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INFLUENCE OF SURFACE ROUGHNESS ON HIGH-CYCLE FATIGUE STRENGTH OF ADHESIVE JOINTS UNDER MODE II LOADING.

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Abstract. *The purpose of this work is to investigate the influence of surface roughness of mild steel substrates on fatigue crack propagation in adhesively bonded joints. In order to verify this effect samples with different roughness surfaces of ASTM A36 steel were prepared as substrates that were used for manufacturing the joints, with a thin epoxy adhesive layer. The bonded joints were tested under standard fatigue loading conditions in end-notched flexure format, widely used to fracture characterization under mode II loading. The experimental data are presented and compared. Experimental tests demonstrated significant influence of different roughness on fatigue life.*

Keywords: *fatigue, bonded joints, surface roughness, mechanical treatment, mode II loading*

1. INTRODUCTION

For many adhesively bonded joins used in structural components the alternating loading defines its service life. In a fatigue loading regime, a structure may fail even in elastic regime. Consequently, it is important to estimate the fatigue strength of bonded joints through the utilization of one of the several methods that have been developed for that purpose. A reasonable estimation of fatigue life is still a quite complex issue due to the multivariable nature of fatigue crack initiation. Some researchers have already carried out studies in fatigue behavior of bonded joints. Thus, authors as (Katnam, *et al*., 2010) investigated the influence of load parameters on fatigue behavior. The fatigue endurance limits obtained, for a number of adhesives, were inside the 15-35% range of the monotonic strength of the joint. Additionally, it was found that increasing the mean load has a deleterious effect on fatigue life for a given fatigue load range. The effect of frequency on fatigue damage was investigated by (Underhill and DeQuesnay, 2006). It was observed no dependence between the load application frequency and the fatigue behavior in the range from 10 Hz to 60 Hz. Fatigue tests were conducted by (Bernasconi, *et al.*, 2010) on thick composite adhesively bonded joints in order to define a fatigue strength criterion. The result of this study was a suggestion for using the maximum elastic stress as an engineering tool for fatigue assessment of composite bonded joints. The model was based on fracture mechanics and divided the joint lifetime into crack initiation and crack propagation phases. They found that a significant fraction of the fatigue life was spent in crack initiation.

Surface preparation plays a very important role in the quality of the interface between adhesive and substrate and, consequently, it has a great effect on the joint fatigue performance. Thus, authors as (Bermejo, *et al*., 2008) pointed the significant influence of any minimal surface treatment of adherends on fatigue life of adhesive steel joints. Authors as (Azari and Papini, 2010) showed a significant effect of surface roughness of aluminum substrates on crack initiation under mixed-mode fatigue loading. Besides, for fatigue and quasi-static loading under mode I crack initiation energy release rate showed no dependency on surface roughness.

An extensive study was carried out by (Da Silva, *et al.*, 2009) in order to investigate effect of material, geometry, surface treatment, environment on the shear strength of single lap steel joints under quasi-static loading. It was concluded that the parameters as overlap size, adhesive thickness, adherend thickness have a significant effect on joints. In an experimental study (Hadavinia, *et. al*., 2003) investigated the crack growth in epoxy bonded aluminum single lap joint under fatigue loading in different environments. They concluded that the join lifetime was controlled by crack propagation and the surface treatment has a pronounced effect in wet environment. Also, authors as (Gomatam and Sancaktar, 2005) investigated the effect of various substrate surface treatments on the fatigue and failure behaviors of single lap joints. They employed various chemical and mechanical modification technics, under a spectrum of fatigue and environmental conditions. They founded a significant effect of surface treatment on fatigue behavior of these joints.

Although the studying of the fatigue strength and the lifetime analysis of the bonded joints have been started some decades ago and a large number of works were concentrated on this issue, the lifetime prediction of bonded joints remains a relatively unexplored issue. As stated by (Wahab, 2012), the research in crack initiation in adhesively bonded joints has not yet been well developed and could be considered in its early stage.

