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USE OF OPTICAL SENSORS FOR CRACK DETECTION ON BRIDGES

Azhar[1] Siti Rabiyah Awaliyah[1], Melysa Apriliya[1], Aisyah fadillah[1] , Putri dwi rahmadhani[1]

[1]*Physics Education, Faculty of Teacher Training and Education, University of Riau, Indonesia*

*Corresponding author's email: siti.rabiyah7375@student.unri.ac.id

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Abstract-Bridges are vital infrastructure in the transportation system that require regular maintenance to ensure user safety. One of the structural damages that often occurs is the appearance of cracks in bridge components, which if not detected early can cause fatal damage to collapse. This study aims to evaluate the effectiveness of the use of optical sensors in detecting cracks in bridge structures in real-time. The methodology used is a literature study of various types of optical sensors, especially Fiber Bragg Grating (FBG), as well as an analysis of case studies of their application in several bridge constructions. The results of the study show that optical sensors are able to detect micro deformations with high accuracy, are resistant to electromagnetic interference, and can be integrated into long-term structural monitoring systems. The conclusion of this study confirms that optical sensors have great potential as an early detection technology for structural damage, and make a significant contribution to the development of smarter and more sustainable infrastructure monitoring systems in the world of civil engineering. more efficient and proactive bridge infrastructure maintenance.

Keywords:*Optical sensors, crack detection, structural monitoring, bridges, Fiber Bragg Grating*

1 Introduction

Bridges are one of the important elements in transportation infrastructure that support people's mobility and distribution of goods. The reliability of bridge structures greatly determines the smooth running of economic and social activities. However, bridges are continuously exposed to dynamic traffic loads, changes in temperature, humidity, corrosion, and other environmental factors that can cause material degradation such as cracks in concrete and steel (Zhao et al., 2020). These cracks are one form of early structural damage that can develop into structural failure if not immediately detected and repaired (Feng et al., 2021). Therefore, continuous and accurate monitoring of bridge structural health is very important to anticipate serious damage and ensure the safety of road users.

The main obstacle in bridge maintenance is the early detection of small cracks that are difficult to identify with conventional inspection methods. Manual visual inspection is the most commonly used method, but this method is highly dependent on the skills and experience of the inspector, and has limitations in detecting microcracks or cracks hidden beneath the surface (Li et al., 2019). In addition, manual inspections are usually carried out periodically at certain time intervals, so there is a possibility that cracks will grow rapidly between inspections and cause delays in repair actions (Guo & Ou, 2018). Other non-destructive methods such as ultrasonic and radiography have advantages in accuracy, but their use requires special equipment and relatively long implementation time, making them less efficient for routine monitoring of large-scale bridges (Wang et al., 2020).

Cracks are the most important quality and major problem in the use of concrete components. Anti-seam is a basic requirement of concrete construction. The development of concrete cracks (including through seams, deep seams, cracks 1 of 0.2-0.3 mm or more) is likely to damage the integrity of the structure, forming a mechanical junction between the structures, which greatly reduces its bearing capacity and directly endangers the stability of the structure. In turn, structural failure and even collapse have occurred (Mao et al., 2014, Bao et al., 2015, Bao and Chen, 2016, Zhao et al., 2015). In recent years, many cases of the collapse of various concrete structures (such as bridges, waterways, tunnels, highways, high-rise buildings, dams, nuclear power plants, television towers, offshore oil platforms, etc.) have occurred frequently, for example: 2004 9 On March 8, the Sandu Shui Bridge collapsed on Chengwen Highway. On June 10, 2004, the Panjin Tianzhuang Bridge in Liaoning collapsed. On May 23, 2004, the departure hall of Charles de Gaulle Airport in France collapsed. On August 28, 2003, the Daman Bridge collapsed. On June 29, 1959, the Sanfeng Department Store in Hancheng, the capital of South Korea, collapsed. The collapse of these buildings caused incalculable economic losses and loss of human life and property, and the social impact was extremely severe (Bao et al., 2017).

Therefore, all countries in the world are paying great attention to the safety of various concrete structures, and allocate a large amount of money to conduct research on concrete structure safety monitoring technology to conduct research on concrete structure safety monitoring technology to achieve concrete structure and long-term impact, real-time, online site monitoring, in order to timely detect structural damage, predict the health of the estimated structure, enable people to take timely effective measures and means to ensure the safety and reliability of the structure, to avoid sudden major changes accidents. Safety in the concrete structure monitoring system, crack monitoring is an important monitoring content. According to modern from a mechanical point of view, cracks are the concentrated performance of internal damage to the concrete structure to a dangerous level, and it is the most direct key parameter to indicate and sign the dangerous situation of the project. Due to the randomness and uncertainty of concrete cracks, concrete crack monitoring has always been a major concern of technical problems that plague academics and engineering circles (Barrias et al., 2018, Barrias et al., 2017, Li et al., 2016).

