EXPERIMENTAL ANALYSIS OF TWO-LAYER COMPOSITE BEAMS

ANÁLISE EXPERIMENTAL DE VIGAS LAMINADAS COMPÓSITAS

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ABSTRACT

Composite materials play an important role in many applications from different fields in engineering practice and their use is increasing. Thus, it is convenient that in the design process, mechanical parameters are evaluated to obtain capable structures according to their purpose. The aim of this work is to study experimentally the mechanical behaviour of laminated beams composed by two-layers connected by an adhesive. Three different material configurations (steel-aluminium, steel-polymer and aluminium-polymer) and two different adhesives were considered for evaluation. The experimental results were obtained using a standard three-point bending test.

Keywords**:** *Two-layer beams; Bi-material beams; Experimental analysis; Three-point bending test*

RESUMO

Os materiais compósitos desempenham um papel importante em muitas aplicações de diferentes áreas na prática de engenharia e o seu uso é cada vez maior. Desta forma, é conveniente que na fase de projeto os parâmetros mecânicos sejam avaliados, de maneira a obter estruturas capazes consoante a sua finalidade. O objetivo deste trabalho é estudar experimentalmente o comportamento mecânico de vigas laminadas compósitas ligadas por um adesivo. Três configurações distintas de materiais (aço-alumínio, aço-polímero e alumínio-polímero) e dois adesivos diferentes foram considerados para avaliação. Os resultados experimentais foram obtidos usando um ensaio convencional de flexão a três pontos.

Palavras-chave*: Vigas de duas camadas; Vigas bi-material; Análise experimental; Ensaio convencional de flexão a três pontos*

1. INTRODUCTION

1.1.Motivation and Goal

The combination of different materials has a key role in various industries such as mechanical, civil, automotive, aerospace, naval, biomedical, and other engineering areas. There is an increasing demand for new, intelligent and multifunctional materials and composite structures are a welcoming solution for this type of requirement.

Layered composite materials, Figure 1, consist of building up a single unit by using subelements of different materials connected through shear connectors or adhesives. Several reasons justify the use of these materials, namely, the possibility of weight reduction, the need for higher stiffness and strength, enhanced fracture, fatigue and corrosion properties, and, last but not least, the cost reduction.

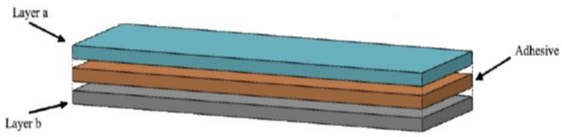

Fig 1 - Example of laminated beam structure.

Nowadays, some current examples of these material combinations can be found in several industries. In particular, the sandwich-beams, which are often used in vehicle and airplane construction, refrigeration and building engineering (Jones, 1998). The timber-concrete beams are a widely used solution in civil construction as well. The increasing use of glass and carbon fiber reinforced polymers in cars, boats and airplanes is proof that composite materials are gaining its space in engineering applications.

In certain applications, the product design requires systems that are made of more than one material. It is on these type of systems that this study will focus on, more specifically on the experimental analysis of laminated composite beams.

The goal of this research work is to extrapolate the mechanical behaviour of these structures to larger scales and different applications.

1.2. Problem Description

With the goal of studying the mechanical behaviour of layered beams, different sets of two-layered beams connected by an adhesive are considered. The experimental results will be obtained by performing three-point bending (TPB) tests. The equivalent laminated beam set will be subjected to a prescribed displacement, at the mid-span of the beam, under quasi-static conditions. The ANSYS software was a supplementary tool used in this work to define the final dimensions of the beam layers.

Three different material configurations will be analyzed, namely Steel S235JR/Alloy 5754; Steel S235JR/PMMA and Alloy 5754/PMMA. Additionally, two adhesives of different nature will be tested: epoxy resin and an insulating glue.

2. BACKGROUND IN THE EXPERIMENTAL ANALYSIS OF COMPOSITE BEAMS

Only a short amount of research works appears in the literature dealing with the experimental analysis of layered beams bonded by an adhesive.

The automotive industry has been showing an increasing interest in composite materials, with several works published in the literature dealing with this subject. An example is a work by (Avalle & Peroni, 2010), in which the authors present a study emphasizing how car body design is an important factor for the vehicle structure behaviour during a collision situation. Although it is a study focused on the impact resistance, layered materials play a key role.

