COMPRESSIVE FATIGUE OF CARBON/EPOXY LAMINATES: AN APPROACH COMBINING RESIDUAL STRENGTH AND SELF-HEATING

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ABSTRACT

This paper presents a novel approach for determining the compressive fatigue endurance limit of a laminate by integrating self-heating tests with a comprehensive energy dissipation model, enabling accurate identification of the energy dissipated during each cycle. On this purpose, a non-linear viscoelastic model is identified from the self-heating curves and the homogenized properties of the laminate. The resin is considered to be at the origin of the dissipative behavior, and therefore the driving force behind the damage and fatigue failure of laminates under compressive cyclic loading. The endurance limit determined through this method serves as a basis for the identification of a residual strength fatigue criterion with information of the dispersion associated with the fatigue curve. The proposed methodology is compared with experimental fatigue results.

1 INTRODUCTION

Several studies have been conducted to characterize the fatigue behavior of laminated composites [1], however, few works concern cyclic compressive loadings. On carbon fiber reinforced plastics (CFRP) submitted to cyclic loadings, due to the dissipative behavior of the resin, the temperature increases. Test standards require that the temperature rise should not exceed 10°C [2], which in practice limits the test frequencies to a maximum of 15Hz. For some aeronautical applications, industrials must estimate materials lifetimes up to 5E+8 cycles (very high cycle fatigue domain, *VHCF*), where each test run can reach a duration of 385 days under maximum recommended test frequency. A recent fatigue campaign carried under a loading ratio of R= $\sigma_{min}/\ \sigma_{max}$ =10 (σ_{min} and σ_{max} being the minimum and maximum applied stresses, respectively) has been started, to investigate the behavior of a quasi-isotropic laminate under compressive-compressive loadings (Fig. 1). Even if the data are limited to 2E+6 cycles, there is a tendency for the curve to flatten from ten thousand cycles and beyond, which suggests the existence of an endurance limit.

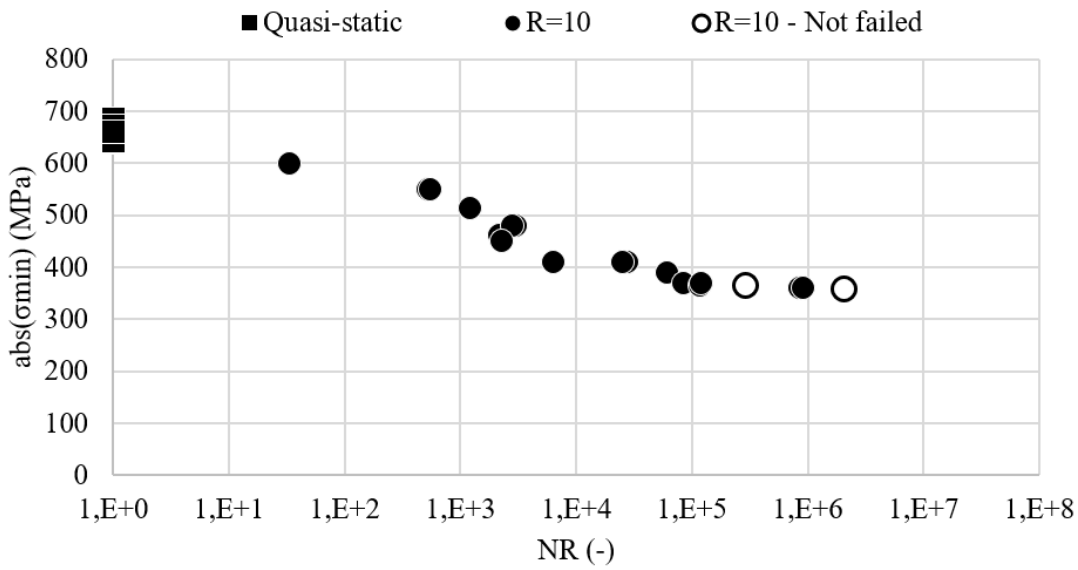

Figure 1: S-N curve of a 48-ply quasi-isotropic laminate under a R=10 loading ratio. N_R is the number of cycles to break, and the stress amplitude is represented by the absolute value of $\sigma_{min.}$

In order to provide answers on the behavior of laminated CFRP in the VHCF domain, and to reduce the duration of fatigue test campaigns, a methodology for identifying a fatigue endurance limit will be proposed in this article. In a first section, a heat build-up curve (also known as self-heating curve) will be plotted according to a detailed test protocol. The dissipative behavior will then be used to identify a non-linear viscoelastic behavior law. Via the stress threshold from which the behavior becomes non-linear, the viscoelastic law allows us to define an estimative of the endurance limit (under a given lading ratio R). In a second part, this endurance limit will be used in the identification of the parameters of a residual strength fatigue criterion [15], compared to the above presented fatigue test results.

