Design and manufacturing of nano satellite frame

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Abstract. Currently, small spacecraft and their constellations are increasingly used in the rocket and space industry due to several their advantages. A version of a nano satellite frame made by a method of composite three-dimensional printing is presented in the research. A finite element analysis, a comparison of a designed structure with an aluminium analogue, and an economic substantiation of the proposed method for manufacturing the nano satellite frame have been carried out. **Key words:** nano satellite, composite, 3D printing, finite element analysis.

1 Introduction

It often happens that when designing small spacecraft, it becomes impossible to use certain design and technological solutions. This is because traditional production methods cannot provide the special set of qualities that additive technologies can give. With their help, may be create products of almost any shape and size. The application of 3D printing by composites to the manufacture of small satellite housings is an important task, since its solution will significantly reduce the costs and time for manufacturing. At the same time, there is a decrease in the mass of the structure, which implies the possibility of increasing the payload, while maintaining the total mass. There is also the next step: the manufacture of housings, assembly and launch of satellites from space stations. 3D printing with composites successfully copes with this task. This opens the way to fundamentally new versions of CubeSats. There will be no need to create spacecraft considering their launch on a launch vehicle. Consequently, this simplifies the design of the hull itself, reduces its weight, which will increase the payload and makes it more cost-effective than analogues [1]. The idea was based on the development of a nanosatellite frame for printing on orbital stations. With the proposed version of the frame design, satellites can be assembled at orbital stations. This manufacturing option will reduce the mass of the product and reduce the cost of putting satellites into orbit. To launch a satellite into orbit from a space station, it is necessary to consider the permissible deviations of geometric dimensions and shape from the specified one. Such deviations are regulated by the design specification for CubeSats. However, the specification implies a metal structure of the frame of the device. For composite construction, the tolerances may be different. The permissible size deviation can be estimated by the friction force that occurs when the composite frame of the CubeSat is rubbed against the rails

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of the deployer during removal. Significant deviations in the shape of the frame from the specified one will lead to excessive friction, which does not allow the CubeSat to leave the deployer. Therefore, it is necessary to know what reactions from friction forces can occur with geometric imperfection of the structure. Therefore, it is necessary to add contact surfaces to the model as in the deployer. For this purpose, additional rails were modelled, along which the satellite will be output. Also, the model was divided into segments for proper fiber laying. The segments will be rigidly connected to each other during the calculation.

2 Mathematical model

The calculation can be started with a displacement value of 0.15 mm. This is the tolerance for the geometric dimensions of the deployer rail in the technological documentation [2]. Having made the calculation and obtained the friction force, it is possible to choose a displacement at which there will be equality of the output force and the friction force

$$n = \frac{P_{po}}{N_f} \tag{1}$$

where P_{po} is the ejecting force of the deployer spring; N_tr is the reaction from the friction force acting on the rails of the cubesat.
When performing a linear calculation, the next step will be to increase the displacement by n times:

$$u \cdot n = u_1 \tag{2}$$

In formula (2): u is the initial displacement at whichN_f was obtained; u_1 is the resulting displacement by proportionally increasing the initial one by n times

Thus, having carried out the calculation with a new displacement; u_1, we get the critical friction forceN_{fcr}.

3 Cubesat frame structure

Based on the features and limitations of 3D printing, some changes were made to the design of the case. The panels with rails have been redesigned for more efficient laying of carbon fiber. We also had to abandon the use of pins, since they had low strength, did not work well for shear and because of the relatively small size, the print quality was unsatisfactory. The configuration of the dovetail panels has been changed. Added various fillets for more efficient printing. The physical model of the nanosatellite frame is shown in Figure 1.