Combinations of aluminium and steel materials were considered with epoxy resin adhesives. A similar study was presented in (Carlberger & Stigh, 2010), in which several bi-material configurations were tested. The authors support the use of adhesive bonded materials, based on the reduction of the assembling time and number of fasteners, as well as the design of a more resistant structure. Another experimental work was presented in (Li & Zhao & Jia, 2018), in which the focus goes into the bending deformation process of two different types of metals. Therein a composite beam was formed by two layers, one of a duplex stainless steel and another of a low carbon steel, with thicknesses of 3 mm and 8 mm, respectively. The obtained results aim to provide a reference for further forming fabrication of a bimetal composite.

The concept of sandwich beam has become quite frequent during the last years and is often a welcome solution. In the literature, several works can be found dealing with this specific type of composite beam. In such studies, each author has a distinct focus, for instance, in (Paczos & Wichniarek, 2018) the authors focus on "honeycomb" beams through analytical and experimental analysis up to the plastic regime. In (Cernescu & Romanoff, 2015) the authors focus on the analysis of sandwich beams taking into account higher-order shear deformation theories. In (Smyczynski & Blandzi, 2018) the authors develop a numerical and experimental model to translate the mechanical behaviour of a five-layer beam.

When the main focus is related to the composite beam behaviour, it is crucial to consider the bonding method used to join the layers. To do so, it is important that when these layers are bonded, certain procedures are followed to prevent the assembly collapse and to understand how the interaction between the layers affects the global structure behaviour.

Although the present work will not focus on the fracture area in specific, some studies can be found in the literature. For instance, in (Sauvage & Aufray, 2017) the authors aim to study the initiation of adhesive damage, using a substrate made of aluminium where the adhesive is glued. TPB tests were made to study this configuration. Different surface treatments of the substrate were considered to detect which produced better results. The authors explain that the substrate choice should be correctly chosen since a thick substrate increases the dispersion and a thin substrate may induce local unwelcome plastic strain.

3. EXPERIMENTAL PROCEDURE

3.1. Laminated Beam Geometry

The present study relies on the analysis and test of a simply-supported laminated beam, under a concentrated force at its mid-span, as depicted in Fig. 2. The laminated beam is composed by two layers, each one corresponding to a different material, and an interlayer (the adhesive).

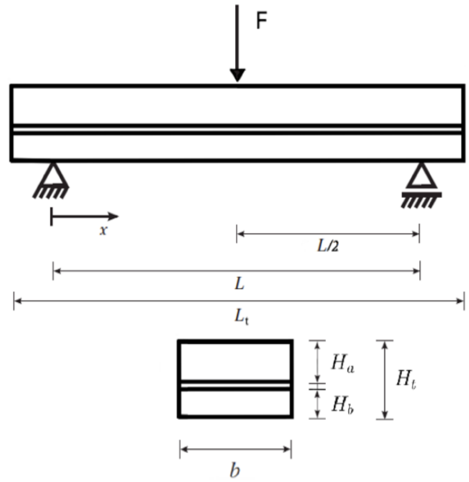

Fig 2 - Laminated beam model and its geometry.

The total beam length and the distance between the supports were taken as $L_t = 200$ mm and L = 160 mm, respectively, and a beam width of b = 25 mm was chosen. H_a and H_b indicate the thicknesses of layers a and b, respectively. H_t indicates the total thickness of the beam taking into account the adhesive layer.

Moreover, since two adhesives of different nature were used, H_{tepoxy} and H_{tpecol}, indicate the total thicknesses using an epoxy resin and a Pecol glue, respectively. These last two values were achieved by averaging the total thicknesses of three samples, considering each material configuration.

Assuming the purpose of combining different materials, Fig. 3 presents a scheme of the three material configurations that were considered.

In Table 1 are given the adopted thicknesses concerning the three material configurations (A, B, C). The values presented in the table were measured using a digital caliper. With this device also the thicknesses of the layers, H_a and H_b were directly measured. After the bonding procedure, the total thickness of the beam taking into account the adhesive layer, H_{tepoxy} and H_{tpecol}, was also registered.

