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Numerical Simulation Analysis of the Bending Performance of NC-UHPC Composite Beams

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Abstract
Using finite element software Abaqus, the ultra-high-performance concrete composite beam (UHPC-NC) was used as an example to simulate the working performance of two types of concrete when working together. By comparing UHPC-NC beams with UHPC beams, it was analyzed how to reasonably use NC and UHPC to fully utilize UHPC's ultra-high performance. By comparing UHPC beams with NC beams, the feasibility of replacing rebar in NC beam bodies was analyzed. Research results show that when the steel fiber volume content of UHPC beams is 2%, the bearing capacity can reach 72.7% of the NC beam with a reinforcement ratio of 1.5%. There is no significant difference in bearing capacity between UHPC beams and UHPC-NC composite beams, but UHPC-NC composite beams have greater economic value

Keywords: numerical simulation, ultra-high-performance concrete composite beam, bearing capacity

I. Introduction

Concrete is one of the most widely used building materials in civil engineering due to its low cost, ease of construction, significant compressive strength, and significant compatibility with reinforcement deformation. However, normal concrete (NC) has low tensile strength and poor strain capacity, limiting its application, especially when structures are subjected to shocks in harsh environments such as earthquakes, corrosion, impact, and explosions. The emergence of ultra-high-performance concrete (UHPC) has greatly improved the mechanical properties of concrete.

Ultra-high performance concrete (UHPC) is a new type of high-tech concrete with ultra-high strength, high toughness, high durability, high workability, and high volumetric stability. Compressive strength can reach over 150MPa, and tensile strength can exceed 8MPa. It has excellent crack and impact resistance, capable of withstanding large deformations without cracking. It can resist chemical erosion and physical wear, suitable for harsh environments; It has good flowability and ease of construction, suitable for various complex construction requirements; It shows minimal volume change over long-term use and is not prone to cracking.

As a new generation concrete material, ultra-high-performance concrete carries the mission of continued development in the civil engineering and construction field. Despite its many advantages, its high material price, strict construction conditions, and curing conditions greatly limit its use.

II. UHPC-NC composite beams

Due to UHPC's high cost, it has not been widely adopted. Currently, it mainly appears as locally reinforced structures or is used in composite structures with other building materials. Liu Zuqiang (2022) conducted UHPC-wrapped high-strength short column experiments, and Wei Guozheng (2024) used finite element software to analyze UHPC fully wrapped high-strength short columns. Qin Chaogang(2024) designed UHPC-RAC composite columns with UHPC and recycled concrete (RAC), improving material utilization. UHPC-RAC composite beam experiments show that UHPC-RAC composite cross-sections can improve the flexural performance of prefabricated composite beams (Qin Chaogang, 2024), while UHPC and normal concrete (NC) composite performance are rarely studied.

Based on this research gap, this study aims to investigate the bending, tensile, and shear behaviors of UHPC beams. Considering two types of concrete materials (UHPC and NC) and one UHPC-NC combination method, the finite element software Abaqus is used to simulate loading at four points of bending to obtain bending and shear failure modes, crack modes, load capacity, stiffness, ductility, and energy absorption. The working performance of integral cast UHPC beams and fully cast normal concrete beams is compared to find the optimal

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combination of UHPC and NC, seeking an effective path to reduce costs.

III. Establishment of finite element models

This paper plans to use threefinite element models, all of which are 1.6-meter-long rectangular beams with cross-sectional dimensions of 150mmx200mm. The first type is an ordinary reinforced concrete beam, with the elevation layout and cross-section shown in Figures 3.1 and 3, respectively 3（a）。 The second type is an ultra-high-performance concrete beam, all made of UHPC material, with a cross-section shown in Figure 3.3(b). The third type is a UHPC-NC composite beam, where UHPC is located in the tension zone with a height of 100mm, and NC is in the compression zone with a height of 100mm. The cross-section is shown in Figure 3.3(c).

