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THE ROLE OF FIBER-REINFORCED POLYMER COMPOSITES IN CIVIL ENGINEERING

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Abstract

Fiber-reinforced polymer (FRP) composite material is a relatively new material that can be used in different types of engineering. Due to its attractive mechanical properties, it has been widely used for decades. The properties mentioned enable worth-mentioning achievements in aerospace, the aircraft and automotive industries, civil engineering, sports equipment, and marine infrastructure.

FRP composites have evolved from being special materials to common engineering materials used in a wide range of applications in civil engineering. This paper covers the advantages and limitations of their use and various possible applications of FRPs in the field of civil engineering, emphasizing different opportunities for strengthening, repairing, or retrofitting reinforced concrete (RC) structures. The main aim is to highlight the importance and possibilities of using FRP composites.

The outcomes of this paper summarize the potential of this composites for continual integration into constructions, especially RC structures, as well as the obstacles that prevent designers from using this material to its full potential. This paper can be used as an overview of the main FRP properties, a source of different references in which a reader can find more detail about the mentioned polymers, and a basis for gaining basic knowledge about this kind of modern composite material.

Key words: *Fiber-reinforced polymer composite, civil engineering applications, retrofitting of structures, reinforced concrete*

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1. HISTORY OF COMPOSITES

In general, composite materials are manufactured as a combination of at least two materials, which together form a new material with improved properties.

The use of composites dates back to ancient times. In 1500 B.C., Egyptians and Mesopotamian settlers used a combination of mud and straw to build strong and durable buildings, [1].

The first composite bow was invented by the Mongols in 1200 AD. They combined wood, bone, and natural resins derived from plants and animals to form pressed bows wrapped with birch bark.

Simultaneously with the development of plastics in the early 1900s, the contemporary era of composites began. Reinforcement was needed to provide additional strength, rigidity, and durability for composite structural applications because plastics alone could not provide enough strength.

In the 1930s, Owens-Corning launched the first glass fiber, and the modern era of the use of fiber-reinforced polymers (FRP) started. In 1938, high-performance resins like epoxies became available.

World War II catalyzed many notable developments and benefits in composites. Beyond being lightweight, which was a principal in military aircraft, engineers discovered that fiberglass composites are transparent to radio frequencies. After World War II, composites were introduced into other industries.

The first carbon fiber was patented in 1961, several years before it became commercially available. In 1966, DuPont chemist introduced an aramid fiber, [2].

Over the next twenty years, composites played a significant role in breakthroughs in aerospace components, sporting equipment, medical devices, and other applications, Figure 1.

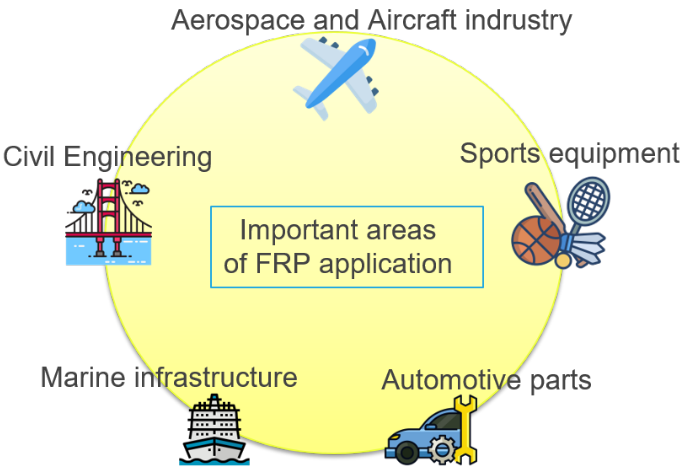

Figure 1. Fields of use of composites

The development of this material is still rising with a focus on sustainable, lighter, and environmentally friendly components.

A timeline of the history of composites is shown below in Figure 2.