3.2. Materials and their Properties

Three samples of each material configuration were obtained, specifically, samples made of Steel S235JR, Alloy 5754 and PMMA

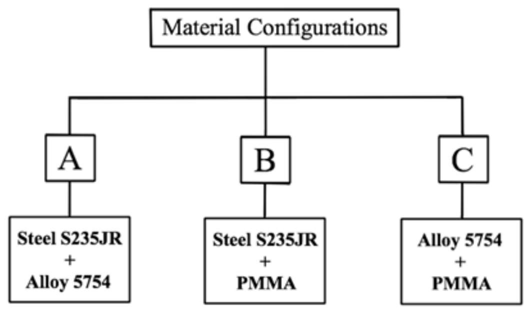

Fig 3 - Diagram of the material combinations studied.

Table 1 - Thicknesses of laminated beam sets.

Thicknesses by configuration	A	B	C
H_a [mm]	3	3	5
H_b [mm]	5	5	5
H_{tepoxy} [mm]	8.11	8.15	10.16
H_{tpecol} [mm]	8.41	8.41	10.41

materials, as shown in Fig. 4. Thus, 36 material samples were obtained to perform a total of 18 bending tests. These numbers reflect three samples of three different material configurations, with two different types of adhesive as specified next.

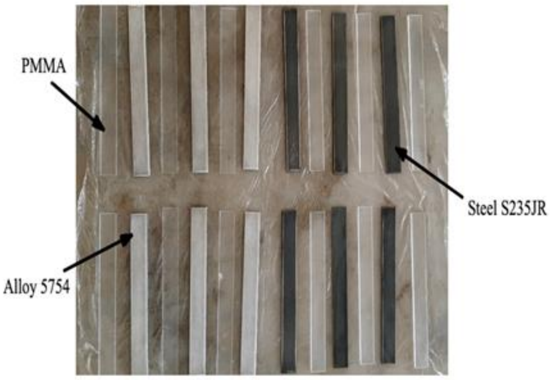

Fig 4 - Different material samples used (before bonding).

The adopted adhesives were the Sicomin epoxy resin SR 1500 (with SD 2505 hardener) and the sealant glue MSP 50 based in rubber with brand-name "Pecol", as illustrated in Fig. 5. On the one hand, epoxy resin is a thermoset, suitable for curing at room temperature. On the other hand, Pecol glue is an elastomer with drying time.

Fig 5 - Adhesives used for bonding (epoxy resin on the left and Pecol glue on the right).

Table 2 shows the mechanical properties of the three materials, namely the S235JR steel, the Alloy 5754 and the PMMA. Regarding the PMMA samples, obtained from a different supplier, their properties were taken from the catalogue provided (Madreperla).

In Table 3 are presented the properties of the adopted adhesives. Due to the non-existence of the Poisson coefficient value for the Pecol adhesive, it was assumed as ν = 0.48, which is the standard value for the rubber.

Table 2 – Mechanical properties of the layers

Mechanical Properties	Material Layers		
	S235JR	Alloy 5754	PMMA
Elastic modulus E [GPa]	210	70	3.3
Shear modulus G [GPa]	81	70	1.19
Yield strength σ_y [MPa]	235	80	76
Ultimate tensile strength σ_u [MPa]	360	210	76
Poisson coefficient ν	0.3	0.33	0.39
Mass density ρ [kg/m^3]	7800	2660	1190

Table 3 - Mechanical properties of each adhesive.

Mechanical Properties	Adhesive Materials	
	Epoxy	Pecol
Elastic modulus E [GPa]	3000	0.9
Shear modulus G [GPa]	1071.43	0.304
Poisson coefficient ν	0.4	0.48
Mass density ρ [kg/m^3]	1200	1570

3.3. Simple 2D FE Model of the TPB Beam

In this study, a 2D FE model of the three-point bending beam was developed in ANSYS, using plane 2D quadratic elements (solid Plane183), and assuming plane stress conditions. The model considers three layers, namely, two layers representing the two different materials and a third one concerning the interlayer (adhesive).

In addition, an applied concentrated force at the middle of the beam was considered. Due to the symmetry of the problem, only one half of the beam was considered in the analysis. This simple FE model was developed in order assess the thicknesses to be used in the various configurations, in order to not surpass the allowable stress limits of each material, considering the machine load capacity of 1 kN.