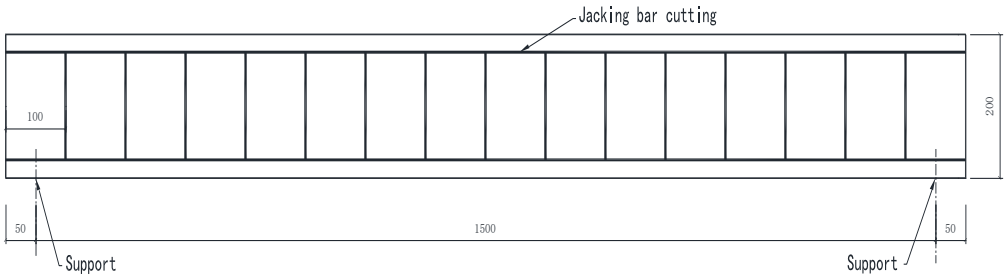

Figure 3.1 Beam Elevation Drawing

3.1 Model Building

In this study, three finite element models established with Abaqus have basic dimensions mentioned earlier. These models correspond respectively to ordinary reinforced concrete (NC) beams, ultra-high performance concrete (UHPC) beams, and UHPC-NC composite beams.

Considering that physical experiments are based on a macroscopic basis, the internal structure of materials is random and even affected by chance (such as uneven concrete mixing or incorrect weighing of material composition). Numerical simulation establishes a heterogeneous model from a microscopic perspective, which has a certain degree of stability and representativeness.Therefore, the results measured by experimental methods cannot fully reflect the working patterns of the material. This paper uses numerical simulation to study the mechanical properties of UHPC-NC.

3.2 UHPC Material Establishment

Concrete microscopic models require separate establishment of various material components (Jin Liu, 2012). XU Z et al. (2012) recommended models containing aggregates, cementitious materials, and steel fibers, while LIANG X et al. (2018) simplified the model to include only concrete matrix and fiber, achieving good simulation results. This study simulated both concrete matrix and steel fiber materials.

Steel fiber generation is done using C++, using objectarx technology and pseudo-random number methods in CAD, then imported into Abaqus to generate a 3D steel fiber model in Abaqus software. Steel fibers are selected at 2% volumetric content, with a length of 15mm and diameter of 0.2mm, using B31 two-node linear beam elements with unit size of 5mm.

Considering the interaction between steel fibers and the concrete matrix leads to a multiplied increase in computational costs and poor convergence. Therefore, it is assumed that the bonding between the two is ideal, i.e., the interaction between the two is not considered. Previous studies have shown that better simulation results can be achieved without considering the interaction (Zhao Qiushan, 2018).

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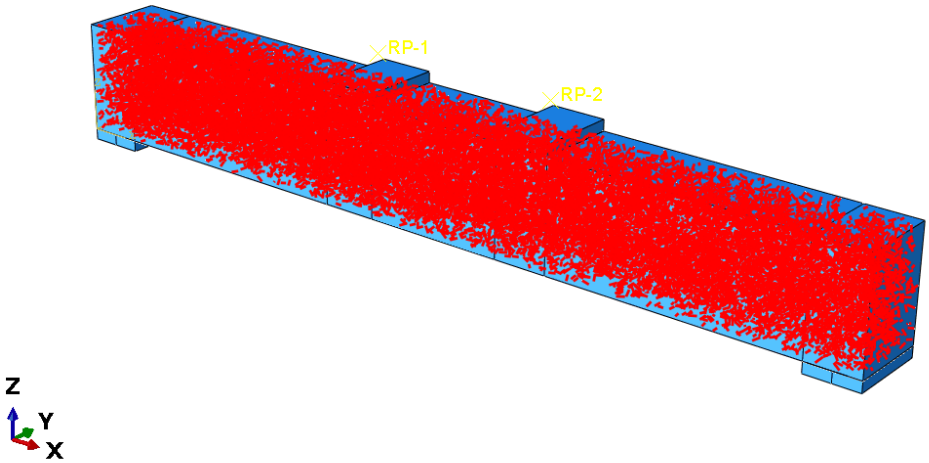
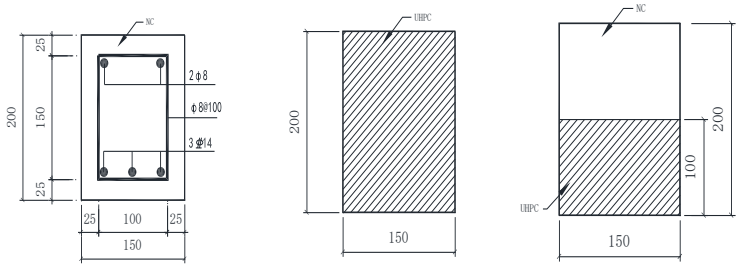


