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Experimental Investigation of Fatigue Strength in Adhesive Bonds

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Abstract – In this study, AISI 1040 carbon steel plate and cylindrical parts used as brackets in wind turbine towers were bonded with 3M acrylic adhesive. The static strength values (shear stress, bending stress and equivalent stress) of the adhesion bond were determined by mechanical test setup. Also; since fatigue occurs inside the tower by thermal stresses and pressures, S-N curves are obtained depending on the equivalent stress varying at R=0 stress ratio of the bonded parts under repeated stress. As a result of the experiments, it was found that the adhesion bond has an infinite life under 35 MPa fluctuating equivalent stress.

Keywords**:** Adhesive bonding, fatigue, static tester, fatigue tester

1. Introduction

Various joining methods such as bonding, soldering, welding, joining with bolts and rivets are used in the joining of machine elements. In recent years, the usage of adhesives has been increasing rapidly, especially in technical applications. Structural adhesives offer several advantages over welding, brazing, bolting or riveting connections. Among these are the low cost of adhesives, compatibility with different sizes and various materials. One of the most obvious advantages over the commonly used mechanical bonding methods is that there is a continuous contact between the surfaces to be joined. At the same time, the advantages of bonding technology include lighter, more durable and environmentally friendly materials. Due to the demand for such materials in the industry, adhesives have become a key technology in various industrial sectors. Adhesives are widely used in the automotive industry, as well as in the civil aerospace, microelectronics and optoelectronics industries [1].

In wind turbines, which have an important place in the renewable energy industry, traditionally welded brackets can be successfully joined into the tower using adhesives. The heat input that occurs after the welded joint process causes internal stresses in the parts. Wind tower turbines are subject to oscillation, even if it is not visible to the naked eye. With this oscillation, cracks occur due to repetitive stresses and these cracks progress over time. In order to prevent this damage, the use of adhesive has recently increased rapidly in joining the brackets into the tower. These bonded brackets are subject to fatigue due to thermal stresses and pressures in the tower due to weather conditions. For this reason, fatigue is of great importance in the adhesive bonds of the brackets inside the tower.

Static, dynamic and fatigue tests are used to evaluate the durableness of raw materials, components or finished products. Fatigue tests are a specialized method of mechanical testing performed by applying cyclic loads to understand how a structure will perform under similar conditions.

In his study, Kinloch discussed the advantages and disadvantages of adhesives used in engineering and showed that it is possible to define three different stages in the formation of an adhesive bond (i. easy spreading of the adhesive, ii. hardening to carry loads, and iii. determination of the bond strength life)[2].

Ojalvo et al. conducted a study on the effect of stress distribution on bond thickness in single lap adhesive joints [3]. Goglio et al. evaluated the dynamic behavior of a two-component epoxy adhesive for structural bonding. In particular, they focused on the effect of strain rate on the tensile and compressive strength of adhesive-treated specimens. As a result of the tests, it was observed that the adhesion strength increased significantly with the increase of the strain rate [4].

Asgharifar et al. applied three-dimensional (3-D) dynamic finite element analysis (FEA) to examine the transient stress distribution of adhesively bonded joints under the action of solid bullets. To support the finite element analysis, they experimentally investigated the behavior of adhesively bonded joints subjected to impact loading via metallic balls as impactors. They numerically examined the effect of process parameters, including the thickness of the adhesive layer, the solid bullet size and velocity, the material properties of the adhesive, and the strain rate effect on the dynamic stress of the joint. Numerical results show a complex 3D stress state in adhesively bonded joints under the action of solid bullets [5].

In their study, Özel et al. experimentally and numerically investigated the mechanical properties of single-lap joint geometry bonded with different top and bottom adhesive configurations under tensile load [6].

Peretz evaluated the shear behavior data of adhesives, the shear moment displacement relationship for thin adhesive layers, with a custom-made torsion device. He calculated the shear stresses from the torsional moment displacement curve, taking into account the linear shear stress distribution along the adhesive thickness and the uniform shear stress distribution in the cross-sectional area [7].

In this study, static bending, shear and equivalent stresses of the adhesion bond in AISI 1040 carbon steel with circular adhesion geometry were determined. In order to determine the fatigue behavior under shear and bending stresses, the spring fatigue device developed by Gonen, Oral and Cakir [8] was revised and a fatigue device that creates dynamic shear and bending stress was designed to examine the fatigue strength of adhesive bonds.

2. Material and Method

Experimental studies can be examined under four groups as surface preparation of samples, adhesive application, static and dynamic experiments.