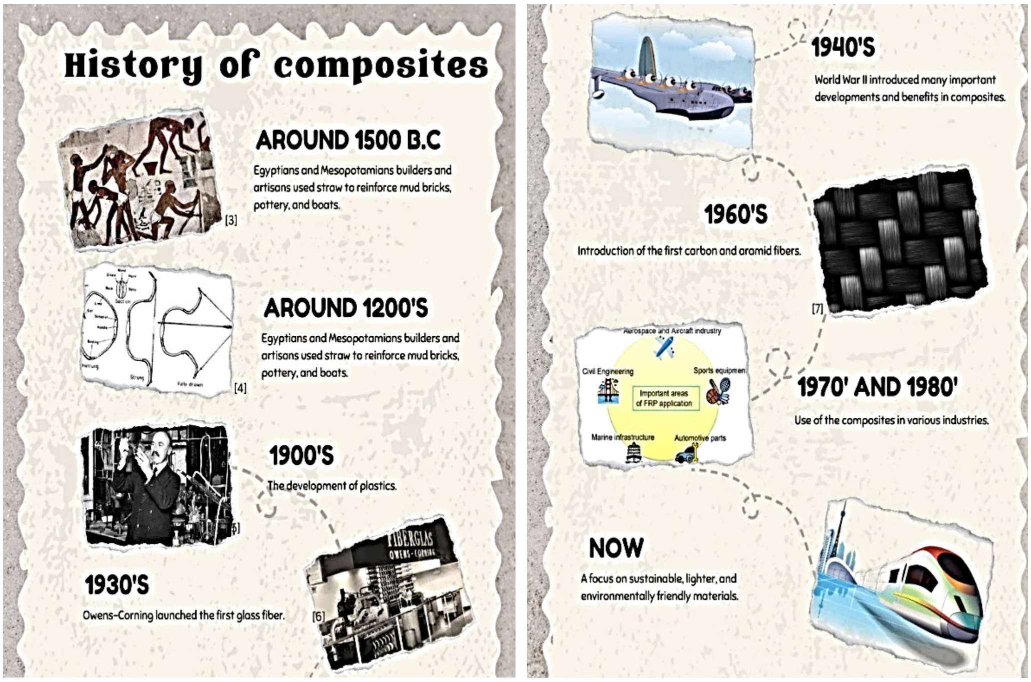

Figure 2. Timeline

2. CHARACTERISTICS OF FRPS

Fiber-reinforced polymer composites are made of two components: thin fibers that are embedded in a specific matrix (metal, ceramic, or polymer), [8], Figure 3. Epoxy resin is a widely used polymer matrix in FRPs. It is characterized by notable adhesive properties along with its strengthening ability. The matrix holds fibers together in order to form the desired shape. Different types of fibers improve the mechanical properties of the matrix, [10]. There are three main types of fibers (glass, carbon, and aramid) whose combination with epoxy resin results in glass (GFRP), carbon FRP (CFRP), and aramid FRP (AFRP). The behavior and characteristics of FRP composite material vary depending on the type of fiber and matrix, [11]. Typical stress-strain relations for different FRPs compared with the relation mentioned for steel are shown in Figure 4.

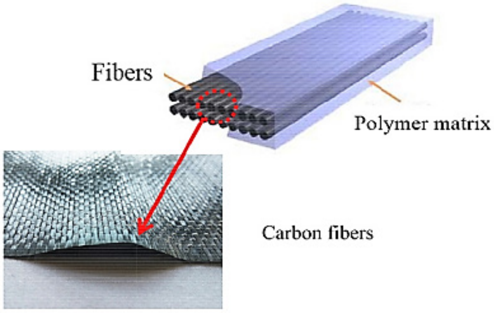

Figure 3. FRP composite material, [9]

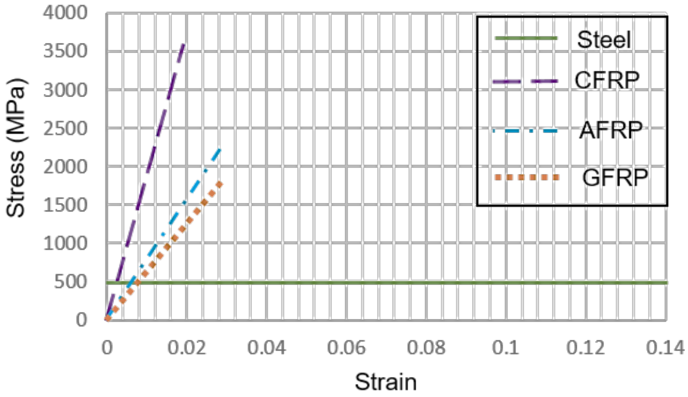

Figure 4. Comparison of stress-strain relations, modified from [11]