Figure 3.2 Model of steel fiber and concrete

3.3 Constitutive Relationship Between Concrete and Reinforcement

Concrete uses C3D8R three-dimensional solid elements, rebar uses T3D2 three-dimensional truss elements, with concrete units sized 25mm and rebar skeleton units sized 25mm. Reinforcement is divided into three types: tensile bars, stirrups, and erection bars. Among them, normal concrete uses C50, with three grade III bars each 14mm diameter in the tension zone to withstand tensile stress from concrete, with a reinforcement ratio of 1.5%. Stirrups and erection bars use 8mm diameter grade I rebar, which does not consider the bending effect of pure bending section upright bars, so the upright bars are cut in the pure bending section. The cross-sections of each beam are shown in the figure below:



(a) (b) (c)

Figure 3.3 Cross-sectional view

Considering that the uprights are structural reinforcement and do not participate in loading, two analysis steps are taken.The first activates the uprights to simulate the beam in its initial state. The second analyzes the uprights "killed" them, ignoring their bending effect on the beam. The stirrups and load-bearing longitudinal bars are merged into a single integrated framework using a merge command and embedded into the concrete.

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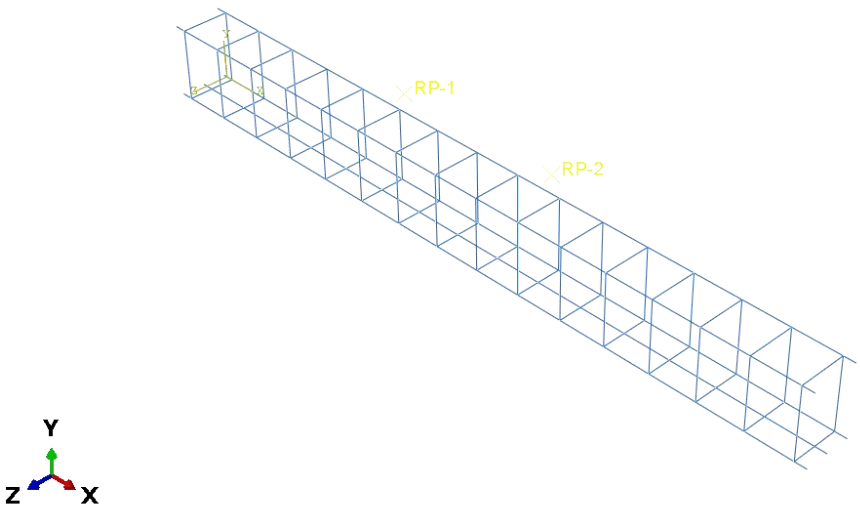

Figure 3.4 Reinforcement framework model

3.4 Interaction

The steel fiber and concrete are embedded together, and the rebar framework is also embedded with the concrete. In the UHPC-NC composite beam body, considering that UHPC is poured first and normal concrete is poured after 1-2 hours of initial setting, the two materials are connected using a "tie" method.

Because the concentrated force directly acts on the beam body, the contact area is too small, which can cause results to fail to converge or even cause errors. Therefore, a shim plate is placed on the beam body, and the load is transferred to the beam body through the shim, with a thickness of 20mm. The beam adopts a four-point bending loading mode, with the specific loading layout shown below:

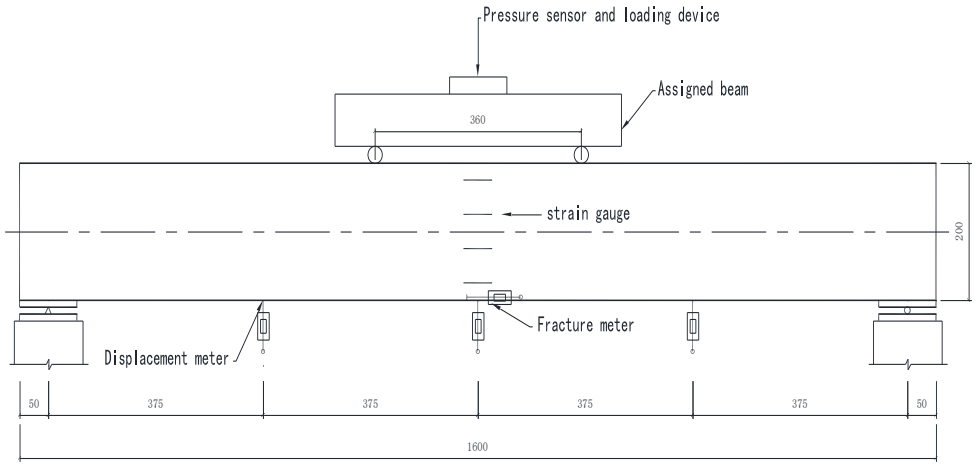

Figure 3.5 Beam loading layout diagram

In finite elements, a shim plate is arranged in the middle of the beam, with a thickness of 20mm and a spacing of 360mm. The shim plate transfers concentrated load to the beam body through "coupling," as shown in Figure 3.6.

3.5 Loads and Boundary Conditions

Each end of the beam has a fixed hinge support at the bottom, contacting the beam body via a backing plate. The beam top is subjected to concentrated load through the backing plate. Finite elements are divided into two analysis steps, both using geometric

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nonlinearity. For UHPC beams and UHPC-NC beams, constraints are defined at both ends of the beam in the initial step, and top loads are applied in step-1. For NC beams, considering that the upright reinforcement is structural rebar and does not bear bending moments, it should be cut off in the pure bending section of the mid-span. By controlling the life and death of the unit with the "model change" function, the upright rebar failure during the loading step is achieved. When a load is applied at the beam top, the pure bending section upright rebar does not bear stress in the compression zone.