In this context, optical sensor technology has emerged as an innovative alternative that has great potential to improve structural health monitoring (SHM) systems. Optical sensors based on Fiber Bragg Grating (FBG) have the ability to detect strain and deformation changes precisely with high sensitivity and fast response time (Ansari et al., 2021). FBG sensors are resistant to electromagnetic interference, have small dimensions, and can be installed in locations that are difficult to reach by other methods (Habel & Krebber, 2017). In addition, multiplexing technology allows the installation of many sensors on a single optical fiber, so that it can monitor several points simultaneously, which is very efficient and reduces the need for complicated cables (López-Higuera, 2019). Various experimental studies have proven that FBG sensors are able to detect cracks on a micro scale that are invisible to visual methods or even other conventional non-destructive methods (Wang et al., 2022; Sohn et al., 2016). This sensor is also capable of providing real-time monitoring data, allowing bridge managers to continuously analyze structural conditions and receive early warnings if damage develops (Feng et al., 2021). This real-time monitoring capability is crucial in the management of large and complex infrastructure assets, where quick and precise decisions are needed to avoid fatal structural failures.

In addition to technical advantages, the implementation of optical sensors also provides economic and operational benefits. Automatic monitoring reduces reliance on time-consuming and costly manual inspections. The data obtained can be stored and analyzed digitally, facilitating the creation of accurate structural condition reports and bridge service life predictions (López-Higuera, 2019). With the integration of optical sensor technology into the Internet of Things (IoT) system, remote monitoring and cloud-based data access are possible, significantly increasing the efficiency of infrastructure management (Feng et al., 2021). However, the large-scale application of optical sensor technology in bridge infrastructure still faces several challenges. Sensor installation must be carried out with high precision so that the data produced is valid and representative. Sensors must be protected from mechanical damage and harsh environments such as humidity, extreme temperatures, and vibrations (Guo & Ou, 2018). In addition, data analysis from optical sensors requires special software and careful interpretation so that monitoring results can be used as a basis for making the right decisions (Sohn et al., 2016). Therefore, further research and development are needed to overcome technical constraints and facilitate the implementation of this technology on a practical scale in the field. This study aims to evaluate the use of optical sensors, especially Fiber Bragg Grating sensors, in detecting cracks in bridges by examining installation methods, data collection techniques, and analysis of monitoring results. This study also compares the effectiveness of optical sensors with conventional detection methods to determine their advantages and limitations in real applications. It is expected that the results of this study can be the basis for the development of a more reliable, efficient, and integrated bridge structure health monitoring system with modern technology to support the safety and sustainability of transportation infrastructure.

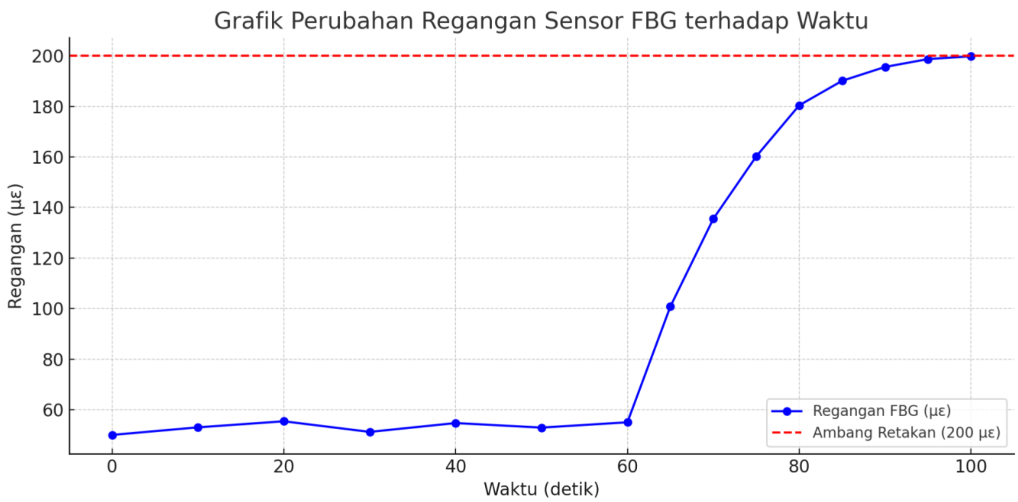
2 Methodology

This study uses a field experiment method to evaluate the effectiveness of using Fiber Bragg Grating (FBG) optical sensors in detecting cracks in bridge structures. Structural health monitoring is carried out by installing FBG sensors at critical points that have the potential to experience cracks based on the results of initial inspections and structural analysis (Wang et al., 2022). FBG sensors are chosen because of their high sensitivity to strain changes and their ability to provide data continuously without being affected by electromagnetic interference (Ansari et al., 2021). The sensor used is a type with a resonance wavelength of around 1550 nm, which has been calibrated for a strain sensitivity of 1.2 pm/με. The sensor is installed on the reinforced concrete structure and steel elements of the bridge using a special epoxy adhesive to ensure close contact between the sensor and the surface of the structure and to protect the sensor from mechanical and environmental damage (Guo & Ou, 2018; Zhao et al., 2020). The fiber optic cable connecting the sensor is directed to a data reader unit placed in a safe location.

