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# ANALYSIS OF THE CYCLIC BEHAVIOUR OF SINGLE LAP METAL/COMPOSITE JOINTS AT ELEVATED TEMPERATURES

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**Abstract.** *The present paper aims to investigate the progressive accumulation of inelastic displacement observed in single lap metal/composite joints under ultra-low fatigue cycles. The joint was fabricated using a polyurethane based composite reinforced with fiberglass, attached to an ASTM A1020 metallic surface using an epoxy adhesive. Experiments were performed using two distinct force amplitudes with three different loading rates each, and they revealed that the displacement hardening induced by inelastic displacement is strongly rate dependent. Also, the experiments demonstrated a direct relation between the load rate and the total amount of cycles until failure as the increment of the load rate made the joint able to sustain a superior number of cycles before failure, what suggests an elasto-viscoplastic behaviour. This article proposes a preliminary mechanical model that can describe the cyclic behaviour for an arbitrary load history. The kinematic hardening evolution with the inelastic displacement is much more significative than the isotropic one, which enables to identify experimentally all material parameters arisen from theory, performing load-unload tests using flat specimen. A reasonable agreement was obtained between numerical and experimental results.*

**Keywords:** *single lap joint, ratcheting, hysteresis, ultra-low cycle.*

## 1. INTRODUCTION

During the past years the search for new and better materials for being used in pipe repairs has increased significantly (Adams, R. D. et al, 1997; Cognard, P., 2006; Beckwith, B. et al, 1996). In this scenario, fiber reinforced polymer matrix composites have received a special attention, once they can replace general metallic connections such as welds, screws and rivets in a simple and safe way. These types of materials not only provide less risk for the environment, but most importantly allow the repair to be made without or with a short downtime. Polymer based composites also have great mechanical properties, good chemical stability, excellent corrosion resistance and a low cure time.

In this context, it becomes necessary to thoughtfully study all properties concerning these kinds of materials. Several researches have already been done (da Costa Mattos, H. S. C. et al, 2017; Motta, E. P. et al, 2018) however, they only analyzed the elastic segment, and none proposed a model to describe the cyclic inelastic behaviour of the materials.

Therefore, this article aims to present an experimental and theoretical study regarding the progressive accumulation of plastic deformation under ultra-low fatigue cycles until the failure. To achieve such results, cyclic load-unload tensile tests were performed for two distinct force amplitudes (1400 N and 1600 N), and with three distinct load rates each in a metal/composite single lap joint composed by a polyurethane based composite reinforced with fiberglass attached to an ASTM 1020 metallic plate using a high-performance epoxy adhesive. All tests were carried out at a 50 °C temperature, to simulate pipes exposed to the sun, a very common condition in Brazil.

## 2. MATERIALS AND METHODS

### 2.1 Materials

The composite material used was Syntho-Glass XT<sup>®</sup> manufactured by Neptune Research Inc., which is a polyurethane pre-impregnated, bi-directional E-glass fiber composite commonly used to repair and reinforce internal and external defects on pipelines. The joints were bonded using the Syntho-Subsea LV<sup>®</sup> Epoxy, also manufactured by Neptune

Research Inc. It is a two-part blend of liquid epoxy, including Kevlar, polymer and aliphatic polyamine curing agents, that can displace water from wet surfaces in order to make a permanent bond. Finally, the metal used ASTM 1020, as mentioned early, chosen simply for being commonly used for pipelines and other industrial purposes.

## 2.2 Methods

The fatigue tests were carried out using two distinct force amplitudes and for each amplitude were used three different load rates. All parameters chosen for the testes were based on previous studies upon these materials (Andrade, B. et al, 2018) which determined that the average rupture force occurred with 2000 N. Therefore, for the first amplitude of 1400 N (70% of the average rupture force) tests were made using the following frequencies:  $5 \times 10^{-4}$  Hz,  $5 \times 10^{-3}$  Hz and  $5 \times 10^{-2}$  Hz., and for the amplitude of 1600 N (80% of the average rupture force) tests were made using the following frequencies:  $5 \times 10^{-4}$  Hz,  $2.5 \times 10^{-2}$  Hz and  $5 \times 10^{-2}$  Hz. They were all made using a Shimadzu AG-X universal testing machine with a of 100 kN capacity load cell and electro-mechanical sensors to control the transverse displacement.