The adopted finite element mesh is illustrated in Fig. 6 and the obtained von Mises stresses are shown in Fig. 7. The number of elements was 6090 elements and 18953 nodes.

3.4. Three-point Bending Test

3.4.1. Samples Preparation

Before starting the bending test itself, the surface cleaning stage and the bounding between layers were performed. Firstly, sandpaper was used to scratch the surface that would contact with the adhesive of all specimens, increasing roughness and, thus, a better penetration. Secondly, pure acetone was used to clean and to deoxidize the surfaces, Fig. 8. Subsequently, the materials were bonded using the adhesives, as mentioned before.

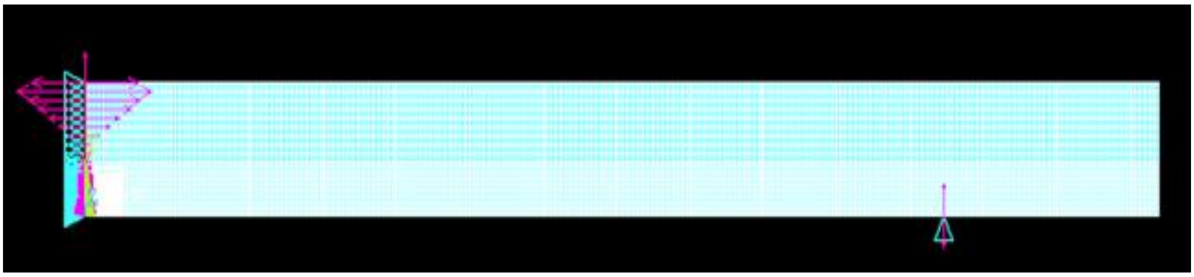

Fig 6 - Finite element mesh of the beam.

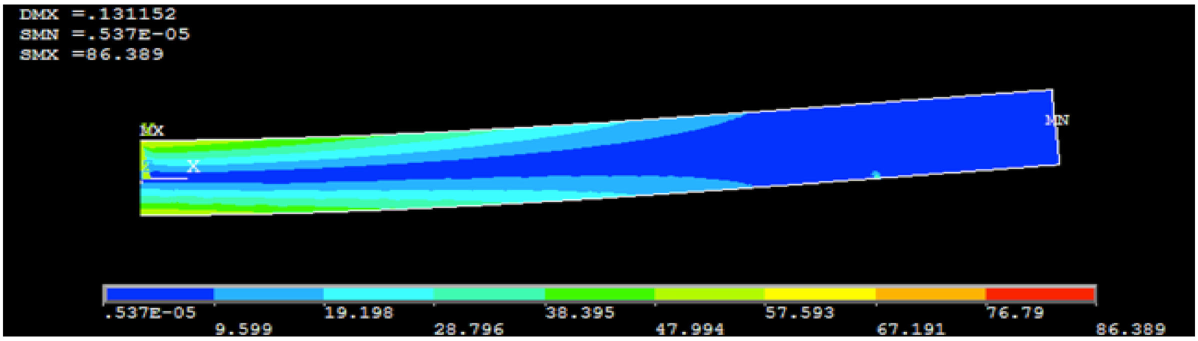

Fig 7 - von Mises stress of the beam.

Fig 8 - Samples preparation

On the one hand, it was important that each surface would be fully covered with glue, avoiding the formation of air bubbles between the adhesive and the material layers. On the other hand, there was the need to carry out the process quickly, otherwise, the adhesive would initiate its curing process, which could lead to imperfections in the final result. This is noticeable specially in the termoset epoxy, which has a lower cure time than the Pecol adhesive.

Once the bonding process was finished the samples of the same configuration (with two types of adhesives) were placed between plates, and six configurations of each type were formed with the two adhesives. This was accomplished such that the thicknesses of the beams were as uniform as possible. The cure process of the beams was carried out by using a set of weights for a period of one week, as illustrated in Fig. 9.

Fig 9 - Bonding process

3.4.2. Experimental Test

The beam properties were inserted in the TRAPEZIUM software and the bending test was performed with a constant imposed displacement rate, see Fig. 10. The chosen test speed was 0,5 mm/min, the lowest possible value to ensure the quasi-static static regime and also to minimize the non-linear viscous interaction of the adhesives. Although the main focus of the work was on the linear elastic response of the beams, the bending tests were performed up to the plastic regime. The obtained results and plots are presented and discussed in the following section.

