the fact that every human activity in the meantime is connected to telecommunication and the internet. Using of internet is one of main human needs because now internet isn't just a place to seek for entertainment but a place to work, even school. Internet network can cover around the world using fiber optic cable. Fiber optic is communication network system which in sending and receiving information signals using light beam, optical source, and optic detector, with fiber optic as a transmission medium. Fiber optic also a transmission medium made from high quality glass, so it has good reliability and advantages than transmission medium made from metal. Fiber optic technology developed very fast, proven that numerous application of fiber optic which telecommunication[7]-[9], computer application[10]-[11], industry[12]-14], doctor equipment[1], military equipment, or public general [15].

Beside as a medium transmission of information, fiber optic can be used as a sensor. Fiber optic sensor could measure temperature, pressure, vibration, displacement, and rotational movement. Work principle for fiber optic sensor is very diverse, basically compare the behavior of light before and after passing the fiber optic[2]. In designing fiber optic sensor, industry players have to ensure the quality and function of a product is up to standard. To make sure of that, experiment and simulation testing are applied. However, experiment test usually requires higher time and cost. Therefore, simulation test utilizing finite element method can be used.

Finite element method is a structure analysis method to discretize a body so it becomes element with finite quantity[3]. This method frequently used to analyze structure strength including fiber optic structure. In previous study, trial against fiber optic polymer (POF) with *Mach-Zehnder Interferometer* (MZI) type affected by condition of temperature and the changed of pressure from environment using finite element method have been done.

The result is obtained the minimum and maximum value of stress and strain, and the optimum value for polymer optical fiber (POF) using Taguchi method. In this study, the writer wants to analyze structure strength of polymer optical fiber with various of temperature until the structure experienced fatigue failure. The writer used finite element method software which is Altair Hypermesh 2019 to analyze fiber optic structure strength. In conclusion later, the writer hopes the maximum value of thermal stress is not too big and life cycle is not too small, and the ideal time to change fiber optic sensor with the new one before it gets fractured.

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1.1 Method

This study completed with finite element analysis software which is Altair Hypermesh 2019 that used for static and fatigue simulation from 9 variation of length and angle of tapered for fiber optic sensor. In this test, type of simulation that used is Linear Static analysis and Fatigue analysis to obtain the thermal stress, total deformation, damage, and maximum life cycle. Fiber optic sensor that used in this study is a Mach-Zehnder Interferometer (MZI) type that has tapered part where the sensor is placed. Variation in this study is the length of the tapered part which is 1 mm, 0.75 mm, and 0.5 mm, and angle of tapered part of 30^0, 25^0, and 20^0, so total number of variations in this study is 9 variations. Fiber optic sensor model which will be tested can be seen in Figure 1 and the information of the used material was displayed in Table 1.

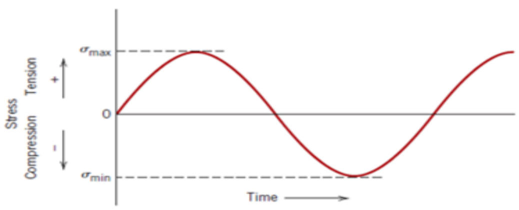
Figure 1: PMMA Optical Fiber with 1 mm Length of Tapered and 25^0 Angle

Table 1: Material Properties *Polymethyl Methacrylate* (PMMA) [4]

Properties	Value
Density (kg/m^3)	1180
Modulus Young (MPa)	2900
Poisson Ratio	0,37
Ultimate Tensile Strength (MPa)	70
Yield Strength(MPa)	69.1
Thermal Expansion Coeff. ($^0C^{-1}$)	7 x 10^{-5}

1.2 Theoretics

Fatigueis a form of failure that occurs in structures subjected to dynamic and fluctuating stresses (e.g., bridges, aircraft, and machine components). Under these circumstances it is possible for failure to occur at a stress level considerably lower than the tensile or yield strength for a static load. The term *fatigue* is used because this type of failure normally occurs after a lengthy period of repeated stress or a strain cycling. The applied stress may be axial (tension-compression), flexural (bending), or torsional(twisting) in nature[5].Figure 2 shows cycles stress and S-N Diagram from a structure that has a fatigue limit.