## 3. RESULTS AND DISCUSSION

### 3.1 Experimental Results

Once the tests were finished, the average force X displacement curves were plotted for each load rate, for both load amplitudes. The curves for the first three cycles are shown in fig. 1 and fig. 2:

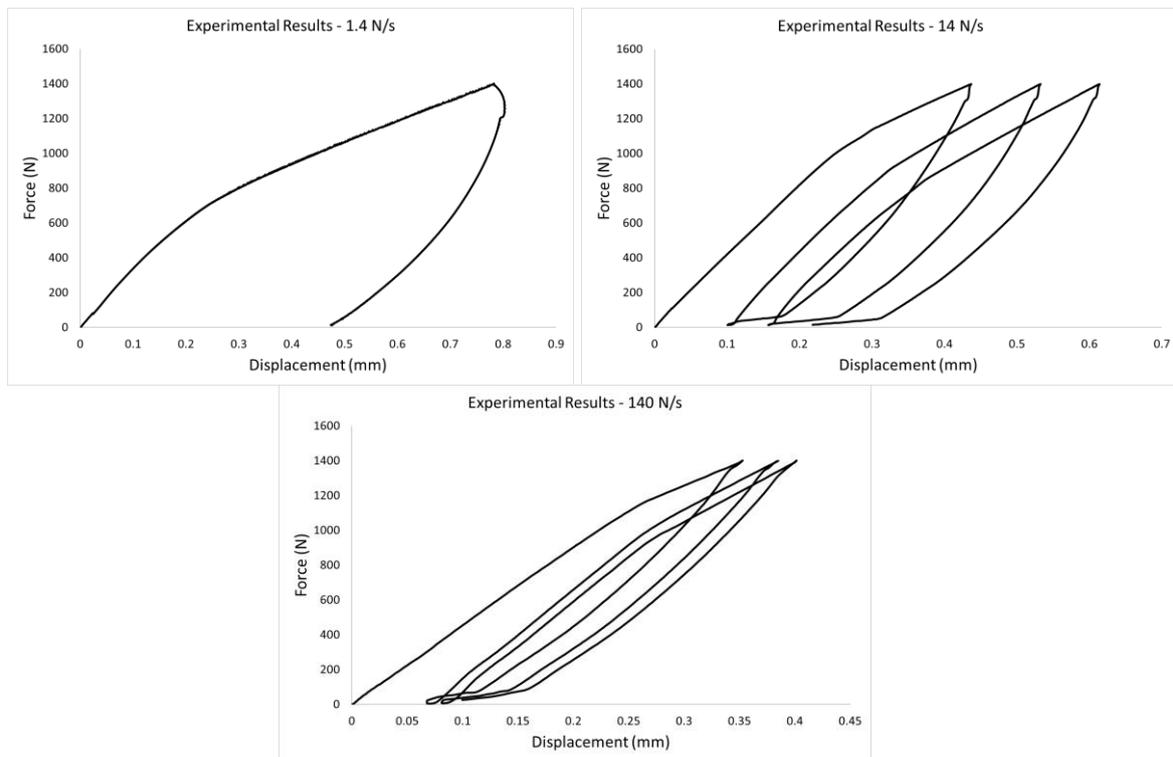


Figure 1. Force x Displacement curves with different load rates (Amplitude 1400 N).

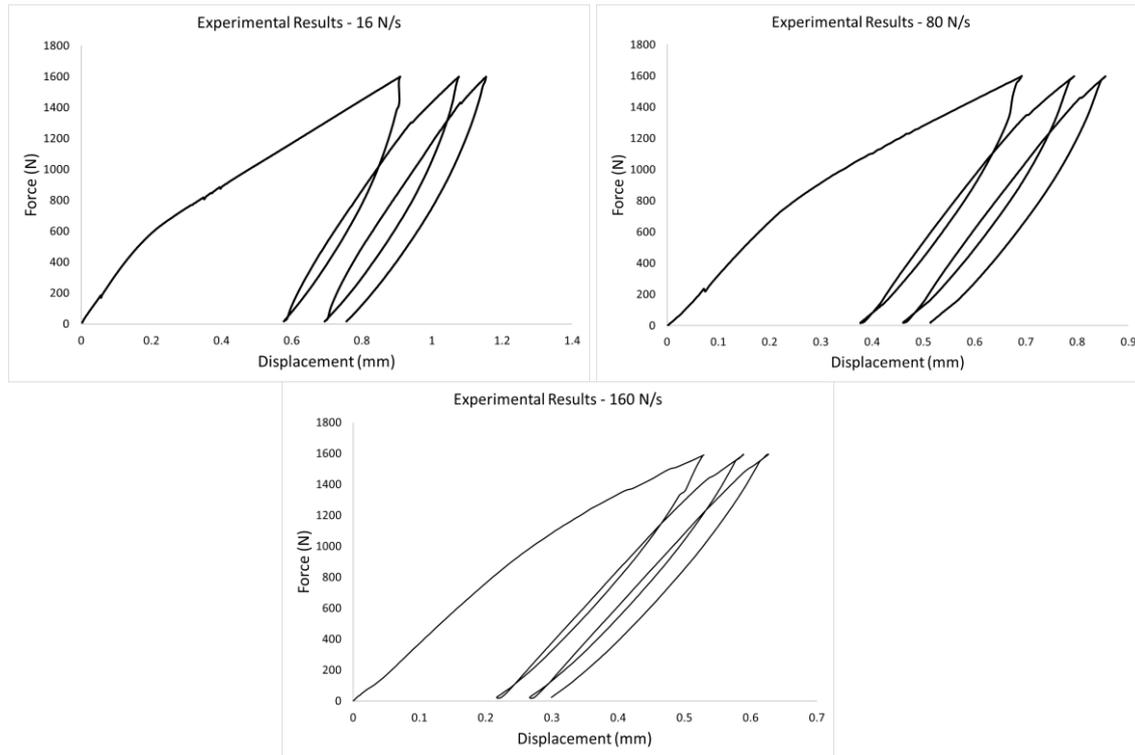


Figure 2. Force X Displacement curves with different load rates (Amplitude 1600 N).