2 MATERIAL AND TESTING SETUP

The material under investigation is a UD laminate, composed of unidirectional carbon fiber /epoxy matrix plies. The plies are of the high strength type (*HS*), pre-impregnated with epoxy resin. The laminate in question is approximately 6.6mm thick, and composed of 48plies distributed to form a quasi-isotropic stacking sequence (with a balanced and symmetrical number of fibers at 0°, 90°, 45° and -45°).

The resin is cured via an autoclave curing cycle, inside a vacuum bag. A counter plate is placed on top of the stacked plies before the vacuum is applied, in order to obtain the same post-cure surface finish on both sides of the panel. The specimens are water-jet-cut from the panels, and have dimensions of 150mm x 25mm (length x wide). Their geometry follows the recommendations of ASTM D3410 [8] standard.

Quasi-static monotonic and cyclic tests were done until sample failure, using a hydraulic tension-compression-torsion *MTS*® testing machine, with load capacity up to 250kN. Special attention is paid to the alignment of the jaws and the specimen during its installation. The test machine must be sufficiently rigid and be able to block the rotation of the jaws, so that there is no misalignment capable of inducing the buckling of the specimen during the test.

3 IDENTIFICATION OF THE ENDURANCE LIMIT

3.1 The heat build-up curve

Self-heating tests are composed of 50-cycle loading blocks, where the specimen is loaded according to the target loading ratio ($R=\sigma_{min}/\ \sigma_{max}=10$, in this case). The applied stress amplitude increases from one block to another (represented here as well by the evolution of the absolute value of σ_{min}). Through each loading block, the temperature of the specimen is measured with an infrared camera. Between them, a zero-stress step allows the specimen to cool down (Fig. 2). The last loading block is conducted to fatigue failure, close to the quasi-static failure stress. This test, like the fatigue ones, were driven in force: a sinus wave with frequencies of 2Hz or 4Hz are applied.