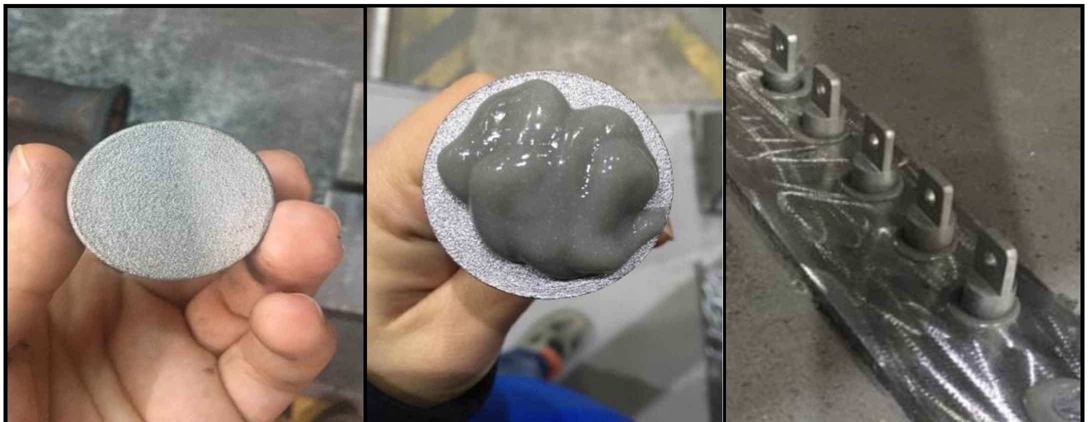
2.1. Material and Sample Preparation

During the experiments, 40 mm diameter AISI 1040 carbon steel, which is the bracket material used in the wind turbine tower, was used. The chemical analysis of the steel is given in Table 1.

Table 1: Chemical analysis (% weight)

C	Si	Mn	P	S	Cr	Ni	Al	Cu	Mo	V
0,380	0,140	0,730	0,025	0,015	0,040	0,040	0,005	0,060	0,009	0,002

Since the adhesive is required to be in full contact with the surface to be adhered, the surface has been cleaned first. The surfaces of the static test samples were cleaned from dust and dirt and shot peened (Figure 1.a). During the shot peening process, the relative humidity is 52.2%, the surface temperature is 23.3°C and the ambient temperature is 21.6°C. After shot peening, the surfaces were cleaned by wiping with ethyl alcohol. After the surface preparation process, the adhesive was applied to the upper sample surface to cover the entire surface (Figure 1.b). 3M acrylic adhesive was used as the adhesive. The test specimens were quickly adhered to a specially designed static test setup (Figure 1.c).



a)Before bonding | b)Adhesive application | c)After bonding

Figure 1: Preparation steps of the static test sample

The surfaces of the samples to be used in fatigue tests as well as in static tests were cleaned from dust and dirt and shot peened (Figure 2.a). Surface roughness values (Rt) were measured before the bonding process. The average calculated surface roughness value is 47.49µm for the lower part (80x120mm^2 plate) and 15.14µm for the upper part. Then the surfaces were cleaned by wiping with ethyl alcohol. After the surface preparation process, the adhesive was applied to the sample surface only to cover the surface of the upper part (cylindrical part with a diameter of 40mm) (Figure 2.b). Adhesive was performed by joining the upper part to which the adhesive was applied with the lower part (Figure 2.c). The adhesive thicknesses obtained from the samples prepared for both fatigue and static tests were determined as approximately 1 mm.

a) After shot peening | b) Adhesive application | c) After bonding

Figure 2: Preparation steps of the dynamic test sample

2.2. Static Test

Since the brackets attached to the tower are forced to shear and bending stress, a non-standard test setup, whose 3D model is given in Figure 3, was used to determine the static shear and bending strength of the bonding. In this setup, the mechanically applied load is recorded digitally with the help of a load cell. As a result of the experiments, the maximum load at which separation occurred was obtained. Five samples were tested to determine the shear and bending stresses. The shear stress was determined with the help of Equation (1), bending stress Equation (2) and equivalent stress values were determined with the help of Equation (3) from the obtained maximum load.

$$\tau_s = \frac{P_{max}}{A_o} \tag{1}$$

$$\sigma_b = \frac{M_b}{I_x} \, . y \tag{2}$$

$$\sigma_{eq} = \frac{\sigma_b}{2} + \sqrt{\left(\frac{\sigma_b}{2}\right)^2 + {\tau_s}^2} \tag{3}$$