There were found dispersive values of axial stiffness, especially when comparing the results for both amplitudes. That dispersion may be explained due to the difficulties of maintaining the same standards for several variables in the manufacturing process. The following tables shows the summary for the results found for axial stiffness and the total number of cycles until failure for each experiment.

Table 1. Mechanical properties and cycles until rupture for various load rates (Amplitude 1400 N).

Load Rate	Axial Stiffness (N/mm)		Proportional limit $F_p$ (N)	Cycles until rupture
	Cycle 1	Cycle 2 until the end*	Cycle 1	-
$5 \times 10^{-4}$	3330	5060	450	2
$5 \times 10^{-3}$	4288	4923	397	7
$5 \times 10^{-2}$	4478	5602	1159	62

Table 2. Mechanical properties and cycles until rupture for various load rates (Amplitude 1600 N).

Load Rate	Axial Stiffness (N/mm)		Proportional limit $F_p$ (N)	Cycles until rupture
	Cycle 1	Cycle 2 until the end*	Cycle 1	-
$5 \times 10^{-4}$	3376	-	221.73	1
$2.5 \times 10^{-2}$	3385	4370	690.39	13
$5 \times 10^{-2}$	3698	4691	737.39	47

Analyzing the experimental results, it can be seen a high dependence between the proportionality limit and the load rate, since the higher the load rate, higher is the proportionality limit. There can also be noticed a relation between the load rate and the total amount of cycle the material endures until failure, once when we increase the load rate, the joint can withstand more cycles until failure. These results lead to the conclusion that the mechanical behaviour of this joint can be approximated as an elasto-viscoplastic material.

Observing fig. 1 and fig. 2, it can be perceived that this material presents a progressive accumulation of plastic deformation under cyclic tensions, a phenomenon known as hysteresis (a phase lag), which leads to the dissipation of mechanical energy and the accumulation of cyclic deformation.

The total displacement can be divided into two distinct parts, an elastic and a plastic portion. Thus, from now on, it is convenient to introduce the definition of elastic and plastic displacement noted, respectively as,  $l^e$  and  $l^p$ . Also, variables  $F$  and  $K$  are, respectively, the rupture force and the axial stiffness of the material.

$$l^e = \frac{F}{K}, l = l^e + l^p \rightarrow l^p = l - \frac{F}{K} \quad (1)$$

One more variable must be added to this paper to complete the characterization of this joint, which is the accumulated plastic displacement, noted as  $p^l$ . It is responsible for describing the history of the plastic displacement throughout a given time during the test, and can be calculated according to the equation below:

$$\frac{dp^l}{dt} = \left| \frac{dl^p}{dt} \right| \rightarrow p^l(t) = \int_0^t \left| \frac{dl^p}{dt} \right| dt \quad (2)$$

The elastic domain of the material can be defined in the interval  $F_{inf}^{el} < F < F_{sup}^{el}$ , where any changes in the load generates only variations of the elastic displacement. Those limits can be represented by the auxiliary variables below:

$$X = \frac{F_{sup}^{el} + F_{inf}^{el}}{2}; Y = \frac{F_{sup}^{el} - F_{inf}^{el}}{2} \quad (3)$$

It is interesting to note from the previous equations that, within the one-dimension context,  $X$  represents the center from the elastic segment whereas  $2Y$  is the size of the elastic segment.  $X$  is an auxiliary variable related to the kinematic hardening (also usually called the backstress tensor), while  $Y$  is the auxiliary variable related to the isotropic hardening.