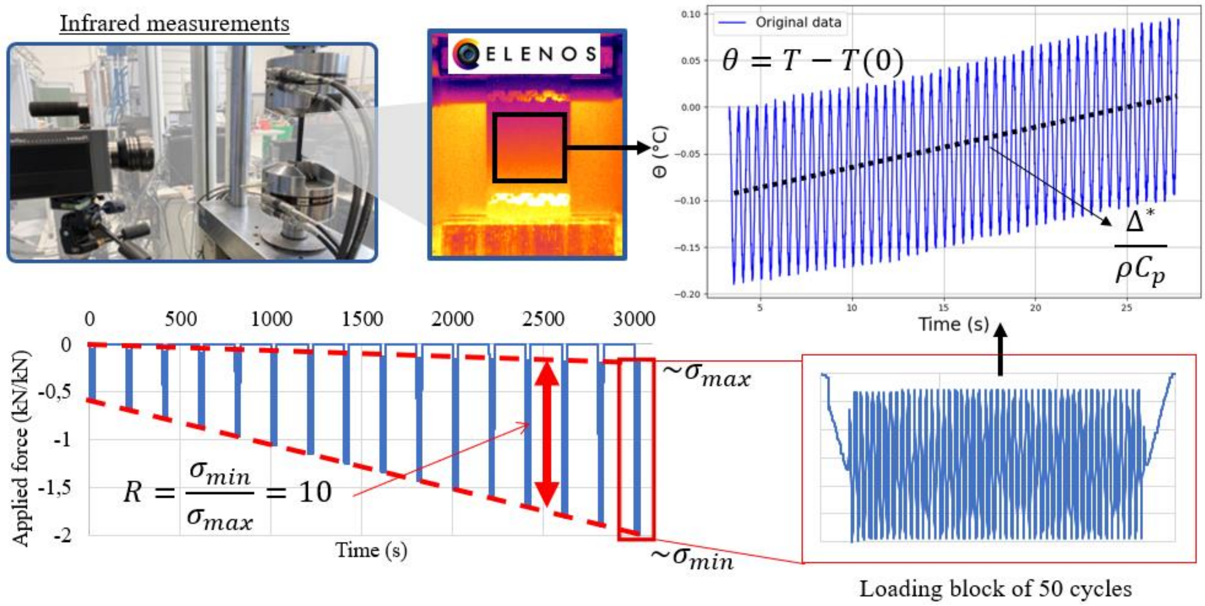

Figure 2: Self-heating test protocol.

To gain access to an intrinsic property of the material, a post-processing of the temperature signal is necessary. The heat equation is solved under a number of precautions and assumptions [10], allowing the average temperature raise observed on the surface of the specimen (θ(t)) to be related, in a simplified way, to two main terms: one depending on the average volumetric dissipated energy per cycle Δ^* (referred to as the average dissipated energy per cycle, or simply dissipation), and another that describes the temperature variations associated with the thermoelastic coupling, with an amplitude C_e (equation (1)).

$$\theta(t) = \frac{f}{\rho C_p}\Delta^*.t + C_e \sin(ft + \phi) \tag{1}$$

Where ρ is the density, C_p the specific heat, f the mechanical loading frequency, and ϕ the phase shift of the thermomechanical coupling signal with respect to the mechanical loading. The term of interest is the average intrinsic dissipation per cycle Δ^*. Graphically, it represents the slope of the mean line fitted over the specimen temperature raise (Fig. 2). This quantity is plotted against the absolute value of the minimum applied stress ($abs(\sigma_{min})$)to form a self-heating curve (Fig. 3).

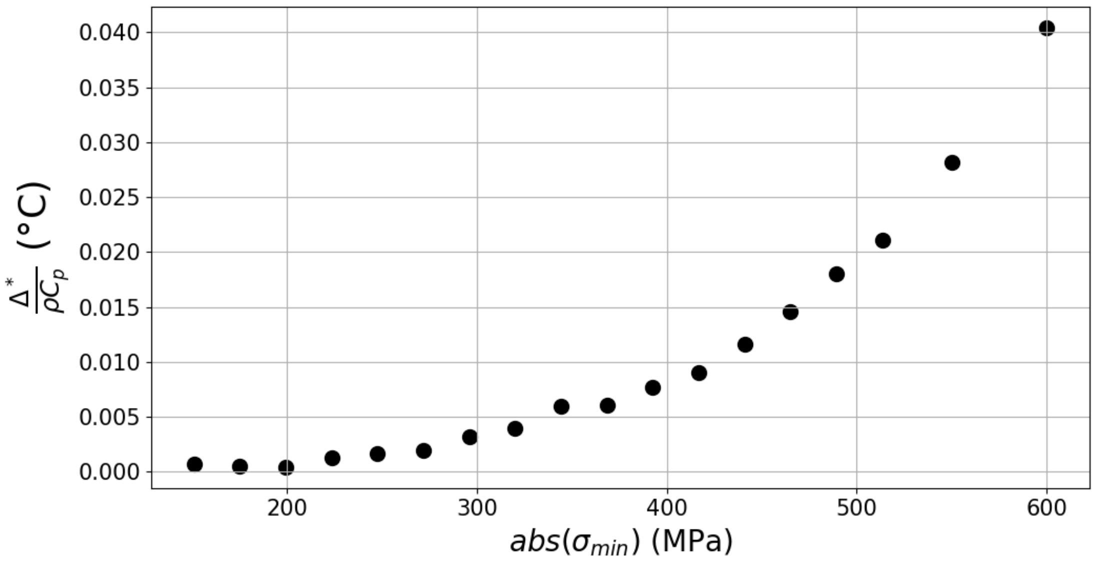

Figure 3: Self-heating curve of a quasi-isotropic laminate at R=10.

In order to link self-heating and fatigue behavior, it is necessary to relate the measured dissipation to the mechanisms leading to the fatigue failure of the material (under compressive-compressive loading in this case). A number of authors [4-7] have shown the major role of the matrix on the performance of UD plies under compressive loading. For fiber-oriented loadings, it is the local shear of the matrix that induces a micro-buckling of the fibers (also called fiber kinking), dominant mechanism under monotonic loading that leads the laminate to failure in a catastrophic manner. In the transverse direction, the failure is due to the appearance of cracks in the matrix [3].