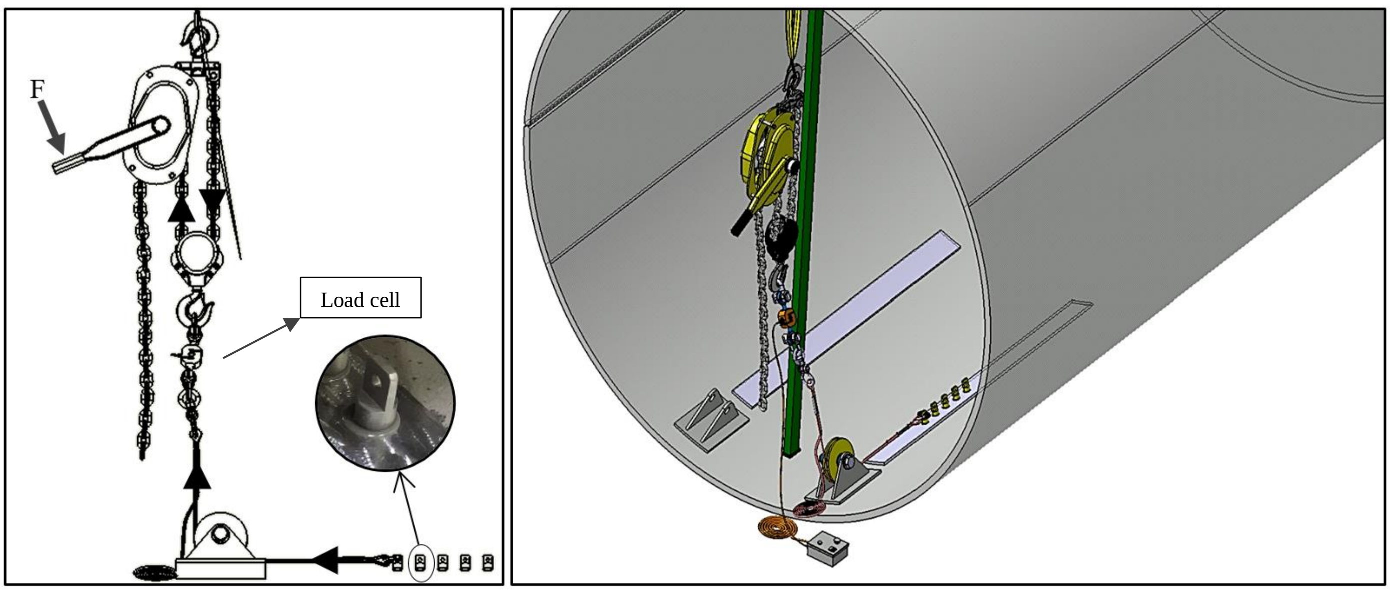


Figure 3: 3D model of static tester

2.3. Fatigue Machine and Testing

In order to determine the fatigue strength of the bonded parts, the fatigue device that applies fluctuating shear and bending stresses, given in Figure 4, was designed. The fatigue tester is driven by a power of 4 kW and 1460 rpm. The engine speed is reduced by 1/6 with the belt-pulley mechanism and the rotational movement is converted into translational movement, which compresses the spring, with the crank-connecting rod mechanism. Meanwhile, depending on the compression amount of the spring, the system transmits the compression force between 0-F (N) to the sample. Springs with different stiffness were used to obtain different repeated stress values.

By the millimetric ruler placed on the side of the fixed bottom plate, the amount of spring compression can be adjusted. The diameters of the springs used in the test device can vary between 32 and 50mm, and their lengths can vary between 102 and 115mm. A counter was used to determine the number of load cycles applied to the samples in the experiments. Since the number of characters in the digital display on the counter is limited; counter provides one unit increment for every 10 load cycles. When the sample separates, the electrical circuit is cut and the system stops automatically with the micro switch placed on the lower table. There is an emergency stop button to stop the device in case of any unexpected situation.

Fatigue tests were carried out at room temperature with 8 specimens at a stress ratio of R=0.