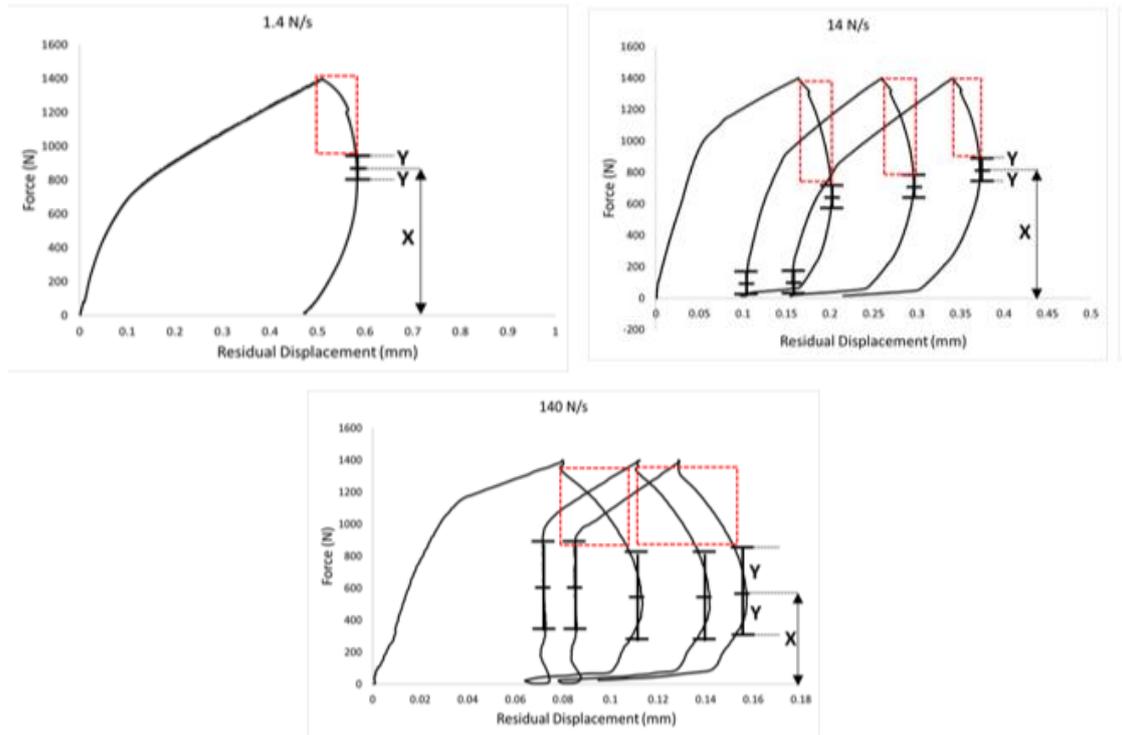


Figure 3.  $F \times l^p$  curves with different load rates (Amplitude 1400 N).

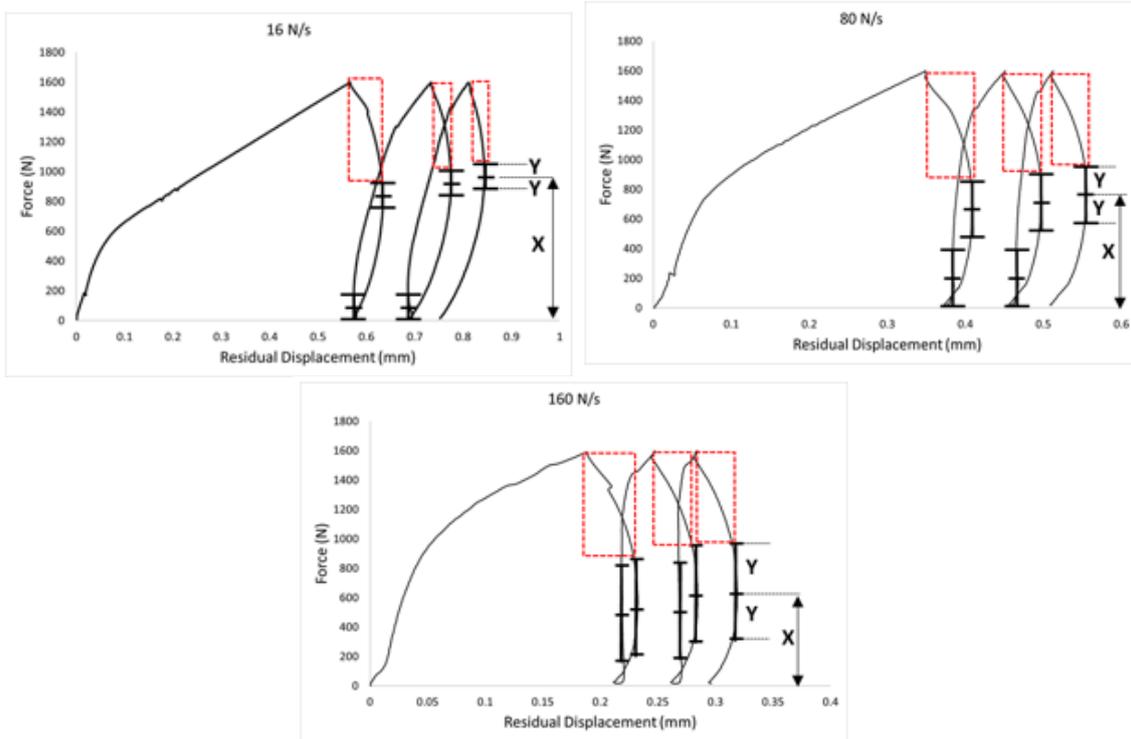


Figure 4.  $F \times l^p$  curves with different load rates (Amplitude 1600 N).