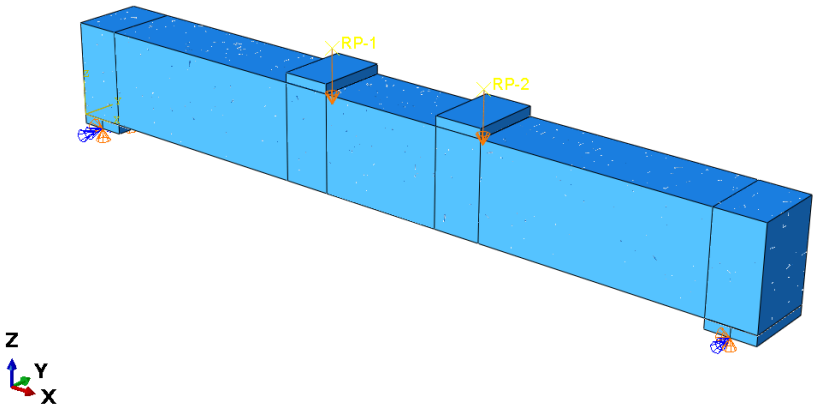


Figure 3.6 Schematic diagram of load and boundary conditions

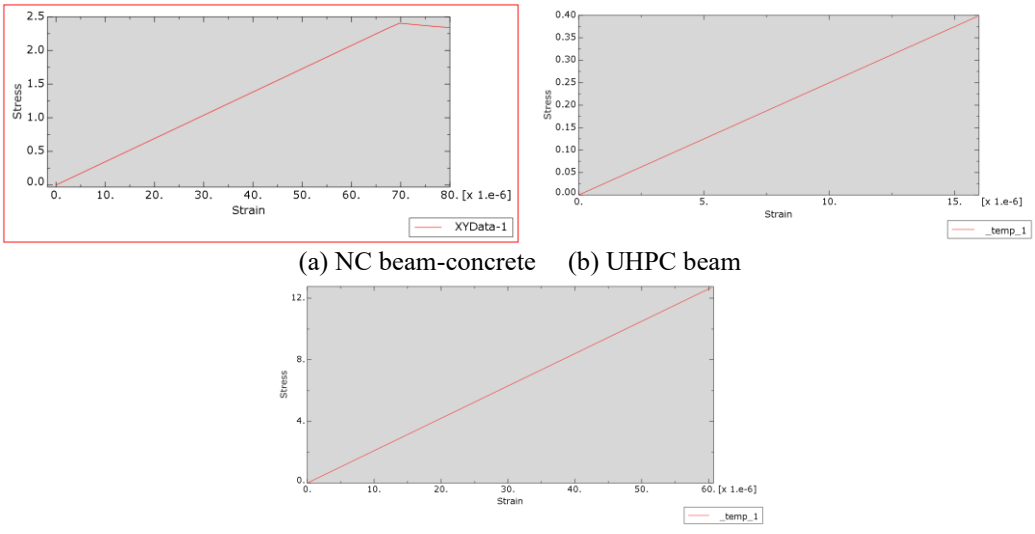
In NC beams, the first analysis step activates the erection bars to serve as structural reinforcement, simulating the initial state of ordinary reinforced concrete. In the second analysis step, the upright bars are "killed" to simulate the state where stressed reinforcement and stirrups act as the reinforcement skeleton under bending moments.

This loading causes a 10mm displacement in the direction of gravity in the pure bending section of the mid-span. The calculation results are as follows:

4.1 Comparison between NC beams and UHPC beams

When the time period is 1, the stress-strain diagram of the tensioned flange at midspan is as follows:

IV. Calculation results



(a) NC beam-concrete (b) UHPC beam

(c) NC beam - rebar

Figure 4.1 Stress-strain diagram of the tension flange

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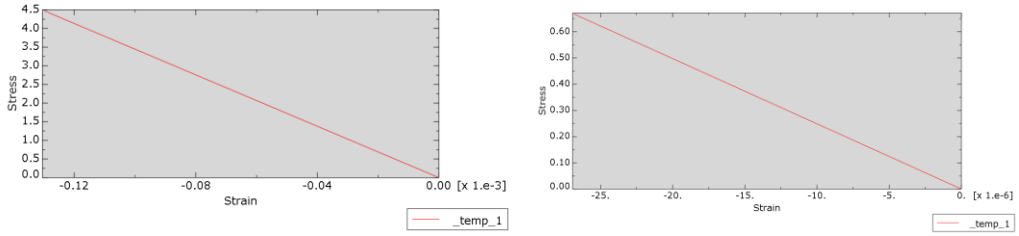
According to the calculation results, when the mid-span strain of the UHPC beam reaches 1.5×10-5mm, the corresponding tensile stress is 0.38MPa. When the mid-span strain of the NC beam reaches 1.5×10-5mm, the corresponding tensile stress is 0.52MPa, and the tensile stress of the reinforcement skeleton is 3.12MPa. At this point, the outermost NC concrete layer has reached the bearing capacity limit and is withdrawn from work, with the tensile stress borne entirely by the tensile rebar, and the stress-strain diagram shows a roughly linear distribution

According to calculation rules, when the UHPC mid-span tensile flange concrete reaches the design tensile strength of 8MPa, the tensile reinforcement strength at the center of the NC beam reaches 240MPa, which is 72.7% of the 330MPa tensile strength of the third-grade reinforcement.



(a) NC beam (b) UHPC beam

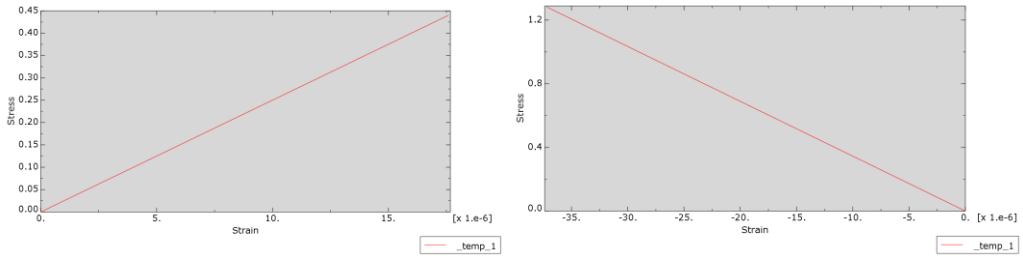
Figure 4.2 Stress-strain diagram of the compressed flange