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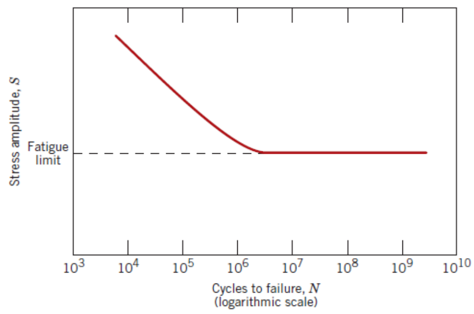

(b)

Figure 2: (a) Reversed Stress Cycle, (b) S-N Diagram. [5]

Thermal stresses are stresses induced in a body as a result of changes in temperature. An understanding of the origins and nature of thermal stresses is important because these stresses can lead to fracture or undesirable plastic deformation[5].

Let's first consider a homogeneous and isotropic solid rod that is heated or cooled uniformly, that is, no temperature gradients are imposed. For free expansion or contraction, the rod will be stress free. If, however, axial motion of the rod is restrained by rigid end supports, thermal stresses will be introduced. The magnitude of the stress σ resulting from a temperature change from T_0 to T_f is

$$\sigma = E\alpha(T0 - Tf) = E\alpha\Delta T$$

Where E is the modulus of elasticity and α is the linear coefficient of thermal expansion. Upon heating (T_f>T_0), the stress is compressive (σ< 0) because rod expansion has been constrained. If the rod specimen is cooled (T_f<T_0), a tensile stress will be imposed(σ> 0)[5].

II. LOADING AND BOUNDARY CONDITIONS

The loading that will be given to the optical fiber is the load due to temperature changes, causing the optical fiber to experience thermal stress. The loading model is then simulated using Altair Hyperworks software to test Static and Fatigue using the finite element method. Changes in temperature used in this study were taken from previous studies, namely from room temperature 25^0C to 110^0C, 120^0C, and 130^0C. Variations in temperature changes will be tested on each fiber optic cable modeling with the aim of knowing the maximum stress, deformation, and strength of the fiber optic cable before it breaks.

From the variation of temperature changes, it can be seen the value of Thermal Stress from Static simulation with loading in the form of temperature changes. The stress value obtained from the simulation is then used to find the fatigue

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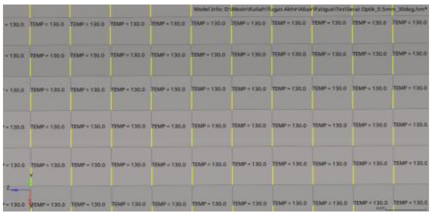
strength of the optical fiber in the form of maximum cycles with repeated loads using Altair Hyperworks.

The definition of temperature change in this simulation is placed on all nodes on the meshing element of the cladding surface of the optical fiber as shown in Figure 3 in the form of a yellow line. Changes in temperature are placed on the cladding surface because the cladding surface is the outer surface that is first exposed to temperature changes from the environment.



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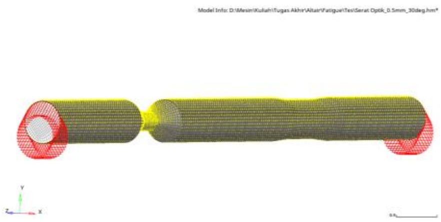

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Figure 3: Loading and Boundary Condition (a) Change of Temperature, (b) Boundary Condition

Boundary conditions are given at the fulcrum of the fiber optic cladding. Boundary conditions will adjust to the type of loading carried out. Figure 3 shows the point boundary conditions for the loading of temperature changes on optical fiber. The type of boundary condition used is a fixed constraint where the displacement and rotation on all axes are zero. This boundary condition represents the contact between optical fibers with one another.