The objective of this experimental study is to investigate, quantify and compare the effect of different mechanical treatment of low carbon steel substrates on fatigue life of epoxy bonded joints, under mode II loading in static and dynamic regimes. Three different substrate mechanical treatments are used: bristle blasting, the most common treatment in industry, grit blasting and sand blasting. Although some studies related that static strength resistance of steel joints have already been carried out and was found that surface treatment has a little effect, the influence of roughness on fatigue life was not yet extensively evaluated. The main goal of this work is to extend the previous studies and evaluate if the previous results are valid when the fatigue loading is involved.

2. MATERIALS AND EQUIPMENTS

The adhesive joints were made using the substrates of ASTM A36 steel and structural intermediate epoxy adhesive NVT, fabricated by Novatec S.A., Rio de Janeiro, Brazil. The distinct roughnesses were implemented on the steel plates surfaces, before they were cut in specimen size. The joints were manufactured individually in a mold and the adhesive thickness was controlled by the utilization of a dispositive especially developed for this function. This dispositive guarantees the specimen’s dimensions repeatability. The bonded joints were tested statically and at high-cycle fatigue loading in a 100kN servo-hydraulic testing machine. Specimen installation in servo-hydraulic machine is presented in Fig.1.

Figure 1. Illustration of specimen installation in servo-hydraulic testing machine.

Two blasting machines were used to obtain necessary mechanical roughness in bonding surface: a manual blasting machine IBIX 25 (IBIX), that uses different types of blast material and a bristle blasting machine MBX (MONTI Tools), which uses high-carbon steel wire bristles. Two blast materials were used for roughening the bond surface: garnet sand 20/40 mesh and grit steel G-25 (Jatofer).

3. STATIC TEST

Quasi-static end-notched flexure (ENF) tests were performed in order to determine maximum load to use in the dynamic test program. The distance between the specimen supports was $2L$ = 160mm. The length of pre-crack was stablished as a_0 = 25 mm. The substrate dimensions can be resumed as length, l = 190 mm, width of 25 mm and thickness of h = 6 mm. The adhesive thickness stablished was 0,5mm and the length of the bonded area was stablished as 150 mm. The illustration of the specimen's geometry can be seen at Fig.2.

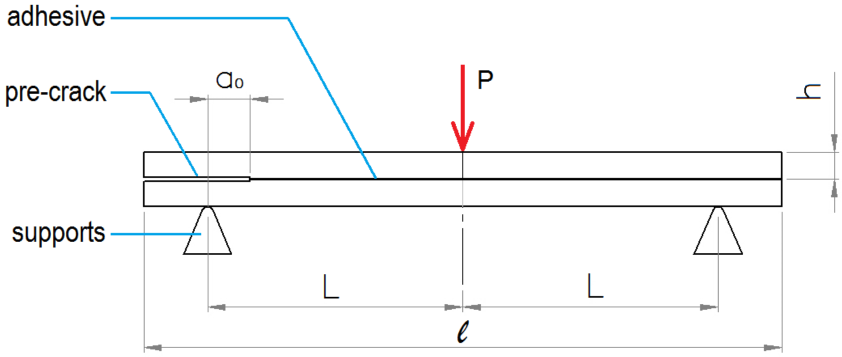

Figure 2. Illustration of end-notched flexure joint dimension and configuration.

End-notched flexure format was used as one the most appropriate test for mode II fracture characterization of bonded joints. Under this type of loading the substrates is exposed to bending moment while the adhesive is submitted to pure shear loading. Quasi-static tests were executed at a crosshead speed of 3 mm/min. The load-displacement curve was registered during the test.

4. FATIGUE TEST

Fatigue tests were performed in four different loading conditions, in the range of 50-80% of maximum load (f %), obtained from static test. Sinusoidal loading waveform with a frequency of 20Hz and loading ratio, $R = P_{min}/P_{max} = 0.1$ were used for fatigue tests. Thus the maximum fatigue load, P_{max} for each level is proportional to this maximum static load. The load amplitude, P_{amp}, and average load, P_{avr} were calculated using classic fatigue expressions. The specimens have been tested until failure occurred or until the number of load cycles reaches 10^6, which is considered infinite life. The load-displacement and load-time graphics have been recorded during the test in order to control the test proceeding.