From the stress-strain diagram of the compression zone, when the compressive flange compressive stress of the NC beam reaches 4.5MPa, the compressive flange compressive stress of the UHPC beam is 0.6MPa. When the mid-span compressive stress of the NC beam reaches the design value of C50 concrete compressive strength of 22.4MPa, the mid-span compressive stress of the UHPC beam is 3MPa, which is 2% of the UHPC compressive bearing capacity of 150MPa. Thus, the bearing capacity of the UHPC beam is based on the design value of the tensile flange reaching the tensile strength.

In summary, when the volume content of UHPC beam steel fibers is 2%, the bearing capacity can reach 72.7% of the NC beam with a reinforcement ratio of 1.5%.

4.2 Comparison of UHPC and UHPC-NC

The compression zone of the UHPC-NC beam uses all C50 normal concrete with a height of 100mm, and the tension zone uses UHPC with a height of 100mm. When the time span is 0.2, the stress-strain diagram is as follows:



(a) Tension flange (b) Compressed flange

Figure 4.3 UHPC-NC beam stress-strain diagram

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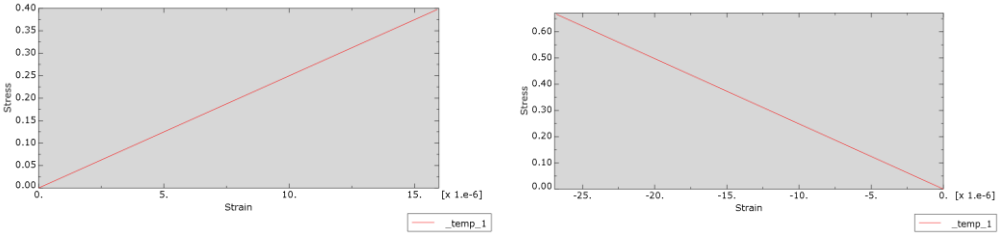
Compared to UHPC beams with a time history of 1



(a) Tension flange (b) Compressed flange

Figure 4.4 UHPC beam stress-strain diagram

In the tensile region, the main tensile stress of UHPC beams and UHPC-NC composite beams is borne by UHPC, with no significant difference in tensile performance. Failure of UHPC beams is based on cracking in the tension zone UHPC, i.e., tensile flange stress reaches 8MPa. For UHPC-NC composite beams, as shown in Figure 4.3, when the tension zone UHPC reaches 8MPa, the compressive flange NC compressive stress is 21.3MPa, reaching 95% of the design compressive strength value of 22.4MPa. It can be approximately considered that the tensile and compressive bearing capacity limits of the UHPC-NC composite beam are simultaneously reached, with the compressive bearing capacity limit slightly higher than the tensile bearing capacity, and the bearing capacity of the composite beam is still based on the cracking of the tensile UHPC in the tensile zone. Thus, UHPC beams and UHPC-NC composite beams have no significant difference in load-bearing capacity, but UHPC-NC composite beams consume less UHPC material and have greater economic value.

V. Conclusion

(1) NC beams are traditional ordinary reinforced concrete beams, and tensile stress is borne entirely by the tensile zone reinforcement. UHPC beams without reinforcement have tensile stress borne by the tension zone UHPC. Comparison results show that when the steel fiber volume content of UHPC beams is 2%, the bearing capacity can reach 72.7% of the NC beam with a reinforcement ratio of 1.5%.

(2) It can be approximately assumed that the tensile and compressive bearing capacity limits of the UHPC-NC composite beam have both been reached, with the compressive bearing capacity limit slightly higher than the tensile bearing capacity. Therefore, the bearing capacity of the UHPC-NC composite beam is based on the cracking in the tension zone UHPC.

(3) There is no significant difference in load-bearing capacity between UHPC beams and UHPC-NC composite beams, but UHPC-NC composite beams consume less UHPC material and have greater economic value.

(4) The bearing capacity of UHPC-NC composite beams is still determined by the tension zone UHPC, and the difference in bearing capacity from NC beams is roughly the same as that between UHPC and NC beams.

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