The software used for meshing is hypermesh 2019 as shown in Figure 4 below. Fiber optic meshing uses quad elements. Meshing is done using 2D size and bias with a size of 0.7 mm. Optical fiber is defined with a thickness of 0.02 mm for the cladding section. The results of the meshing have 0 failures which prove that the meshing results are good.

(a)

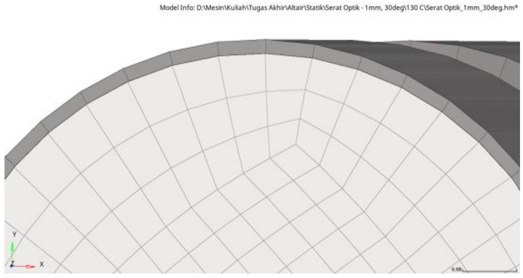

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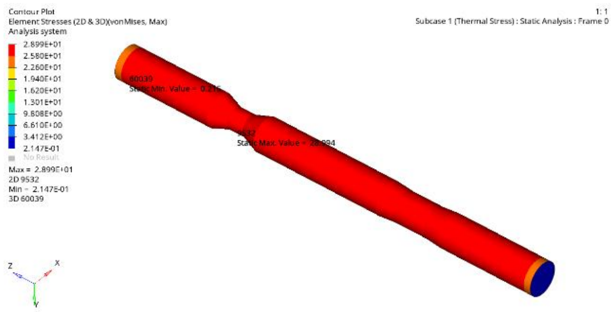
Figure 4: Meshing (a) Meshing 0.07 mm, (b) Meshing Detail 0.07 mm

III. RESULTS AND DISCUSSIONS

Static with Temperature Changed of 110^0C

Static analysis results with temperature changes up to 110^0C obtained the highest Thermal Stress in optical fiber with a length variation of 0.5 mm compared to other variations. The highest thermal stress value was obtained in optical fiber with an angle of 20^0 of 28.99 MPa, an angle of 25^0 of 30 MPa, and an angle of 30^0 of 31.51 MPa on the tapered section. The simulation results can be seen in Figure 5. The location of the maximum thermal stress is at the connection of the tapered optical fiber sensor because there is a difference in the cross-sectional area between the two ends of the optical fiber and the cross-sectional area at the tapered optical fiber section, thus making the thermal stress value larger.



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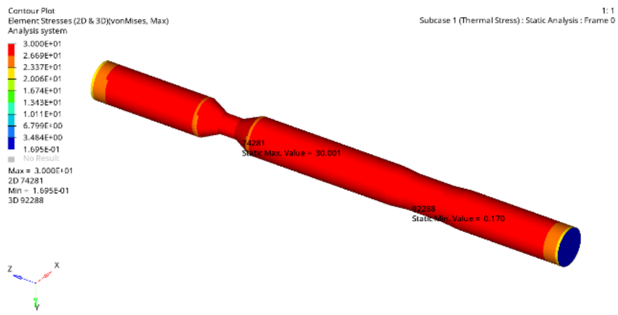

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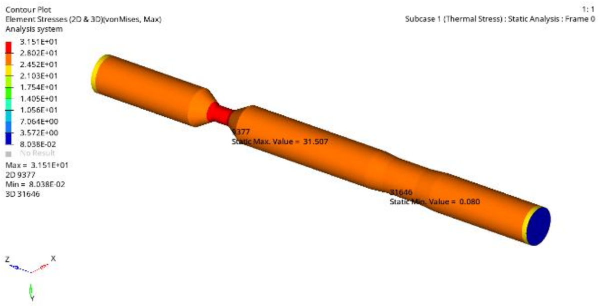
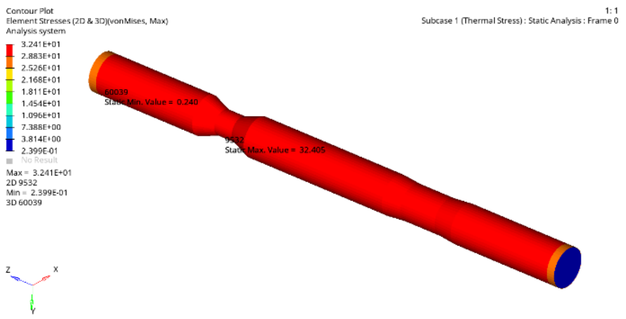