It is possible to extrapolate this reasoning for fatigue loadings. In the fiber direction, fatigue failure can be due to a progressive damage evolution of the resin, leading to the appearance of fiber kinking after a certain number of cycles (the stiffness of the matrix decreases as damage appears, favoring the micro-buckling). In the transverse direction, the cyclic loading leads to the initiation of cracks in the matrix. Whether for stresses in the fiber direction or transversal to them, the evolution of the matrix properties under cyclic loading that can be at the origin of the laminate failure. Therefore, the aim is to track the global state of the resin by correlating it with the applied stress amplitude. Since only the matrix is responsible for the dissipative behavior in CFRP (considering the elastic behavior of fibers), the cyclic dissipation Δ^* proves to be a strong candidate to indicate this supposed evolution.

3.2 Nonlinear viscoelastic behavior law and the identification of the endurance limit

To describe the dissipative behavior of the material, a nonlinear viscoelastic law called "spectral" has been identified. This law was developed by Maire [11] in order to describe the behavior of both UD plies and a whole laminate (through the classical laminate theory). It was then adapted by Schieffer [12] to specifically describe the behavior of an epoxy resin and a UD ply by multi-scale modelling. In the present work, we use this model to describe dissipation directly on the laminate scale. It is important to note that the aim is not to model the whole multi-axial mechanical behavior of the laminate, but only its dissipation. The Helmholtz free energy potential of the material (ψ) is written according to the following equation (equation (2)). Since the macroscopic loading is uniaxial, a 1D formulation is adopted.

$$2\rho\psi = (\varepsilon - \varepsilon^{ve}).E.(\varepsilon - \varepsilon^{ve}) + \sum_{k=1}^{n} \frac{1}{\mu_k}(\varepsilon_k^{ve}.E_R.\varepsilon_k^{ve}) \tag{2}$$

The total strain ε is decomposed in an elastic portion ε^e and in a viscoelastic portion ε^{ve}. E is the Yong modulus, E_R is the relaxed viscoelastic modulus. The model is composed by a number of n 20 elementary viscous branches (n=20), each one with an associated viscous characteristic time (τ_k). This model presents two main originalities with regard to usual viscoelastic behavior laws. The first one is the way each viscous branch is defined: they are associated to a characteristic viscous time τ_k and have an associated weight μ_k, given by equations (3) and (4), respectively. The weights μ_k, associated to the characteristic times τ_k, are arranged in a gaussian distribution, bounded between n_1 and n_2 (equation (5)). This is the origin of its "spectral" name.

$$\tau_k = 10^k \tag{3}$$

$$\mu_k = \frac{1}{n_0\sqrt{\pi}} \exp\left[-\left(\frac{n_k - n_0}{n_c}\right)^2\right] \tag{4}$$

$$n_k \in [n_1, \dots, n_2] \tag{5}$$

The second originality consists in introducing a non-linear function $g(\sigma)$ (equation (8)) that is involved in the evolution laws of the viscous internal variables ε^{ve} and ε_k^{ve} (equations (6) and (7), respectively). The dissipated power, from which the average cyclic dissipation Δ^* is calculated, is given by the equation (7).

$$\dot{\varepsilon}^{ve} = g \sum_k \dot{\varepsilon}_k^{ve} \tag{6}$$

$$\dot{\varepsilon_k}^{ve} = \frac{1}{\tau_k}(\mu_k g E_r^{-1}\colon \sigma - \varepsilon_k^{ve}) \tag{7}$$

$$g(\sigma) = 1 + \gamma\left(\sqrt{\sigma . E_R . \sigma}\right)^p \tag{8}$$

$$D = \sigma . \dot{\varepsilon}^{ve} - \sum_n \sigma_k^{ve} . \dot{\varepsilon}_k^{ve} \tag{9}$$

$$\sigma_k^{ve} = \rho \frac{\partial \psi}{\partial \varepsilon_k^{ve}} = \frac{1}{\mu_k} E_r . \dot{\varepsilon}_k^{ve} \tag{10}$$