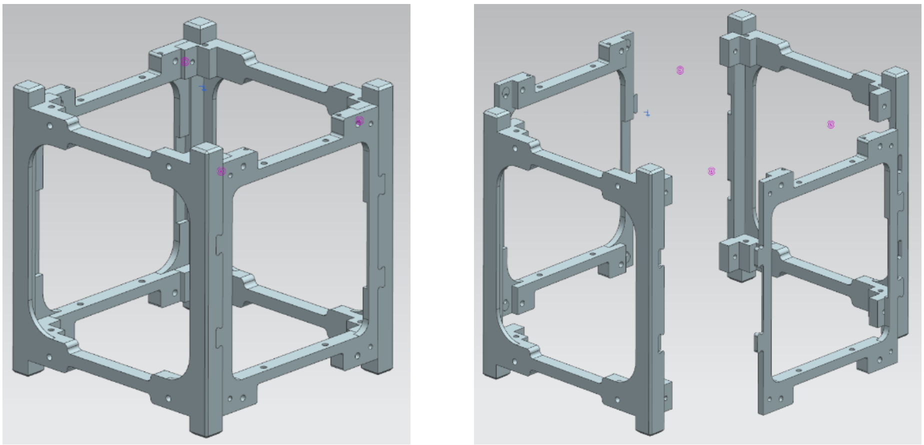

Fig. 1. Physical model of the nanosatellite frame structure.

The construction model of an analog frame made of aluminum is shown in Figure 2.

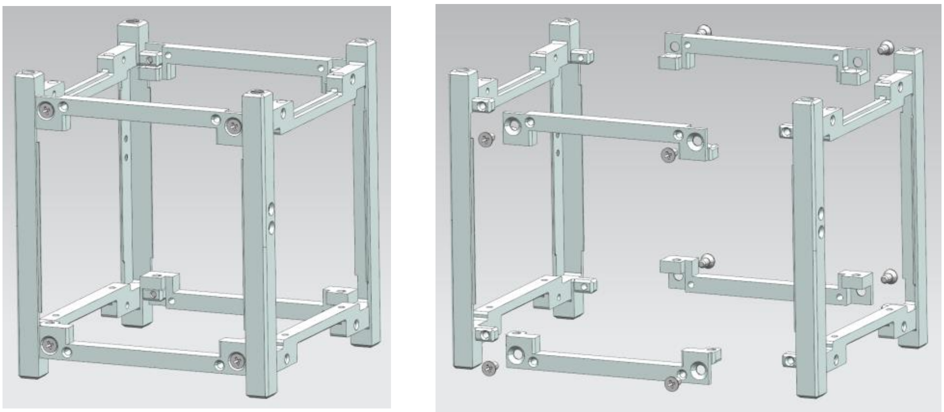

Fig. 2. Model of an aluminium nanosatellite frame.

4 Materials

For the material of the deployer rail, aluminum alloy 7075 was used, which is recommended by the developers of the CubeSat program Aluminium propertis are shown in table 1. The material of the composite parts of the satellite is carbon fiber based on a thermoplastic matrix of polyester etherketone (PEEC) and carbon fiber. For non-reinforced elements, the same plastic used as the matrix in the composite was used. The characteristics of the polymer binder are shown in table 2. Carbon fiber propertis are shown in table 3 [3, 4].

Table 1. Characteristics of 7075 aluminum alloy.

Properties	
Density [kg/m^3]	2810
Youngs Modulus E [GPas]	71.7
Shear modulus G_{12} [GPas]	26.9
Poisson's Ratio ν_{21}	0.33
Limit stress σ [MPas]	572

Table 2. Characteristics of polymer matrix

Properties	
Density [kg/m^3]	1320
Youngs Modulus E [GPas]	4
Shear modulus G_{12} [GPas]	1.47
Poisson's Ratio ν_{21}	0.36
Limit stress σ [MPas]	110

Table 3. Material characteristics of carbon fiber.

Properties	
Density [kg/m^3]	1300
Youngs Modulus E_{1+} [GPas]	50
Youngs Modulus E_{1-} [GPas]	45
Youngs Modulus E_{2+} [GPas]	4
Youngs Modulus E_{2-} [GPas]	4
Shear modulus G_{12} [GPas]	0.5
Poisson's Ratio ν_{21}	0,36
Limit stress σ_{1+} [MPas]	750
Limit stress σ_{1-} [MPas]	190
Limit stress σ_{2+} [MPas]	15
Limit stress σ_{2-} [MPas]	15