(c)

Figure 5: Fiber Optic Static Simulation Results Contour (a) 0,5 mm, 20^0, (b) 0,5 mm, 25^0, (c) 0,5 mm, 30^0

Static with Temperature Changed of 120^{0}C

Static analysis results with temperature changes up to 120^{0}C also obtained the highest Thermal Stress in optical fiber with a length variation of 0.5 mm compared to other variations. The highest thermal stress value was obtained on optical fiber with an angle of 20^0 of 32.41 MPa, an angle of 25^0 of 33.53 MPa, and an angle of 30^0 of 35.21 MPa on the tapered part. The simulation results can be seen in Figure 6. The location of the maximum thermal stress is at the connection of the tapered optical fiber sensor because there is a difference in the cross-sectional area between the two ends of the optical fiber and the cross-sectional area at the tapered optical fiber section, thus making the thermal stress value larger.



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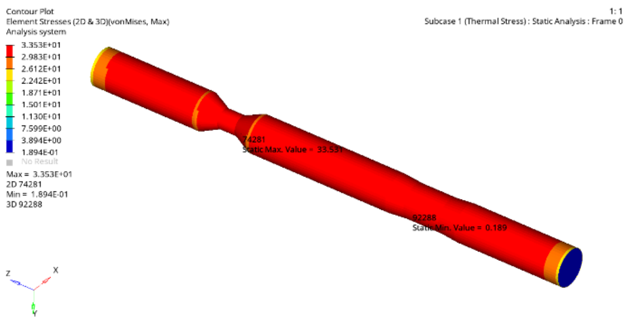

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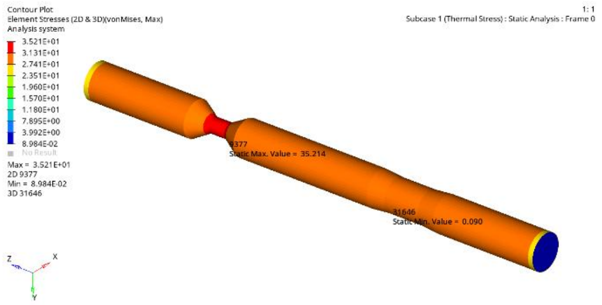

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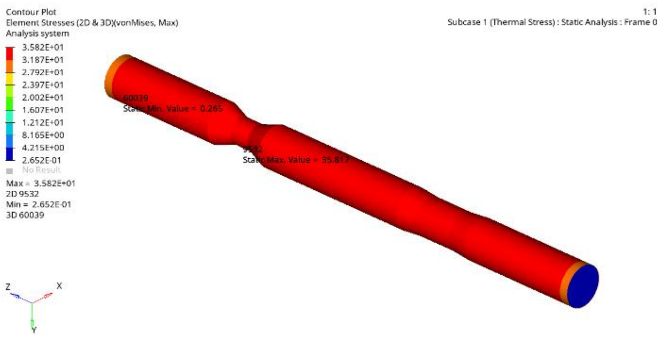
Figure 6: Fiber Optic Static Simulation Results Contour (a) 0,5 mm, 20^0, (b) 0,5 mm, 25^0, (c) 0,5 mm, 30^0

Static with Temperature Changed of 130^{0}C

Static analysis results with temperature changes up to 130^{0}C also obtained the highest Thermal Stress in optical fiber with a length variation of 0.5 mm compared to other variations. The highest thermal stress value was obtained on optical fiber with an angle of 20^0 of 35.82 MPa, an angle of 25^0 of 37.06 MPa, and an angle of 30^0 of 38.92 MPa on the tapered section. The simulation results can be seen in Figure 7. The location of the maximum thermal stress is at the connection of the tapered optical fiber sensor because there is a difference in the cross-sectional area between the two ends of the optical fiber and the cross-sectional area at the tapered optical fiber section, thus making the thermal stress value larger.