### 3.2 Modelling

Based on former mechanical characterizations from polymeric materials made by the authors (da Costa Mattos, H.S. et al, 2013) the following equations are proposed to describe the cyclic inelastic behavior of a single lap joint:

$$F = K(l - l^p) \quad (4)$$

$$\frac{dp^l}{dt} = \left\langle \frac{|F-X| - F_0}{K} \right\rangle N \quad (5)$$

$$\frac{dl^p}{dt} = \frac{dp^l}{dt} S_g; S_g = \begin{cases} 1, & \text{if } (F - X) \geq 0 \\ -1, & \text{if } (F - X) < 0 \end{cases} \quad (6)$$

$$\frac{dX}{dt} = a(p^l) \frac{dl^p}{dt} - b(p^l) X \frac{dp^l}{dt} \quad (7)$$

$$\frac{dY}{dt} = v_2(v_1 + F_0 - Y) \frac{dp^l}{dt} \quad (8)$$

The solution from the previous equations describe the mechanical behaviour of the material, mainly based on the elasto-viscoplastic model postulated by Lemaitre and Chaboche (1990) founded in the evolution law for the kinematic hardening proposed by Armstrong and Frederick (1966). Where  $K$ ,  $F_0$ ,  $v_1$ ,  $v_2$  and  $N$  are positive material constants, while  $a$  and  $b$  are positive parameters that varies with the evolution of the accumulated plastic displacement.

#### 3.2.1 Experimental identification of the constants $v_1$ and $v_2$

Through the analysis of the elastic segment from each test, its size remains approximately constant, therefore the value for  $Y$  is constant and the size of the elastic segment is equal to  $2F_0$ , where  $F_0$  is the proportionality limit obtained in a very low load rate tensile test. Thus, as no evolution of the isotropic hardening is observed, this leads to the conclusion that, for this joint,  $v_1 = v_2 = 0$ .

### 3.2.2 Experimental identification of the constants K and N

For large displacements,  $\frac{dF}{dt} \rightarrow 0 \therefore \frac{dl^p}{dt} \approx \frac{dl}{dt}$ . Therefore, for practical purposes, assuming in this paper that the limit curve can be approximated as the  $Fxl^p$  curve with the lowest load rate, and plotting in the same chart the  $Fxl^p$  curves from the first tensile load cycle with different load rates, it is possible to obtain experimentally the viscous term  $K \left( \frac{dl^p}{dt} \right)^{1/N}$  induced by the load rate in each test by a given inelastic deformation. Thereby, the preliminary values of the  $K$  and  $N$  parameters can be calculated using the least square technique in fig. 3 and fig. 4, and then corrected during the simulation using a Newton-Raphson numerical algorithm (Press, W.H. et al., 1991). Table 3 summarizes the parameters  $K$  and  $N$  for each load amplitude.

Table 3. Values of k and n for different load amplitudes.

Load Amplitude (N)	k (N.s)	N
1400 N	4000	3
1600 N	3266	2

### 3.2.3 Experimental identification of the constants a and b

Assuming the initial conditions:

$$p^l(t=0) = p_0^l = 0, \quad l^p(t=0) = l_0^p = 0, \quad X(t=0) = X_0 \quad (9)$$

As  $a$  and  $b$  can be approximated as constants, it is possible to solve the equation 9 for  $l^p$  analytically. Thus, inserting it in equation 7 considering a cyclic load-unload test executed with a very slow load rate that does not suffer viscous

effect,  $K \left( \frac{dl^p}{dt} \right)^{1/N} \rightarrow 0$ , the following expressions can be obtained:

$$F = \frac{a}{b} + \left( X_0 - \frac{a}{b} \right) \exp[-b(l^p - l_0^p)] + F_0, \text{ load } Sg = 1 \quad (10)$$

$$F = -\frac{a}{b} + \left( X_0 + \frac{a}{b} \right) \exp[b(l^p - l_0^p)] - F_0, \text{ unload } Sg = -1$$

Normally, virgin metallic samples present the initial condition shown in equation 9 as  $p_0^l = 0$ ,  $l_0^p = 0$  and  $X_0 = 0$  (da Costa Mattos, H. S. et al., 2010). Hence, this single lap joint has presented a non-zero initial kinematic hardening  $X_0 = 100N$ . This initial anisotropy seems to be common in polymeric materials and is related to the sample manufacture process.

Assuming that  $a$  and  $b$  are constants in each load and unload cycle, it is possible to identify the value of those parameters in each load or unload cycle using the equation 10 and the least square technique, as presented in tab. 4 and tab. 5. The values of  $a$  and  $b$  are very dispersive and no correlation of those parameters with load amplitudes, signal, or accumulated plastic displacement could be made.