This law depends on 8 parameters: E, E_R, n_c, n_0, n_1, n_2, γ and p. For carbon/epoxy material, classical parameters describing the Gaussian spectrum of viscous branches (n_c, n_0, n_1 and n_2) can be found in Carrère *et al.* [13]. The elastic modulus E can be calculated either by the classical laminate theory with the UD ply properties, or identified experimentally in the monotonic compressive tests. The relaxed viscoelastic modulus E_R is taken on the first part of the self-heating curve (lowest stress levels) by adopting a linear viscoelastic behavior (g=1, γ=0). Finally, the coefficients of the nonlinear function (γ and p) are identified in order to describe the whole self-heating curve (Fig. 4).

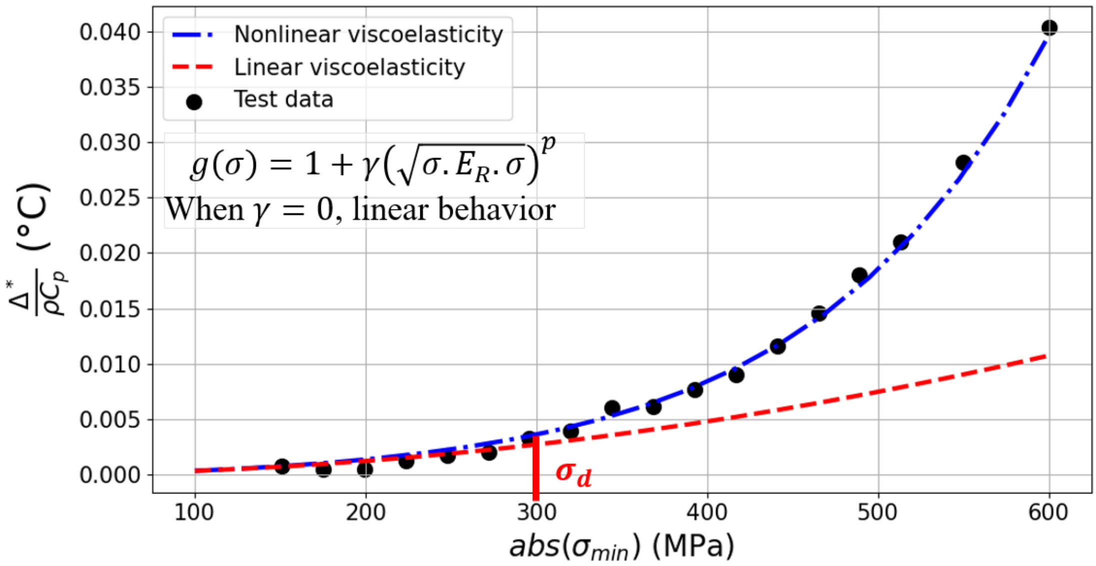

Figure 4: Identification of the nonlinear viscoelastic behavior law: contribution of nonlinearity and endurance limit.

As discussed in the previous section, fatigue life under compressive loading can be related to the damage in the matrix. The endurance limit σ_d is therefore taken at the stress amplitude $abs(\sigma_{min})$ above which the nonlinear mechanisms become non-negligible, in this case, when the dissipation predicted by the nonlinear model becomes 15% greater than the one predicted by a linear behavior (arbitrary choice). The endurance limit evaluated in this way (about 300 MPa, as shown in Fig. 4) is consistent with the fatigue data presented in Fig. 1, obtained on the same material and for the same loading ratio.

4 FATIGUE CRITERION AND COMPARISON OF THE PROPOSED METHODOLOGY WITH EXPERIMENTAL RESULTS

The previously proposed value is used in a fatigue criterion and compared to experimental fatigue data. The chosen criterion is based on a notion of residual strength, originally proposed by Sendeckyj [14] and modified by Angrand [15] to include an endurance limit. The equation (11) allows to link a couple ($abs(\sigma_{min})$, N_R) to the strength that the specimen would have had before the fatigue loading. This value is called equivalent static strength and is noted σ_e. The static strength of the material is assumed to follow a two parameters Weibull distribution, as in equation (12). The parameters identification procedure consists of determining C and S that gives the least dipersed Weibull distribution (including results from quasi-static monotonic tests and equivalent static strength from fatigue tests). In is worth mentioning that the endurance limit present in this criterion is taken based on the approach presented in the previous section.