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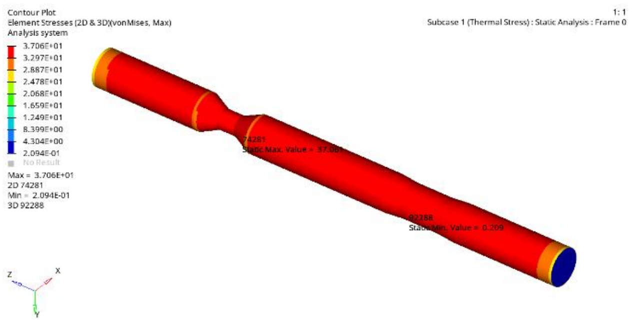

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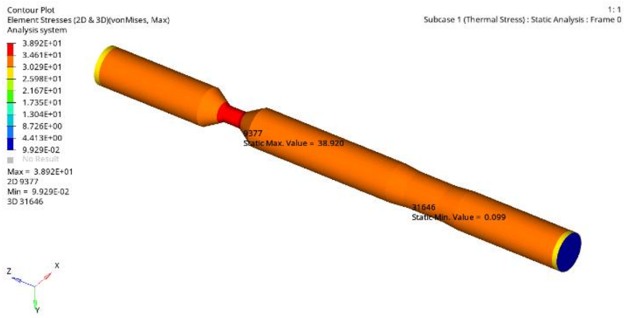

(c)

Figure 7: Fiber Optic Static Simulation Results Contour (a) 0,5 mm, 20^0, (b) 0,5 mm, 25^0, (c) 0,5 mm, 30^0

Fatigue with Temperature Changed of 110^0C

Fatigue analysis results with temperature changes up to 110^0C obtained the lowest maximum number of cycles in optical fiber with an angle of 30^0 and a length of 0.5 mm worth 3.531 x 10^6. The simulation results can be seen in Figure 8. The critical point of this fiber optic sensor is at the tapered section connection because that section is part of the fiber optic sensor that gets the highest thermal stress value. This is in accordance with the theory where the voltage value is inversely proportional to the maximum number of cycles, so if the thermal stress value is greater, the maximum number of cycles obtained will be smaller.

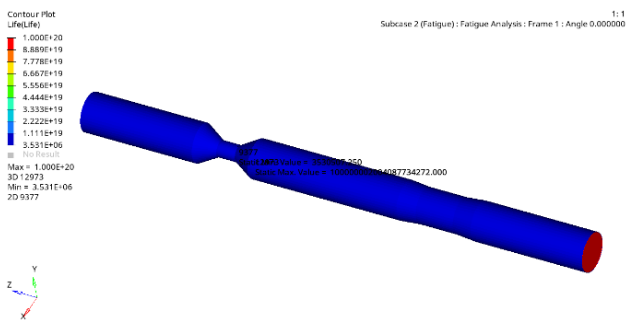

Figure 8: Fiber Optic Fatigue Simulation Result Contour 0,5 mm, 30^0

Fatigue with Temperature Changed of 120^0C

The results of Fatigue analysis with temperature changes up to 120^0C obtained the lowest maximum number of cycles on optical fiber with an angle of 30^0 and a length of 0.5 mm worth 0.954 x 10^6. The simulation results can be seen in Figure 9. The critical point of this fiber optic sensor is at the tapered section connection because that section is part of the fiber optic sensor that gets the highest thermal stress value. This is in accordance with the theory where the voltage value is inversely proportional to the maximum number of cycles, so if the thermal stress value is greater, the maximum number of cycles obtained will be smaller.