2.1. Benefits of FRP composites

FRP composite material has superior properties over its individual components or traditional engineering materials such as steel, aluminum, copper, etc. The main advantages that make them suited for a wide range of applications are, [12]:

- High specific strength
- High specific modulus
- Lightweight
- Good corrosion resistance
- Improved fatigue and impact resistance
- Easy to transport and install

These composites can be used for demanding applications without substantially increasing weight. Great corrosion resistance is one of the reasons for the longer service life of FRP applications. The longevity of FRP products provides cost savings over the product's life cycle. Also, its use reduces the need for heavy maintenance like sandblasting, scraping, and painting.

Composite materials provide worth-mentioning insulation because of their low thermal conductivity; thus, they perform well in different environments, from subzero to high temperatures, [13].

2.2. Limitations of FRP composites

Regardless of the various advantages of FRP composite material, there are a number of disadvantages that limit its use in different areas:

- Its strength perpendicular to the fibers is extremely low in comparison with the same one along the fibers
- Generally brittle behavior with a linear elastic response in tension up to failure
- High initial cost
- The design, manufacturing, and testing of FRP components should be highly specialized
- Low long-term temperature resistance

FRP composites are orthotropic materials; thus, the mechanical behavior of the materials is different in two directions. The material is very strong and stiff parallel to the fibers, but perpendicular to the fibers, the strength can only be attributed to the specific resin.

These composites are brittle, and failure occurs when tensile strength is exceeded. The absence of ductility is one of the main concerns when using FRPs.

The initial cost of products using FRPs appears to be higher, but reduced labor and transport costs and an extended structural lifetime increase savings compared to using conventional materials.

In general, the strength of FRPs decreases significantly above 50°C; thus, they cannot be used at high temperatures for a long time. In the case of high-temperature-resistant resins, the strength of FRPs can be stable for a long time at 200-300 °C.

3. USE OF FRP COMPOSITES IN CIVIL ENGINEERING APPLICATIONS

FRP composites enable important achievements in the functionality, safety, and economy of construction. The use of FRPs in civil engineering has evolved slowly from a special material to a common engineering material used in a wide range of applications, [14]. Due to their attractive characteristics previously mentioned, these composites have become significant materials in the construction industry as alternatives for internal or, more frequently, external reinforcement and for retrofitting and strengthening structures.

Despite the fact that these composites can be used in different civil engineering applications, they are most often used for retrofitting, repairing, and strengthening various structures.

It is known that "retrofitting" means strengthening and/or repairing load-bearing structural elements in existing structures, [11]. "Strengthening" is the first type of retrofitting that includes upgrading the structure’s initial strength or ductility in order to account for new levels of loading. Otherwise, "repairing" means restoring the original, initial load-carrying capacity, Figure 5.

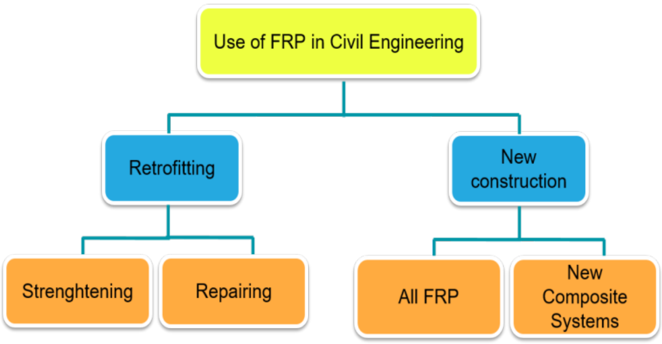

Figure 5. Use of FRPs in civil engineering applications

This paper covers FRP retrofitting of RC structural elements more in detail and highlights its main properties.

3.2. FRP retrofitting of reinforced concrete elements

Traditional seismic retrofitting methods do not always provide reliable solutions, so FRP composites are the present durable retrofitting solution. In addition, with their reduction in cost, installation without worth-mentioning disturbance to the functionality of buildings, and increased need for strengthening structures, FRP strengthening systems have become one of the most effective methods for strengthening.