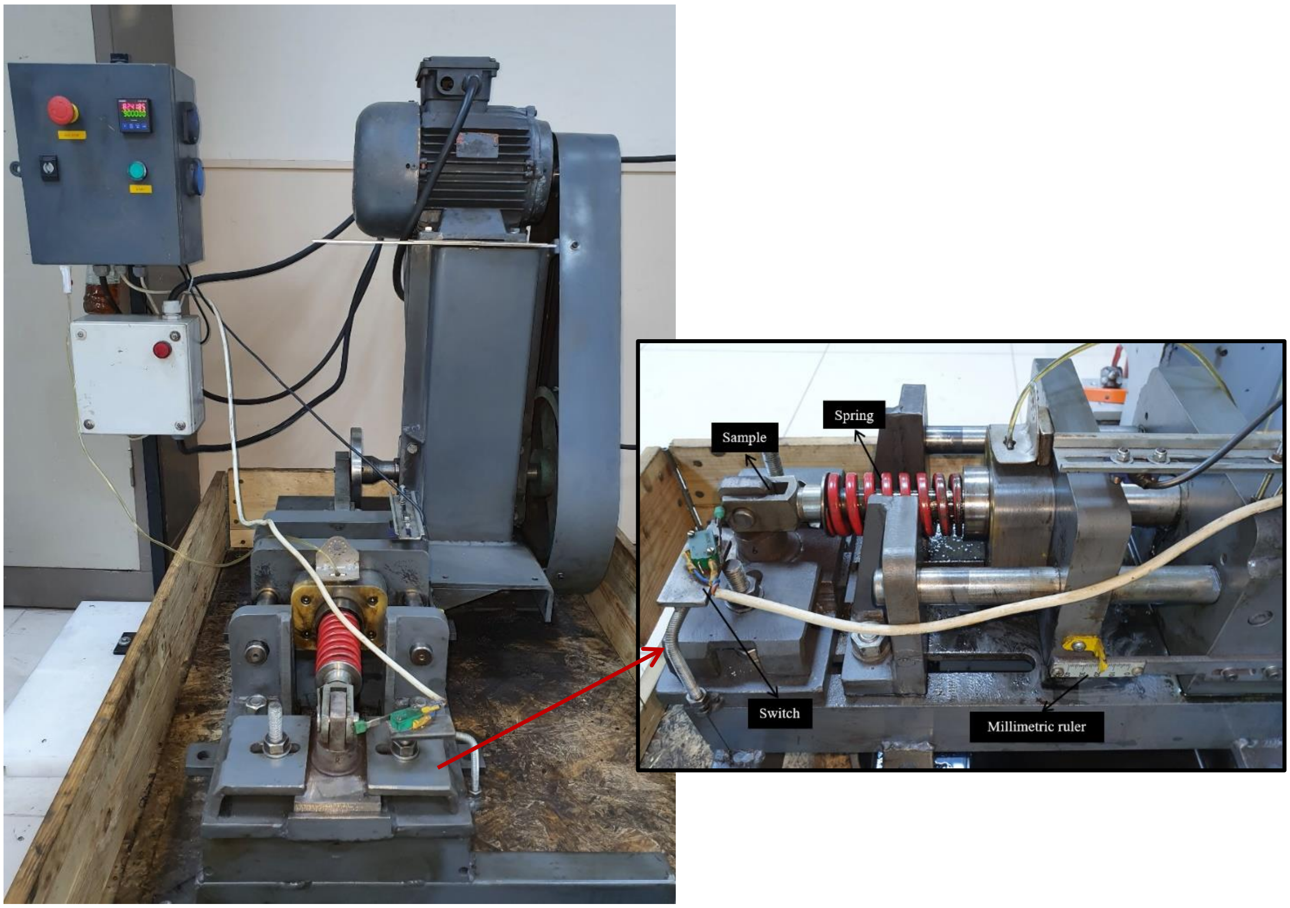
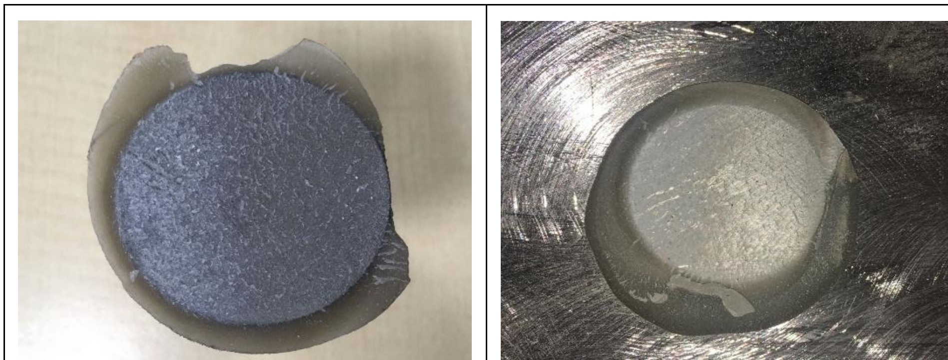


Figure 4: Fatigue testing machine

3. Results and Discussion

The specimens that broke off by the static and dynamic tests are given in Figure 5 and Figure 6, respectively. When the figures were examined, it was seen that the samples showed a homogeneous separation from the adhesive part (cohesion). No gaps or discontinuities were observed on the adhesion surfaces. For this reason, it can be said that the bonding process and adhesive type are suitable for AISI 1040 carbon steel.