Monitoring data in the form of changes in reflection wavelengths from FBG sensors are collected automatically with a one-second sampling interval using a high-resolution Optical Spectrum Analyzer (OSA) (Feng et al., 2021; Wang et al., 2022). The data is then processed and analyzed using MATLAB and LabVIEW software to interpret wavelength changes into strain values and detect early indications of crack formation (López-Higuera, 2019). Data analysis also involves comparing strain patterns between sensors installed in critical areas and safe areas to eliminate external interference and identify crack characteristics (Sohn et al., 2016). The thresholding method is used to set the maximum strain value limit that indicates the onset of crack formation (Li et al., 2019). In addition, monitoring data can be integrated with an Internet of Things (IoT)-based monitoring system to enable remote monitoring and automatic early warning system creation, thereby increasing the effectiveness of bridge structural health management (Feng et al., 2021).

2.1 Preparation of figures and tables

This study produces strain monitoring data on bridge structures using Fiber Bragg Grating (FBG) sensors installed at critical points prone to cracks. The FBG sensor records changes in reflection wavelengths influenced by structural deformation due to static and dynamic loads, which are then converted into strain values. This data is visualized in Graph 1 as changes in strain over time during the monitoring period.



Graph 2.1 shows changes in strain against time during the monitoring period.

2.1.2 Working Principle of Fiber Bragg Grating Sensor and Data Conversion

FBG sensors work based on the Bragg effect, which is the reflection of light at a certain wavelength that changes according to changes in strain or temperature in the optical fiber. The mathematical relationship of changes in wavelength to strain is:$\Delta\lambda \mathrm{B} \varepsilon$

$$\varepsilon \frac{\Delta\lambda \mathrm{B}}{\mathrm{K} \cdot \lambda \mathrm{B}}$$

(2.1)

Where

- ε = strain ($\mu\varepsilon$)
- $\Delta\lambda$B = change in wavelength (pm)
- λB = initial Bragg wavelength (nm)
- K = sensor sensitivity coefficient (pm/με).

In addition to strain, temperature changes can also affect λB\lambda_BλB, but in this study the use of sensors is equipped with temperature compensation using reference sensors (Habel & Krebber, 2017). This ensures the accuracy of pure strain readings due to mechanical loads.

2.2.2 Stress Calculation and Relationship with Elastic Modulus

The measured strain ε\varepsilonε is related to the stress σ\sigmaσ in the material using the linear Hooke's law:

$$\sigma = \mathrm{E} \cdot \varepsilon \tag{2.2}$$

where E is the modulus of elasticity of the bridge material, for example reinforced concrete has a value of E≈25,000 MPa, while steel is around E=200,000E = 200,000E=200,000 MPa (Guo & Ou, 2018). This stress value is used to determine whether the structure has passed the elastic limit and is starting to experience damage.

2.3.2 Crack Development and Propagation Analysis

The application of FBG sensors allows progressive monitoring of cracks by observing the increase in local strain. Cracks usually start to form when the strain exceeds a critical value that can be determined by the thresholding method:ε_{crit}

$$\varepsilon_{crit} = \varepsilon_0 + \alpha\sigma_y \tag{2.3}$$

Where:

- $\varepsilon_0$is the initial strain before cracking
- $\sigma_y$is the yield stress of the material
- $\alpha$is an empirical correction factor

This value can be varied according to the type of material and field conditions (Li et al., 2019). Once the strain passes , the sensor will record a dramatic spike, which marks the development of the crack. $\boldsymbol{\varepsilon_{crit}}$

2.4.2 Dynamic Load Influence and Natural Frequency Analysis

Bridge testing also takes into account dynamic loads due to traffic and wind. The natural frequency of the structure is calculated using the formula:

$$f_n = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \tag{2.4}$$

Where is the structural stiffness and mmm is the effective mass. A significant decrease in the natural frequency value can indicate damage or cracks that reduce stiffness (Wang et al., 2022). The strain data recorded by the sensor were also analyzed using Fourier transform to identify the vibration frequency and dynamic pattern of the structure.$\boldsymbol{k}$