It is known that these composites can be applied in various ways for strengthening beams, columns, beam-column joints, slabs of buildings, and bridges. They are available for strengthening and/or retrofitting in many forms, including sheets and wraps, laminates, and less often strings and bars, [14], Figure 6.

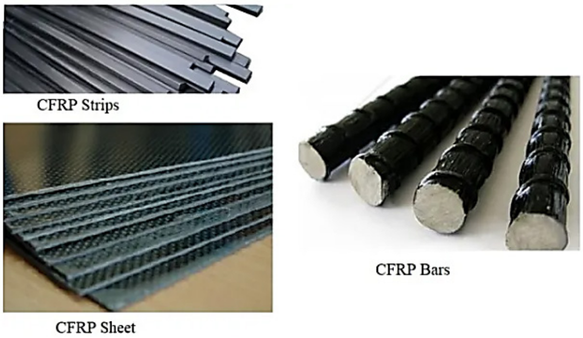

Figure 6. Examples of different forms of FRP composite (CFRP), [15]

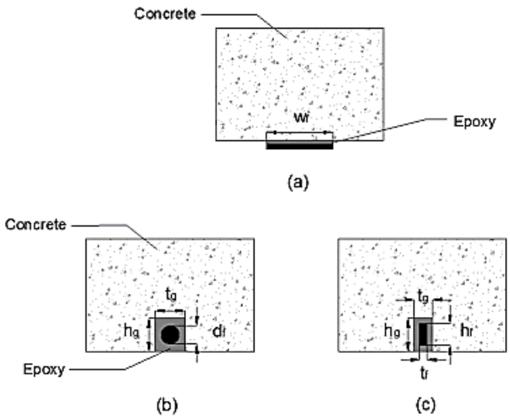

Figure 7. FRP strengthening a) EBR FRP plate or sheet; b) NSM FRP rod or bar; c) NSM FRP laminate or strip, [16]

It is recognized that there are two main ways of strengthening systems: the external bonding reinforcement (EBR) method and the near surface mounting (NSM) method. First, FRP sheets or wraps are used as an external strengthening method for enhancing the flexural, shear, torsional, and/or axial capacities of reinforced concrete structural elements. Additionally, it can increase the confinement, stability, and ductility of elements, [11]. Section wrapping using FRP sheets has become an effective and common way of performing seismic retrofitting. Second, the NSM technique is an appealing method that is based on applying a specific adhesive and laying FRP bars, rods, or strips into pre-cut grooves in the concrete cover, Figure 6. This method developed as a consequence of one of the main drawbacks of applying external bonding reinforcement due to debonding between FRP and concrete.

3.2.1. Near surface mounted technique for FRP reinforcement

FRP reinforcement is installed in specific grooves that have been prepared previously (desired depth, width, spacing in the concrete cover, cleaned, and filled with adhesive material), [16], Figure 8.

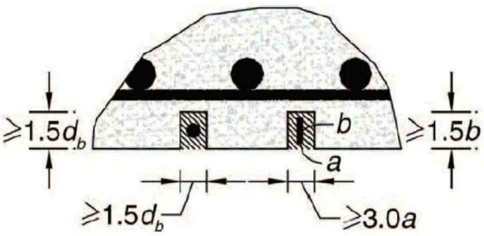

Figure 8. NSM FRP reinforcement applied in the concrete cover, [17]

The NSM technique can be used as an effective and successful method for flexural and shear strengthening of RC structural elements, Figure 9.

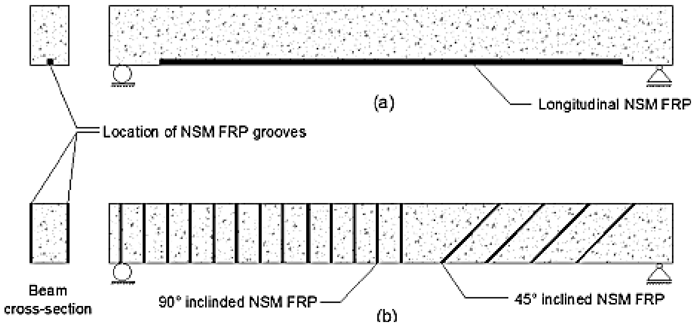

Figure 9. FRP strengthening of beam using NSM technique, [16]

This retrofitting method does not require considerable surface preparation except for the grooving mentioned. It is one of the main benefits of this technique. Furthermore, the installation of FRP reinforcement using this system is independent of the surface tensile strength of the concrete. It provides notable anchorage capacity due to the larger bond surface and reduces installation time. The use of the NSM system requires a relatively large cover depth, which is not so common in older, existing structures, [14]. It is the worth-mentioning limitation of the system mentioned, and the reason for the widespread use of externally bonded retrofitting techniques.