$$abs(\sigma_{min}) = \frac{<\sigma_e - \sigma_d>}{(1-C+C.N_R)^S} - \sigma_d \text{ with } <\sigma_e - \sigma_d> = \begin{cases} \sigma_e - \sigma_d & \text{si } \sigma_e - \sigma_d \geq 0 \\ 0 & \text{sinon} \end{cases} \quad (11)$$

$$P(\sigma_e) = \exp\left[-\left(\frac{\sigma_e}{\beta}\right)^{\alpha}\right] \quad (12)$$

The parameters identification procedure is inspired by the methodology originally proposed by Sendeckyj [14], and by the work of Demilly *et al*. [16], and will not be detailed in this work. Figure 5 shows the comparison between the chosen criterion and the previously presented fatigue data. One can see that the results of the fatigue tests and the associated scattering is quite well reproduce by the present criterion. Since the endurance limit is fixed without a statistical description, the dispersion bounds tend, at the end of the curve, to the value of σ_d.

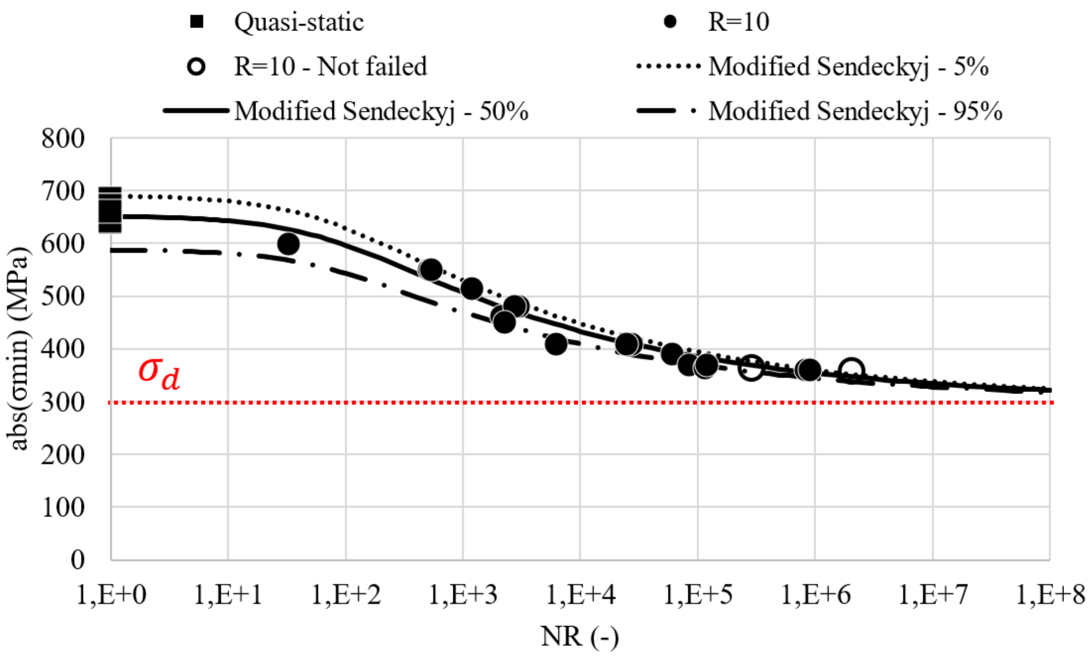

Figure 5: Comparison between the identified criterion and its endurance limit with fatigue data.

5 CONCLUSIONS

An endurance limit identification methodology has been proposed, based on the modelling of the material dissipation. For so, self-heating test were conducted in order to build a self-heating curve. This curve is modelled thanks to a nonlinear viscoelastic model. The endurance limit is defined as the stress amplitude above which it is necessary to consider the non-linearity of viscoelasticity to correctly describe dissipation. The endurance limit estimative provides a fast prediction of the capabilities of carbon fibers/epoxy laminates on the domain of very high cycles fatigue. A validation using fatigue points at 1E+7 and 1E+8 cycles shall be proposed during the conference. To better understand the transition between linear and nonlinear regimes and how this transition impacts the material lifetime, ply-scale models shall be studied, based on the work of Gutkin *et al*. [6], for example.

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