5 Calculations

5.1 Geometric imperfection

There will always be geometric imperfections in the manufacturing process of the product. It is necessary to understand what manufacturing tolerance is possible for a carbon fiber construction. The calculation for geometric imperfection was made in the Siemens Femap program. The program allows you to conduct finite element analysis of composite structures, as well as to solve contact problems. The calculation procedure is described below. The model was divided into segments in such a way that the laying of the fiber was as close as possible to the laying in a real structure. All segments were rigidly connected to each other so as not to lose the integrity of the model. A friction coefficient of 0.21 was established between the contact surfaces of the satellite frame and the deployer rails as the most suitable for such materials [5]. A gap was created between the deployer rails and the cubesat racks. The gap is 0.15 mm, which corresponds to the tolerance in the technical documentation of the developers of "CubeSat" [2]. On the satellite body itself, there is a size tolerance in three orthogonal planes: XY, YZ, XZ ± 0.1 mm. The critical deviation of the size values is achieved when deformed with a maximum displacement of 0.15 mm. This is caused by exceeding the tolerance for the dimensions of the cubesat and there is contact with all the rails of the deployer. The ejecting force of the deployer spring directly depends on the mass of the objects being ejected. Based on the recommendations of the developers of various dispensers, the buoyant force should provide a speed of 1.1 - 1.7 m/s when launching from the orbital station, depending on the mass of the satellites [6]. The output load of the spring must be at least 15.6 N to put three satellites into orbit with a mass of 1.3 kg each [7].

After calculating the friction force by formulas 1 and 2, we find the critical friction force.

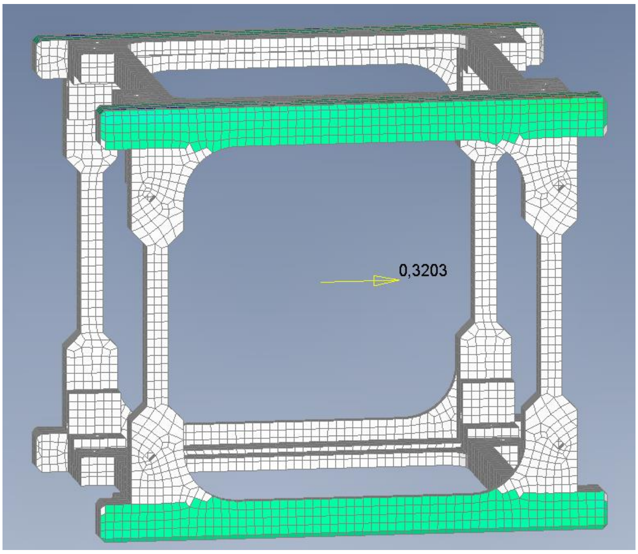

Fig. 3. The reaction of the friction force during deformation of 0.3 mm.

With a geometric imperfection of 0.3 mm, the friction force reaches its critical value of 0.3203 N. If the deformation is greater than 0.3 mm, then the structure will jam in the deployer. Thus, the structure can be operated at deformation values of less than 0.3 mm. It also follows that the use of carbon fiber as the main material of the satellite increases the operating ranges of manufacturing errors.

5.2 Modal analysis

The analysis of free oscillations was carried out in the Siemens Femap program to assess the overall rigidity of the structure and to identify shortcomings with subsequent refinement [8, 9, 10]. We will take the frequency of the aluminum frame as the base natural frequency. After applying all the boundary conditions, we will get the result of the analysis. Figure 4 shows the first natural frequency of the aluminum model.

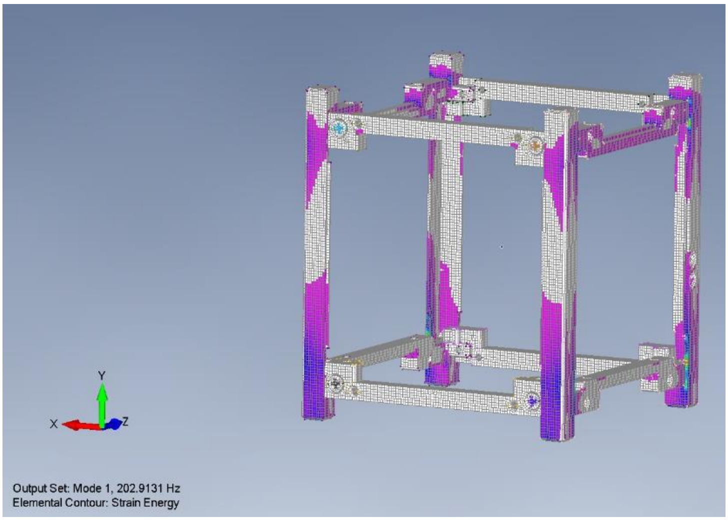

Fig. 4. The first natural frequency of the aluminum model.