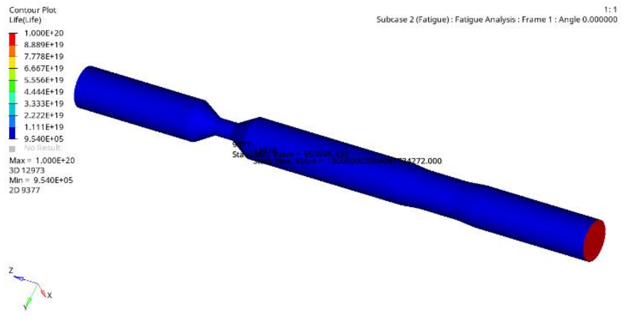

Figure 9: Fiber Optic Fatigue Simulation Result Contour 0,5 mm, 30^0

Fatigue with Temperature Changed of 130^0C

Fatigue analysis results with temperature changes up to 130^0C obtained the lowest maximum number of cycles on optical fiber with an angle of 30^0 and a length of 0.5 mm worth 0.294 x 10^6. The simulation results can be seen in Figure 10. The critical point of this fiber optic sensor is at the tapered section connection because that section is part of the fiber optic sensor that gets the highest thermal stress value. This is in accordance with the theory where the voltage value is inversely proportional to the maximum number of cycles, so if the thermal stress value is greater, the maximum number of cycles obtained will be smaller.

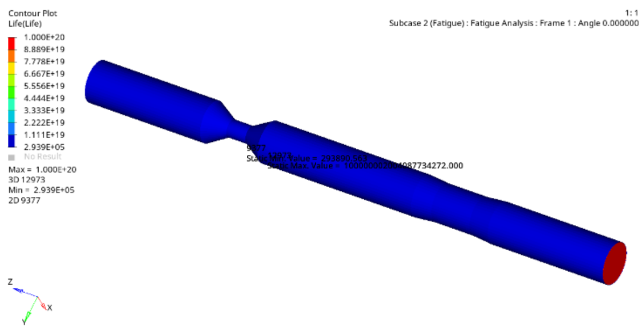

Figure 10: Fiber Optic Fatigue Simulation Result Contour 0,5 mm, 30^0

S-N Diagram

The S-N diagram shows the relationship between the repeated stress value (S) used during the Fatigue simulation and the maximum number of cycles (N) when the optical fiber is fractured. Table 2 and Figure 11 show the value of the thermal stress and the maximum number of cycles for each variation of optical fiber that has been tested.

Table 2: Rated Thermal Stress and Maximum Number of Cycles

Length (mm)	Angle	Temperature Changed (^{0}C)	Stress Amplitude, S (MPa)	Cycles to Failure, N
0.5	20^0	110	28,99	13,2 x 10^6
0.75	20^0	110	28,85	14,06 x 10^6

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1	20^0	110	28,79	14,57 x 10^6
0.5	25^0	110	30	7,588 x 10^6
0.75	25^0	110	29,91	8,004 x 10^6
1	25^0	110	29,82	8,45 x 10^6
0.5	30^0	110	31,51	3,531 x 10^6
0.75	30^0	110	31,28	3,959 x 10^6
1	30^0	110	31,09	4,393 x 10^6
0.5	20^0	120	32,41	3,566 x 10^6
0.75	20^0	120	32,25	3,8 x 10^6
1	20^0	120	32,17	3,938 x 10^6
0.5	25^0	120	33,53	2,051 x 10^6
0.75	25^0	120	33,43	2,163 x 10^6
1	25^0	120	33,33	2,283 x 10^6
0.5	30^0	120	35,21	0,954 x 10^6
0.75	30^0	120	34,96	1,07 x 10^6
1	30^0	120	34,75	1,187 x 10^6
0.5	20^0	130	35,82	1,099 x 10^6
0.75	20^0	130	35,64	1,171 x 10^6
1	20^0	130	35,56	1,213 x 10^6
0.5	25^0	130	37,06	0,632 x 10^6
0.75	25^0	130	36,95	0,666 x 10^6
1	25^0	130	36,83	0,703 x 10^6
0.5	30^0	130	38,92	0,294 x 10^6
0.75	30^0	130	38,64	0,33 x 10^6
1	30^0	130	38,41	0,366 x 10^6