3.2.2. External bonding FRP reinforcement

The most common system for FRP retrofitting structural elements is external bonding of FRP sheets, wraps, laminates, or bars. They can be installed in various ways in order to enhance, increase, or restore the flexural and/or shear strength of elements (for example, RC beams). Furthermore, they can be used to increase the axial strength, ductility, and energy dissipation properties of RC columns.

The procedures for FRP installation for the RC members are shown below:

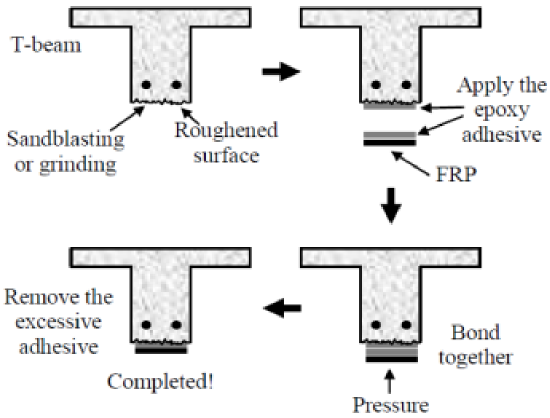

Figure 10. Procedure of external bonding retrofitting technique, [18]

Various failure modes are described in the following table, [18], and Figure 11:

Table 1. Different failure modes of FRP strengthened elements

Failure modes	Description
Concrete crushing	If premature failures are prevented, the ultimate flexural capacity of the member is reached when either the FRP composite fails by tensile rupture or the concrete crushes in compression.
FRP rupture	
End cover separation	Failure of the concrete cover is initiated by the formation of a crack at or near the plate end due to high interfacial shear and normal stresses caused by the abrupt termination of the plate.
End interfacial separation	This debonding failure is initiated by high interfacial shear and normal stresses near the end of the plate that exceed the strength of the weakes element (concrete or epoxy).
Flexural crack induced debonding	Flexural crack induced debonding happens when the concentrated bond stress at the crack location exceeds flexural strength.
Shear crack induced debonding	Shear crack indued debonding occurs in the zone where both shear and bending moment are significant. It is caused by the combination of two mechanisms. The first one is similar to that of flexural crack induced debonding. The second is by the vertical movement of the inclined crack.

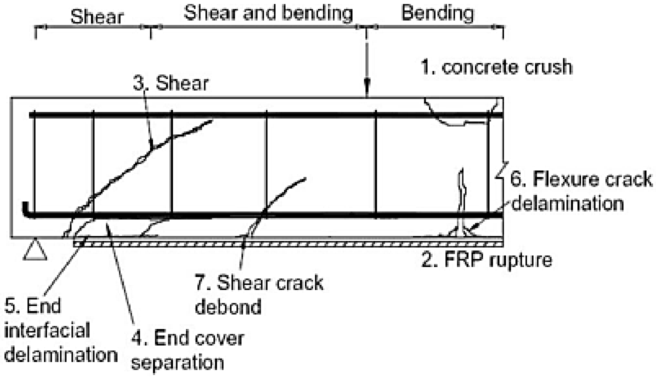

Figure 11. Different failure modes of FRP strengthened elements, [18]

Flexural and shear FRP external applications are described in detail below.

- Flexural and shear applications

The flexural strength of RC structural elements can be upgraded, or restored by different FRP schemes, Figure 12.

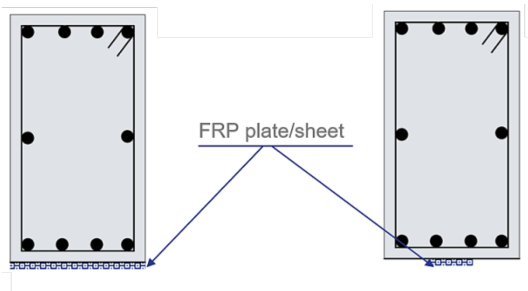

Figure 12. Use of FRP for flexural strengthening

The strengthening at the soffit of the beams is shown below.