The resulting frequency is 202.9 Hz. We will take this value as the base value. Next, we will calculate the carbon fiber model to compare the natural frequencies. Figure 5 shows the first natural frequency of the carbon fiber model.

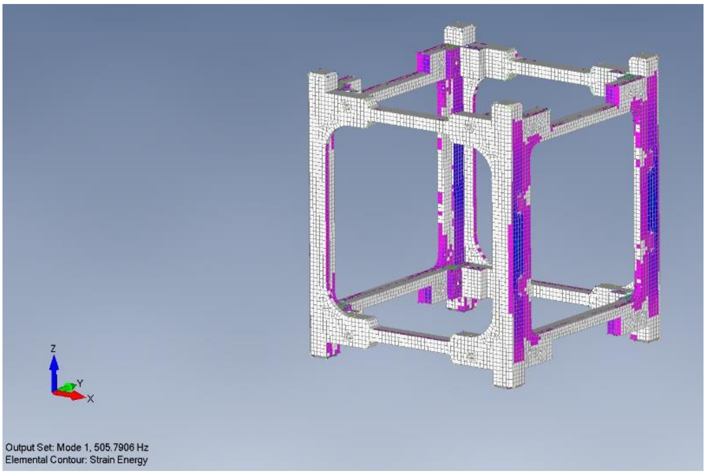

Fig. 5. The first natural frequency of the carbon fiber model.

The resulting first frequency is 505.8 Hz, which already shows that the design has a sufficiently high specific stiffness. We need the remaining frequencies to assess weaknesses in the model. To do this, the distribution of energy across the frame will help us. Some frequencies turned out to be almost equal. This is explained by the symmetry of the design. Next, data on the natural frequencies and free energies of carbon fiber and aluminum frames will be given.

Table 4. Natural frequencies and maximum normalized energies for a carbon fiber frame.

Natural frequency number	Natural frequency, Hz	Maximum rated energy
1	505.8	339.53
2	506.8	328.02
3	524.0	153.40
4	524.3	170.98
5	640.6	464.42
6	645.8	972.93
7	648.4	331.18
8	653.3	468.48
9	657.9	337.76
10	662.8	591.58

Table 5. Natural frequencies for aluminum alloy frame.

Natural frequency number	Natural frequency. Hz
1	202.9
2	221.3
3	296.5
4	360.3
5	503.6
6	503.7
7	512.3
8	512.4
9	765.2
10	868.9

In almost all frequencies, the energy was distributed evenly along the rails and some parts of the panels. The most dangerous elements were the attachment points of the payload. Therefore, they will need to be finalized. As can be seen from the tables, the first three natural frequencies of the carbon fiber frame are greater than those of the aluminum frame. The first natural frequency of the carbon fiber frame is approximately 2.5 times higher than the first natural frequency of the aluminum frame, which indicates a sufficiently high specific rigidity of the structure.

6 Experimental

The results of the analysis showed that the proposed design is suitable for operation under specified conditions. Thus, the next step is the manufacture of the proposed frame structure.

A continuous fiber laying scheme was developed for the proposed model. Examples of laying some of the word parts of the model are shown in Figures 6, 7.