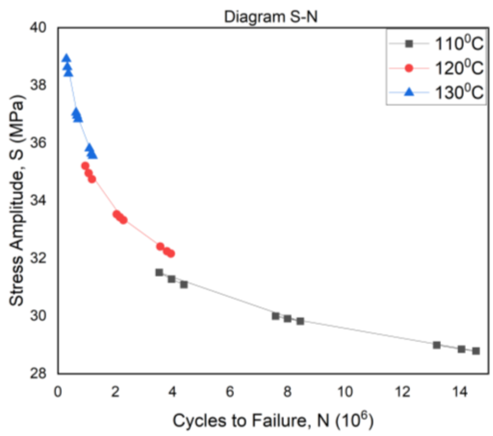

Figure 11: S-N Diagram

Based on the results of the S-N diagram plot showing the relationship between the influence of the stress magnitude, in this case the thermal stress, and the maximum number of cycles, it can be concluded that the lower the thermal stress value, the higher the maximum number of cycles obtained. This is also related to the discussion in the previous sub-chapter where the relationship between the thermal stress value and the maximum number of cycles produced is inversely proportional. While the shape of the S-N diagram which is getting more and more sloping shows that the optical fiber with Polymethyl Methacrylate (PMMA) material has an endurance limit/fatigue limit, where in this case, the fatigue limit of PMMA-based optical fiber is around 30 MPa.

According to Filograno et al[6], a fiber optic sensor placed close to the train tracks will respond to the test equipment and show changes in light waves, and the fiber optic sensor will stretch when the train wheel passes through the sensor section. Therefore, the author concludes that if the train wheel passes through a rail that has a fiber optic sensor, the sensor receives 1 cycle of voltage. Table 3 shows the calculation variables for the number of cycles. The calculation of the lowest and highest maximum number of cycles of optical fiber is as follows:

Table 3: Variable Calculation of the Number of Cycles

Variable	Value
Train Wheel	24
Number of Train/days	10
Day/Year	365

$$Time = \frac{Max.\,Number\ of\ Cycle}{Train\ Wheel\ x\ Number\ of\ Train\ x\ Years}$$

Lowest maximum number of cycles:

$$Time = \frac{294.000}{24\ x\ 10\ x\ 365}$$

$$Time = \ 3{,}35\ Years\ (3\ Years\ 4\ Months)$$

Highest maximum number of cycles:

$$Time = \frac{14.570.000}{24\ x\ 10\ x\ 365}$$

$$Time = \ 166{,}3\ Years\ (166\ Years\ 4\ Months)$$

IV. CONCLUSION

Based on the results of the research that has been done, some conclusions can be drawn as follows:

1. Based on the results of the Static simulation, the largest Von-Mises Thermal Stress value occurs in fiber optic sensors with a tapered length variation of 0.5 mm and an angle of 300 with a temperature change of up to 1300 C with a value of 38.92 MPa. Meanwhile, the smallest Von-Mises Thermal Stress value is found in fiber optic sensors with a tapered length variation of 1 mm and an angle of 200 with a temperature change of up to 1100 with a value of 28.79 MPa.
2. Based on the results of the Fatigue simulation, it can be concluded that variations in the value of different loads will result in different number of cycles as well. The higher the loading value, the lower the number of cycles obtained, such as the number of cycles obtained with the largest thermal stress of 38.92 MPa, which is 294,000 cycles. While the number of cycles obtained with the smallest thermal stress of 28.79 MPa is 14,570,000 cycles.

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3. Based on the calculation of the maximum number of cycles with real conditions, the time when the optical fiber sensor will break is 3 years 4 months for the fastest time and 166 years 4 months for the longest time.

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