Fig 10 - Laminated beam under a TPB test.

4. RESULTS AND ANALYSIS

4.1. Experimental Results and Plots

This section shows the experimental results for the three material configurations A, B and C. Namely, the values for the maximum displacements of the beams, obtained at mid-span, and the maximum rotations, obtained at the edge of the beams. The results refer to a nominal force value F_{nom} = 300 N, this force has been selected because it ensures that all material configurations were within the linear elastic regime.

These values were achieved through linear interpolation for the adopted nominal force and, subsequently, by averaging the obtained results of the samples. Also, their standard deviations (SD) are described.

The experimental displacements were generated directly through the TRAPEZIUM software, as when a bending test is started, a real-time plot of the prescribed mid-span displacement versus its corresponding force. In contrast, the rotation angle values were achieved afterwards through additional software, named IMAGEJ.

With the support of time, force and displacement values, it was possible to select which photo corresponded to a certain applied force value.

Then, with the angle command of IMAGEJ software, the beam rotation value was measured, as is illustrated in Fig. 11.

Figures 12, 13 and 14 give the mid-span forces versus displacements obtained on each material/adhesive configuration.

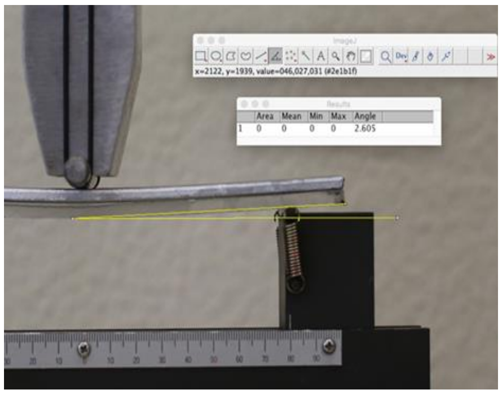

Fig 11 - Rotation angle calculation.

4.1. Analysis and Discussion of the Results

The plots in Figs. 12, 13 and 14 are provided along with the obtained standard deviations, thus reflecting the three tested samples.

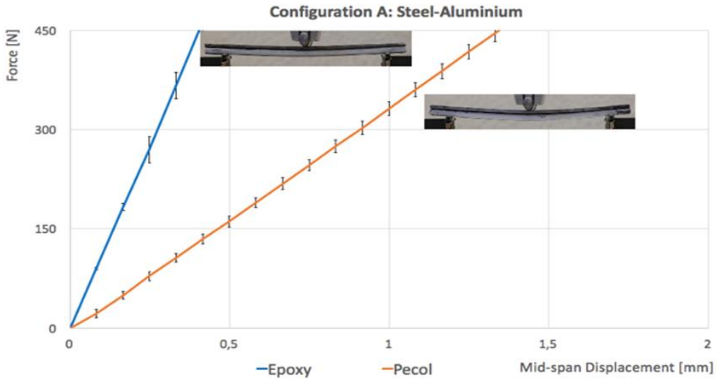

Fig 12 - Applied mid-span force Vs displacement produced in configuration A for both adhesives.

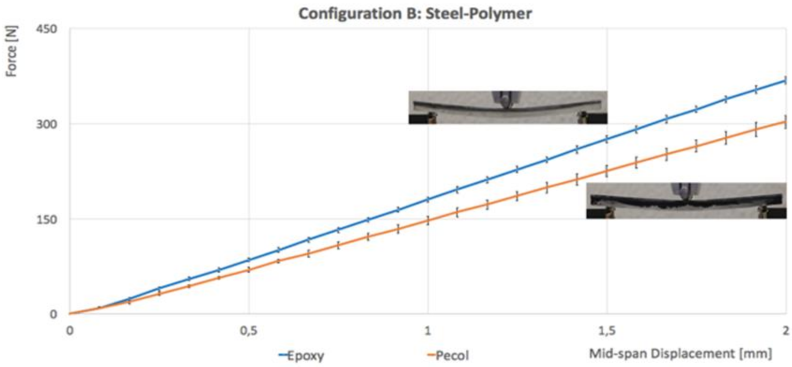

Fig 13 - Applied mid-span force Vs displacement produced in configuration B for both adhesives.