Upper part | Lower part

Figure 5: Fracture surfaces of static test specimens

Upper part | Lower part

Figure 6: Fracture surfaces of fatigue test specimens

Static test results are given in Table 2. Shear, bending and equivalent stresses were calculated with the help of equations 1, 2, and 3 using F_{max} values. For the applied bonding process, the average shear, bending and equivalent stresses were calculated as 7.89 N/mm^2, 71.05 N/mm^2 and 71.13 N/mm^2, respectively.

Table 2: Results of static tests

Test number	**F_{max} (N)**	**τ_s (N/mm^2)**	**σ_b (N/mm^2)**	**σ_{eq} (N/mm^2)**
1	10840	8,63	77,64	78,59
2	9908	7,88	70,96	67,89
3	8809	7,01	63,09	63,86
4	10271	8,17	73,56	74,46
5	9771	7,78	69,98	70,83

With the help of the designed fatigue device, the Wohler (S-N) curve obtained by recording the load cycles after separation of the bonded parts as a result of the applied repeated stresses is given in Figure 7. In the standard [9] on fatigue tests of structural adhesives, it is stated that the number of 10^6 cycles is sufficient for statistical analysis. However, in our study, separation was observed on the adhesion surfaces at 35.52 MPa equivalent stress value but at 11.8 x10^6 load cycle. According to this result, it can be said that the application of the bonding process and the fatigue resistance of the adhesive are suitable. Fatigue tests will also be carried out at intermediate values in order to get clearer information about the variation of the curve at repetitive equivalent stresses between 51.03MPa and 35.52MPa. As seen in Figure 7, it can be said that AISI 1040 carbon steel has an indefinite life below 35.52 MPa when joined with 3M's acrylic adhesive. Also, the 35.52 MPa equivalent stress value is nearly half of the static equivalent stress.

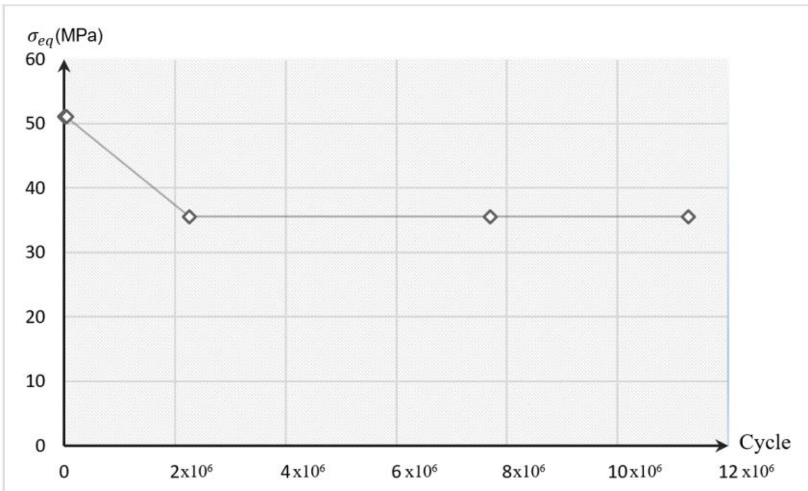


Figure 7: S-N Curve

4. Conclusions

In this study, in which the static and fatigue strengths of the bonds obtained by joining AISI 1040 carbon steel with 3M's acrylic adhesive, the following results can be given:

- As a result of both static and fatigue tests, a cohesive separation was observed on the adhesion surfaces. It was observed that there were no discontinuities on the surfaces and the separation was homogeneous.
- Adhesive type and bonding method have been found to be suitable for AISI 1040 carbon steel.
- As a result of static tests, the average shear stress of the adhesion bond is 7.89 N/mm^2, the bending stress is 71.05 N/mm^2 and its equivalent stress is 71.13 N/mm^2.
- As a result of fatigue tests, it has been observed that the adhesion bond has an infinite life under 35.52 MPa repeated equivalent stress.

Symbols

F	Applied Force, N
σ_b	Bending Stress, N/mm^2
σ_{eq}	Equivalent Stress, N/mm^2
τ_s	Shear Stress, N/mm^2
F_{max}	Maximum Force, N
A_0	Bonding Area, mm^2
M_b	Bending Moment, Nmm
I_x	Moment of Inertia, mm^4
y	Distance to Neutral Axis, mm

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