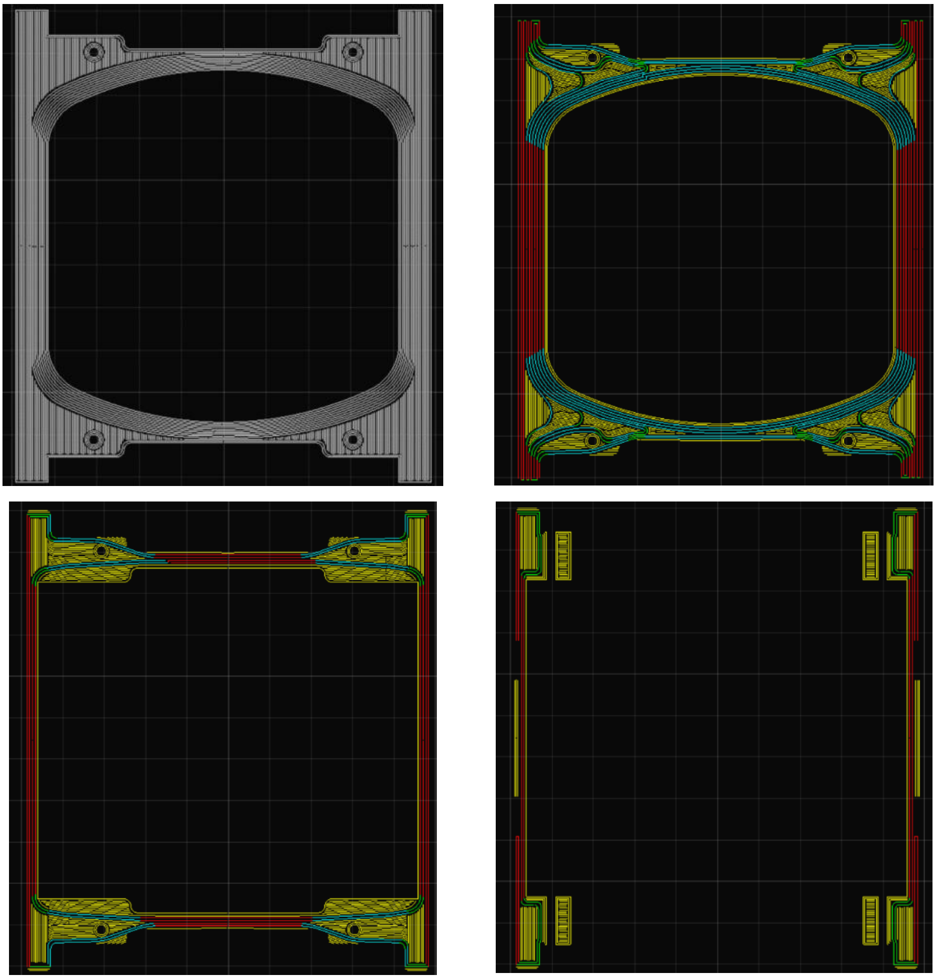

Fig. 6. Examples of layers for a panel with rails for 3D printing.