Figure 13. The application of flexural strengthening, [20]

Figure 14. The application of flexural strengthening, [21]

The way of strengthening of RC one-way and two-way slab is shown in Figures 15 -16. FRP strips are inserted to the soffit along the required direction or directions in the case of two-way slabs, [22].

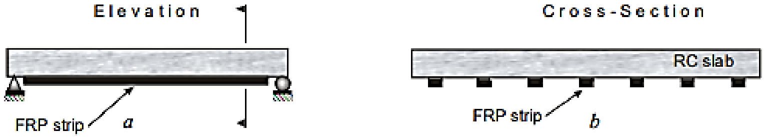

Figure 15. One-way slab strengthening, [22]

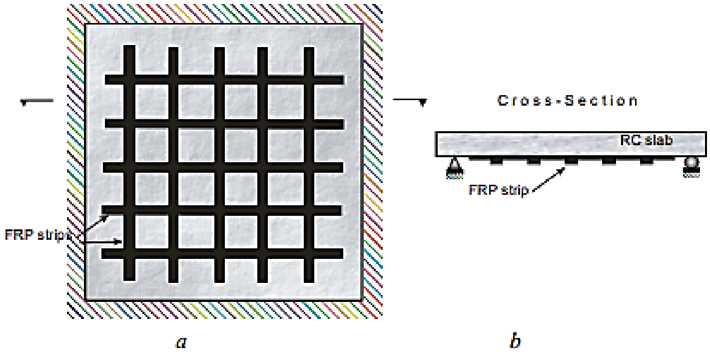

Figure 16. Two-way slab strengthening, [22]

FRP wrapping is a common way to increase the ductility, confinement, and shear capacity of walls, columns, and beams. It is worth mentioning that the fibers are oriented in the directions of the hoops, [14].

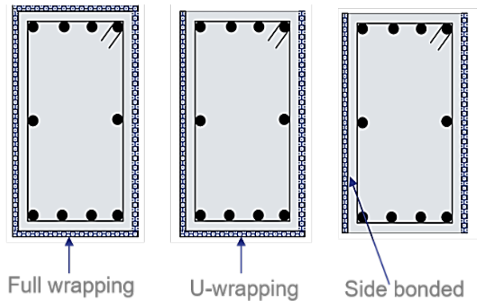

Figure 17. Various wrapping methods

The possible wrapping methods for beams are shown in the Figure 17.

Even if full wrapping of the section is the most effective method, it often cannot be used because of the presence of the slab. U-wrapping and side-bonded FRPs should be used.

The effectiveness of the new, additional layer decreases when there is more than one FRP-wrapping layer.

The example of FRP application at slabs is shown in the Figure 18.

a) midspan *b) at the support*

Figure 18. FRP slab strengthening, [14]

3. CHALLENGES

One of the main challenges is the installation of the appropriate anchorage system for different FRP applications and improving the bond between FRP and the concrete surface with stress transfer between them. Overlapping of the FRP sheet in the fiber direction can be a successful method in closed wrapping. On the other side, it is a significant construction challenge in open FRP systems (FRP laminates, side-bonded, U-shaped wrapping, etc.); thus, debonding is the most common, sudden, and brittle type of failure. An important condition for the safe use of FRPs to their full potential is knowledge of the long-term performance and durability properties of these modern materials.

Furthermore, one of the major drawbacks to FRPs full potential is the lack of design codes and a simplified FRP design book for structural engineers, [23].

4. CONCLUSIONS

In general, it can be said that FRP composites represent attractive materials for wide application in various types of engineering, such as civil engineering. Significant achievements can be obtained according to its benefits: high ratio of strength to density, great corrosion behavior, lightweight, and easy transport and installation. On the other side, FRPs have brittle behavior with a linear elastic response in tension up to failure and anisotropic behavior, which limits their use.

Also, this paper summarizes descriptions of different opportunities for retrofitting RC structural elements. It can be utilized as a review of FRP properties and as a basis for gaining basic knowledge about this kind of modern composite material.

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