Table 4. Values of  $a$  and  $b$  throughout the cyclic load-unload tensile test (Amplitude 1400N).

Cycle	Phase	Load Rate: 1.4 N/s			Load Rate: 14 N/s			Load Rate: 140 N/s		
		$p^l$ (mm)	a (N)	$b$	$p^l$ (mm)	a (N)	$b$	$p^l$ (mm)	a (N)	$b$
1	Load	0 - 0.5141	20000	29.8	0 - 0.1602	16500	33	0 - 0.0672	1000	300
	Unload	0.5141 - 0.5474	40000	1	0.1602 - 0.46	30000	1	0.0672 - 0.1055	18000	60
2	Load	-	-	-	0.46 - 0.2031	8000	22	0.1055 - 0.11323	70000	1
	Unload	-	-	-	0.2031 - 0.2962	30000	1	0.11323 - 0.13768	4000	200
3	Load	-	-	-	0.2962 - 0.3306	8000	9	0.13768 - 0.14594	100000	0.1
	Unload	-	-	-	0.3306 - 0.4204	30000	0.01	0.14594 - 0.1543	4000	200

Table 5. Values of  $a$  and  $b$  throughout the cyclic load-unload tensile test (Amplitude 1600 N).

Cycle	Phase	Load Rate: 16 N/s			Load Rate: 80 N/s			Load Rate: 160 N/s		
		$p^l$ (mm)	a (N)	$b$	$p^l$ (mm)	a (N)	$b$	$p^l$ (mm)	a (N)	$b$
1	Load	0 - 0.5638	4300	3.9	0 - 0.349	3600	4.5	0 - 0.2012	4300	3.9
	Unload	0.5638 - 0.7272	7000	5.3	0.349 - 0.46	8400	6.4	0.2012 - 0.2856	3000	1.5
2	Load	0.7272 - 0.8938	10500	5.4	0.46 - 0.5299	16800	7	0.2856 - 0.3348	16000	0.5
	Unload	0.8939 - 1.0107	5000	7.3	0.5299 - 0.616	2700	10	0.3348 - 0.3711	9500	34
3	Load	1.0107 - 1.1425	11800	5	0.616 - 0.6796	14500	0.8	0.3711 - 0.3954	40000	0.1
	Unload	1.1425 - 1.2237	10000	7	0.6796 - 0.7431	2000	14.8	0.3954 - 0.428	35000	81

### 3.2.4 Numerical simulation

The numerical solution of the problem is obtained using a Retuning Map algorithm in which plastic increment is given by the solution of the non-linear set of differential equations 6 to 10. Thus, using the Operator Partition method to reduce this set of equations into a sequence of initial value problems, the numerical simulation from the elasto-viscoplastic behaviour of this composite is performed through a semi-implicit integration method (Simo, J.C. et al., 1997). To include small oscillations due to the machine control that affects the material behaviour (especially rate dependent materials), the numerical simulation performed in this research used the load history  $F(t)$  obtained from the experiments that were collected from the universal testing machine load cell.

Therefore, fig. 5 presents a comparison between the numerical and experimental results from the tests with 1400 N of amplitude using the parameters from tab. 4. As can be observed, a reasonable correlation could be found between the results. Some differences are perceived mainly in the unload process due to the suddenly return of the displacement related to the accommodation of the bounded joint and to the unwanted displacement mentioned in item 3.1, which is not considered in the model. Analogously, using the parameters from tab. 5, fig. 6 presents a comparison between the numerical and experimental results from the tests with 1600 N of amplitude. As can be seen, a better correlation between the numerical and experimental results was obtained, since a smaller value of unwanted displacement was perceived in the experimental results from those samples.