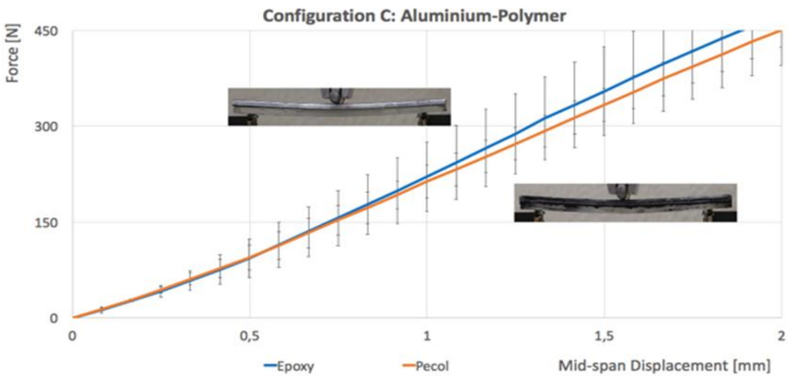

Fig 14 - Applied mid-span force Vs displacement produced in configuration C for both adhesives.

Configuration A is the case in which the difference between the slopes of the two adhesive curves was found to be larger. Being this the most rigid configuration when compared with the other two, it was the one, as expected, that led to the highest values of applied force before reaching plasticity. In contrast, the one with the Pecol adhesive achieved higher displacements values before reaching plasticity.

Note that, as expected, the standard deviations increase with the load. In this particular configuration, small deviations were observed.

Concerning configuration B, it can be observed a more similar behaviour exhibited by both adhesives, being always the epoxy resin the adhesive that contributes to a global higher configuration stiffness. It should also be noted that in configuration B, made of Steel + PMMA, present a bigger deformation when compared to the cases of configurations A and C. Likewise, this configuration also provided the highest value of the rotation angle produced at the end of the beam.

Regarding configuration C, see Fig. 14, both lines present the highest standard deviation when compared to configurations A and B, also noticeable in Table 4. One possible reason for this discrepancy can be related to the load cell reading of the testing machine. In other words, when placing a sample in the testing machine, there is the need to manually adjust the upper part of the bending device so that it remains on the verge of contact with the beam. Since this manual calibration was not properly adjusted, the load cell produced less accurate values. Since configuration C was the first to be tested, subsequently, when testing samples of configurations A and B, greater care was taken with this detail, which led to more accurate results. Besides that, it can be seen a sligtht non-linearity at the beginning, possibly attributed to PMMA. As for the standard deviations, relatively low values were obtained.

It is interesting how different values were obtained in all cases. This fact reinforces the idea of how significant is the choice of materials depending on the purpose for which a particular structure is designed.

4. CONCLUSIONS

The present work comprised the experimental analysis of bi-material beams bonded by two different types of adhesives.

Samples of three different materials were adopted, forming three different configurations, namely Steel-Aluminum, Steel-PMMA and Aluminum-PMMA. All with two different types of adhesive, namely an epoxy resin and a Pecol sealant glue.

A total of three samples were obtained for each specific configuration/adhesive in order to ensure repeatability. Some discrepancies were observed in particular in the case of the samples with epoxy adhesive. The obtained results may lead to the following conclusions:

Table 4 – Experimental results for the three configurations with each adhesive for a nominal force of 300 N.

Configuration	Adhesive	Displacement δ [mm]	SD δ [mm]	Rotation angle θ [°]	SD θ [°]
A	Epoxy	0.275	0.017	0.517	0.149
	Pecol	0.908	0.035	1.250	0.048
B	Epoxy	1.628	0.031	1.536	0.196
	Pecol	1.979	0.074	1.959	0.119
C	Epoxy	1.308	0.226	1.255	0.195
	Pecol	1.364	0.104	1.022	0.322

- In configuration A, since it is the configuration formed by the two most rigid materials, the highest force values are obtained when compared to the other configurations for the same level of deformation of the beams;
- Since the Pecol glue exhibits a higher level of elasticity, the displacement taking the Pecol as the adhesive were always higher when compared to the samples bonded with the epoxy resin;
- Since the epoxy resin has a higher bonding capacity than the Pecol glues, greater interaction between the layers in the former case was obtained as expected when compared to the latter.

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