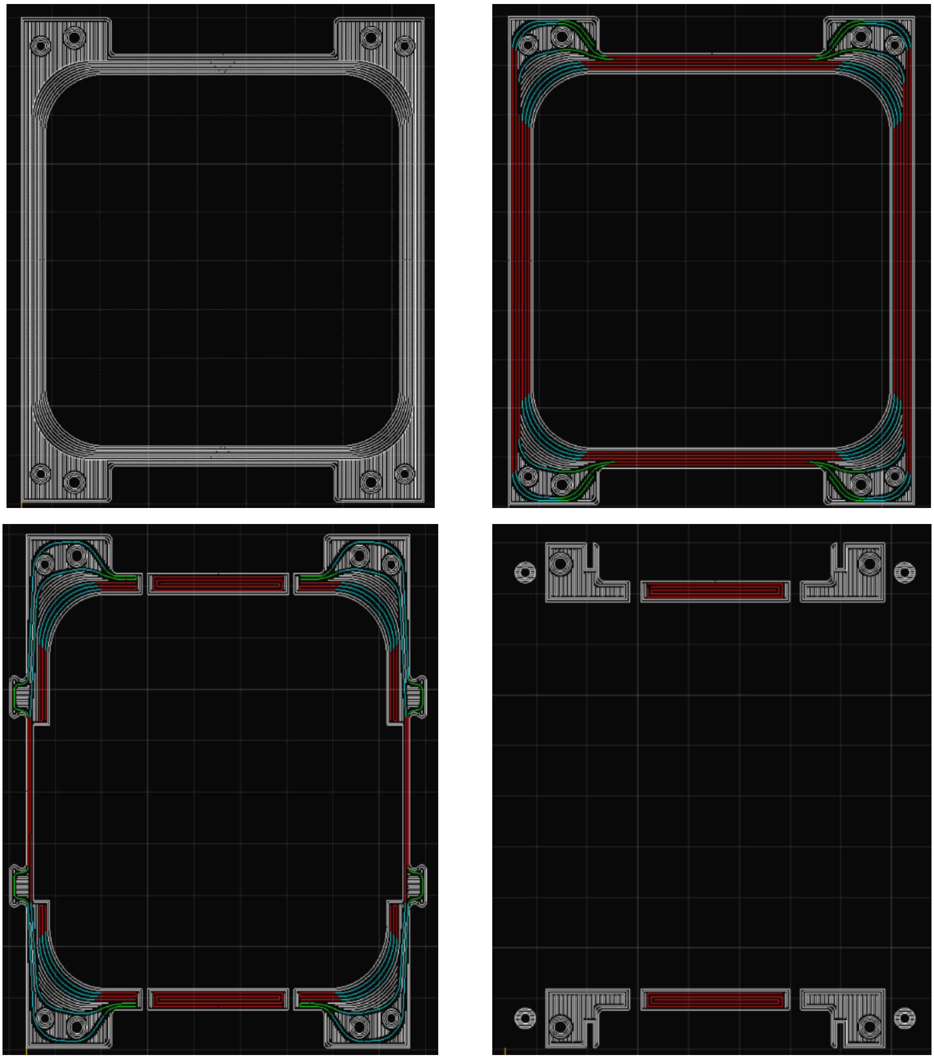

Fig. 7. Examples of layers for a dovetail panel for 3D printing.

The process of printing parts, assembling the body and installing the payload.

Fig. 8. Nanosatellite production.

Then comparative mass and economic analyses were carried out.

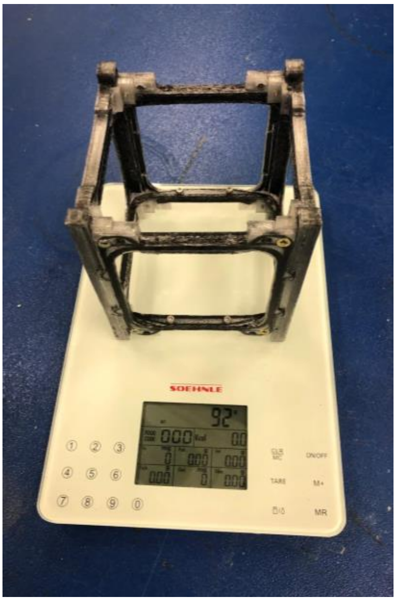

Fig. 9. Mass of the carbon fiber construction.

Fig. 10. Masst of the aluminium construction.

It can be seen from the figures that the mass of the case made of carbon fiber by 3D printing is 92 g. The mass of the case made of aluminum is 119.9 g. Therefore, the composite structure turned out to be 24% lighter. It should be noted that the design of the composite frame has not been optimized. It is possible to further reduce the mass by reducing the thickness of the panels, since the proposed design showed large reserves in rigidity. You can change the geometry of the panels, coordinating with the distribution of energy on the frame. To improve the ways of attaching both the payload and the parts to each other. You can change the printing trajectories by getting rid of excess plastic.

After conducting a comparative economic analysis, it was found that it is 3 times more profitable to produce such a frame from carbon fiber by three-dimensional printing. Therefore, it is advisable to use 3D printing technology for the manufacture of nanosatellite housings. Moreover, if we consider production in orbit, then in the future the costs will be even less. It will be possible to optimize the product, thereby reducing its weight. It will only be necessary to deliver the elements of the satellite payload and materials for manufacturing. There will be no sense in removing the deployers, which also have a tangible mass and lay large margin coefficients in the satellite design.

7 Conclusion

As a result of the work done, the following results were obtained: In the Siemens NX program, a small spacecraft body design was developed for production at the orbital station, considering 3D printing technology. A calculation was made for the geometric imperfection of the model using finite element analysis, which showed the possibility of operability of the structure in extreme operating conditions. The calculation of free vibrations of the proposed design was carried out, which showed a large margin of rigidity, compared with a similar aluminum structure. Fiber laying has been developed for the proposed model in the manufacture by 3D printing. The body of the nanosatellite was made of carbon fiber, the mass of which, when compared with an analog made of aluminum, turned out to be 24 less %. A comparative economic analysis of the manufacture of the proposed housing was carried out, which showed the feasibility of using 3D printing, at a cost less than 3 times. The feasibility of manufacturing the proposed model in orbit when installing a 3D printer on the orbital station was shown.

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