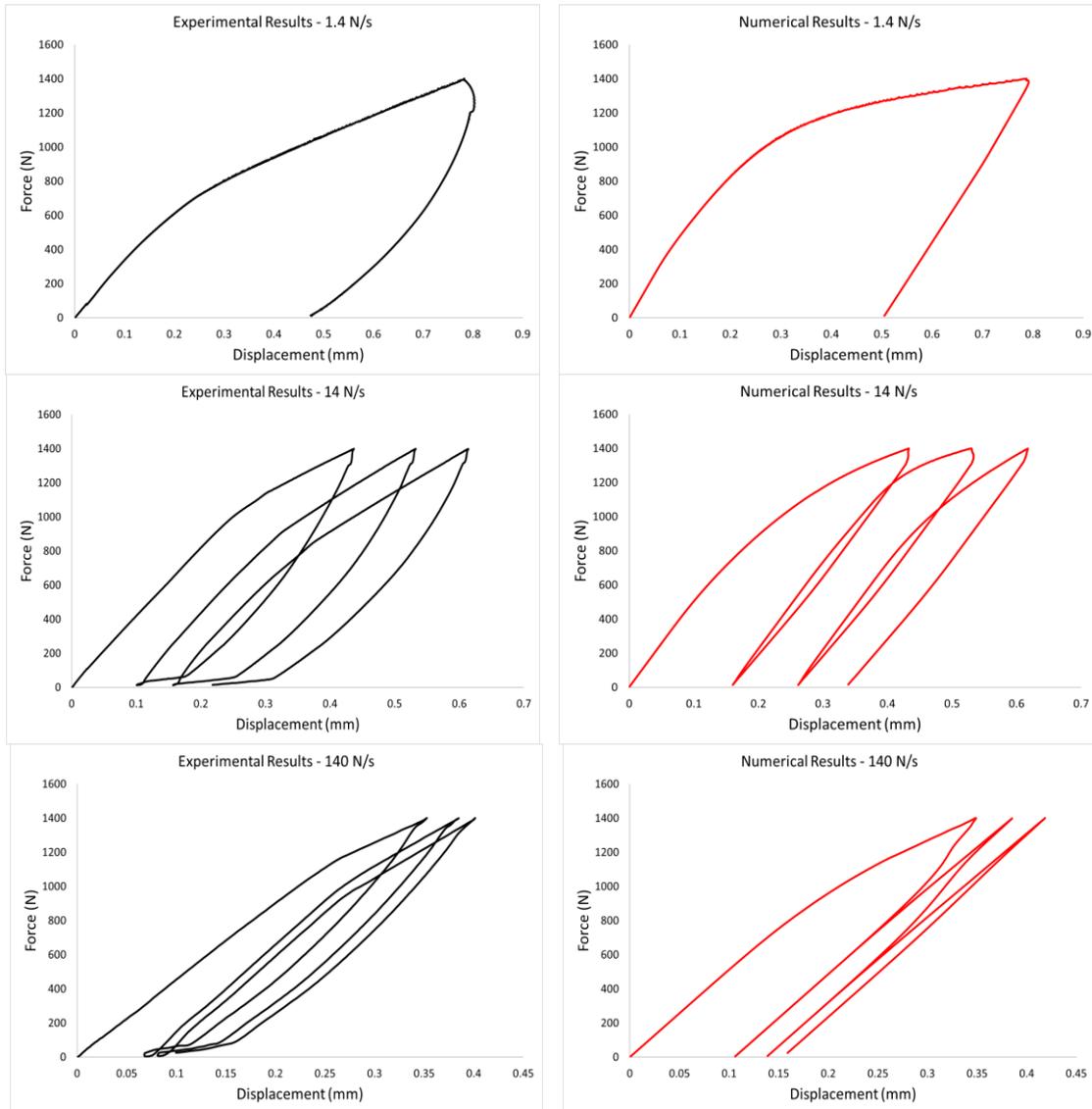


Figure 5. Comparison between numerical and experimental results (Amplitude 1400 N).