It was used 36 specimens in the experiment. All of them were tested in the same environment conditions: room temperature of 25°C and relative humidity of 55%. The crack lengths were measured after testing using a stereoscopic microscope.

5. RESULTS AND DISCUSSION

Firstly, quasi-static tests were performed with grit blasted specimens. Three tested specimens presented similar behavior during the tests. Bristle blasting and sand blasting specimens tested in static regime changed the geometry up to ultimate substrate material yielding. The adhesive failure didn't occur, thus there wasn't any crack propagation during the test. Therefore, these tests weren't considered, and the reference load for fatigue tests was calculated using the quasi-static test data of grit blasting specimens. The load-displacement curve obtained from quasi-static test is presented in Fig.3.

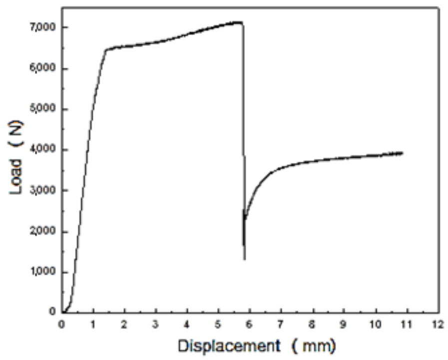

Figure 3. Load-displacement curve of quasi-static test of grit blasting specimen.

Analyzing the load-displacement curve it is possible to see that the failure occurs after the significant plastic deformation of the specimen. The values of yield point were used as the maximum reference load to determine the dynamic test program. The average yield point was calculated as $P(y)_a$= 6293N. Then, the fatigue test program was determined, see Table 1.

Table 1. The fatigue test program.

Level	f (%)	P_{max} (kN)	P_{min} (kN)	P_{amp} (kN)	P_{avr} (kN)	R
1	50	3.15	0.315	1.416	1.731	0.1
2	60	3.78	0.378	1.699	2.077	0.1
3	70	4.41	0.441	1.982	2.423	0.1
4	80	5.03	0.503	2.265	2.769	0.1

The quantitative results of fatigue tests are presented in Table 2. The dynamic tests performed at four loading levels showed significant influence of surface mechanical treatment for fatigue life.

Table 2. Results of fatigue test for the specimens with different mechanical treatment.

Level	f (%)	P_{max} (kN)	P_{min} (kN)	Numbers of cycles to fail with different mechanical treatments (N)		
				Grit blasting	Sand blasting	Bristle blasting
1	50	3.15	0.315	10^6	10^6	10^4
2	60	3.78	0.378	10^5	10^5	10^4
3	70	4.41	0.441	10^4	10^4	10^3
4	80	5.03	0.503	10^3	10^4	10^3

Although all the tested specimens had a good fatigue behavior, as expected, the joints that had worse result in quasi-static tests had the best results in fatigue tests. The best performance in fatigue tests was obtained by the specimens that have grit blasting and sand blasting mechanical treatment. They have a fatigue life, overcoming 10^6 cycles with 50% of reference load. The specimens with bristle blasting treated substrates lasted only 10^4 cycles.

6. CONCLUSIONS

In this work high-cycle fatigue tests of adhesively bonded joints with three different substrate mechanical treatments were performed under mode II loading. It was observed that substrate surface mechanical treatment plays a significant role in fatigue behavior of adhesive joints. The grit blasting mechanical treatment demonstrated the worst resistance under quasi-static loading, but had the best resistance to fatigue loading. Furthermore, grit blasted and sand blasted joints have fatigue life, of 10^6 cycles, with 50% of reference load. Bristle blasted joints, widely used in industry demonstrated the worst result, reaching only 10^4 cycles under fatigue loading.

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8. RESPONSIBILITY NOTICE

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