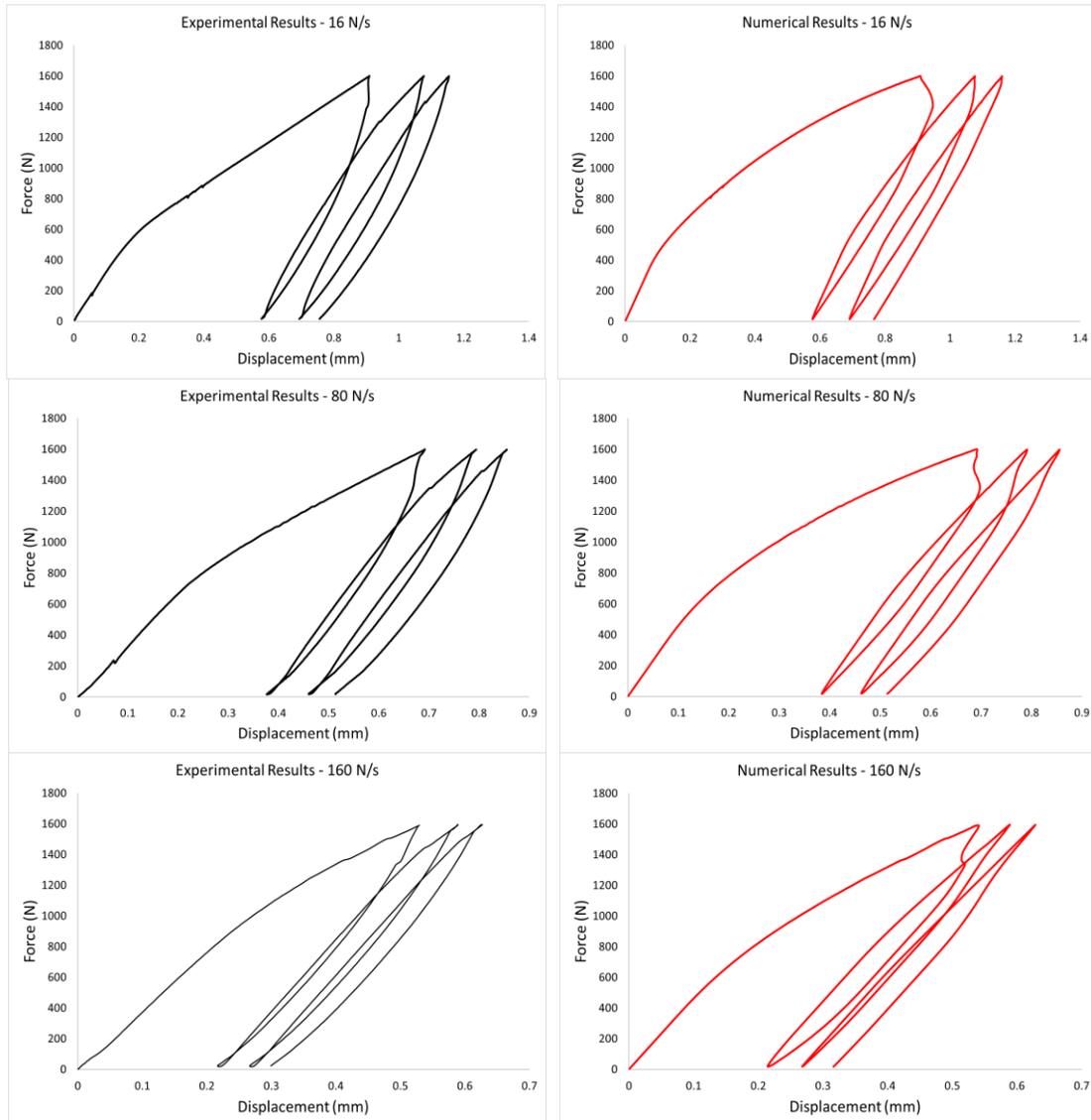


Figure 15. Comparison between numerical and experimental results (Amplitude 1600 N).

Progressive accumulation of inelastic displacement occurs even with a negative load rate, leading the sample to positive accumulate inelastic strain even in the unload process, making the specimen failure by fatigue. Consequently, this elasto-viscoplastic model can be used to estimate the cyclic behaviour of this single lap joint allowing the determination of an approximate value from the increment  $\delta p^l$  of the accumulated inelastic strain per cycle. This can be used to define a fatigue failure criterion in further studies, for example, when the accumulated plastic strain is greater than a given limit. This behavior was also seen by the authors in former researches in different polymers (da Costa Mattos, H.S. et al., 2013 and Motta, E. P. et al., 2018).

#### 4. CONCLUSION

The study presented in this paper shows that the joint studied, composed by polyurethane based composite reinforced with fiberglass, attached to an ASTM A1020 metallic surface using an epoxy adhesive, did not present a correlation between its axial stiffness and the load rate. However, its proportional limit is strongly dependent with the load rate change. This material exhibits hysteresis, which leads to accumulation of inelastic displacement. Also, the higher the load rate of the cyclic load unload tensile test, the lower was the number of cycles until failure, what leads to the conclusion that the mechanical behaviour of the single lap joint analysed in this paper is elasto-viscoplastic.

A great evolution in the kinematic hardening was noted, whereas no evolution could be seen in the isotropic hardening, which may explain the fact that positive accumulated inelastic displacement was seen even in the unload process. This behaviour was seen in former studies by the authors on different polymeric materials (da Costa Mattos, H.S. et al., 2013 and Motta, E. P. et al., 2018) enabling the full characterization of the elasto-viscoplastic behaviour from this material with

just tensile load-unload test, without the need of a fully reversed cyclic test, allowing the use of flat test specimens instead of round ones, what eliminates potentially buckling problems.

The preliminary elasto-viscoplastic model presented in this paper was able to describe the mechanical behaviour of this single lap joint under cyclic load-unload tensile tests. It was originally conceived for small strains, resulting in a non-linear system of ordinary differential equations that is capable to describe the stress or the strain of the material through an arbitrary strain or stress history. It combines enough mathematical simplicity, allowing its use in engineering problems with the capability of describing complex non-linear mechanical behaviour, such as inelastic deformation, ratcheting, strain hardening, among others common phenomenon observed in cyclic tests of polymeric materials. Basically, it is a variation on the classic Lemaitre-Chaboche model for metallic alloys, where the main difference is seen in the parameters  $a$  and  $b$ , because they are considered constants on the original equations, whereas this paper proposes that those parameters change its values according to the accumulated inelastic displacement  $p^I$ .

Although a reasonable correlation between the numerical and experimental results were obtained, the values of  $a$  and  $b$  change chaotically for each load-unload cycle, so no expression could be proposed in this paper to determine their behavior to a given accumulated inelastic displacement. This was probably related to unwanted displacement seen in the unload process and to an accommodation of the adhesive.

Another interesting remark during the identification of the parameters is that a residual anisotropic was found probably related to the material manufacturing process.

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