2.5.2 Signal Analysis and Data Processing

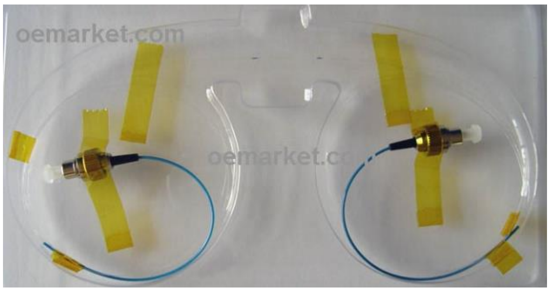
Raw data from FBG sensors contain noise and fluctuations that must be processed. Filtering methods such as Kalman Filter and wavelet transform are used to separate the original signal from the disturbance (Sohn et al., 2016). Kalman Filter predicts the system state optimally by minimizing the mean square error, while wavelet transform provides a good time-frequency representation for transient detection such as sudden cracks.

2.6.2 Comparison with Conventional Methods and Advantages of Optical Sensors

Visual and ultrasonic inspection methods are limited by subjectivity and low inspection frequency (Li et al., 2019). FBG sensors provide continuous monitoring, objective data, and can be integrated with IoT systems for remote monitoring (Feng et al., 2021). This enables early warning before cracks develop into dangerous structural failures.

2.7.2 Technical Challenges and Development Prospects

Technical challenges include protecting the sensor from physical damage and environmental conditions such as extreme temperatures and humidity (Guo & Ou, 2018). The development of sensors with nano-protective coatings and automatic temperature calibration systems is essential. In addition, the integration of machine learning algorithms for data pattern classification can automate crack detection and damage progression prediction (Sohn et al., 2016).



Gambar 2.1 The image of the Fiber Bragg Grating (FBG) strain

2.8.2 Stretch in straight position.

Strain can be interpreted as the occurrence of relative changes in the dimensions of a material due to experiencing stress (Zemansky, 1992). If a material is strained, the material will experience changes (deformation). Strain can occur due to tension or compression. Materials that receive strain due to pulling or compression will cause a shift. The magnitude of the strain due to pulling in a straight direction and position can be seen in Figure 2.6. When the material is in a straight position, the magnitude of the strain can be calculated using equation (2.1).

$$\varepsilon = \frac{Lt - L}{L} = \frac{\Delta L}{L} \tag{2.5}$$

Where:
ε = Strain
L_0=initial length
Lt = length when experiencing strain

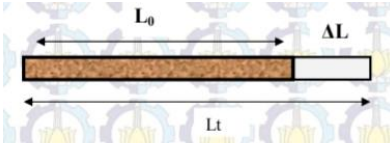


Figure 2.2 Strain in straight position

2.9.2 Strain at inclined plane position

The magnitude of strain experienced by a material when it is in an inclined position will be different from the material when it is in a straight position. The strain experienced by a material when it is in an inclined position is smaller when compared to the material that is in a straight position. So the magnitude of the strain received by the material depends on the position of the object when it receives force. The increase in length of a material due to strain in an inclined condition can be seen in Figure 2.3 The increase in length of a material due to strain can be calculated using the equation

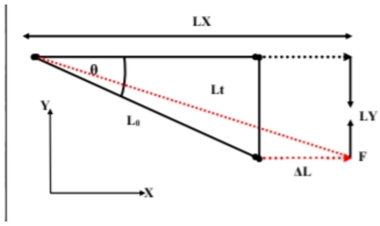


Figure 2.3 Strain scheme in inclined position

$$Lt=\sqrt{[L.\cos\theta+\ \Delta L^2}+L.\sin\theta \qquad (2.6)$$

Lo = Initial length
Lt = Length when subjected to strain
ΔL = Increase in length
0 = Slope or angle

2.10.2 Structural Monitoring With Fiber Optic Sensors

The management and safety control of highly relevant infrastructures (such as bridges, dams, tunnels) require regular monitoring, both in the short and long term, aimed at obtaining significant parameters that determine the structural behavior. In addition to physical (temperature, humidity,...) and chemical (pH, oxidation, carbonation) factors, very important elements are "mechanical" parameters such as stress, strain, displacement, crack width (Glišić & Inaudi 2007).

In recent years, great technical developments have involved the field of structural monitoring, and the use of fiber optic sensors has become more widespread (Leung 2001). These devices, which are dielectric materials insensitive to electromagnetic disturbances, are an ideal choice for many applications and are easy to handle and capable of recording very small lengths (down to 2 microns) with high precision. There is a wide variety of sensors used both for industrial applications, and for structural control (Udd 1995, Inaudi 1997). A recent classification based on diffusion and technical maturity was proposed by Inaudi & Del Grosso (2008), as shown in Figure 2.4

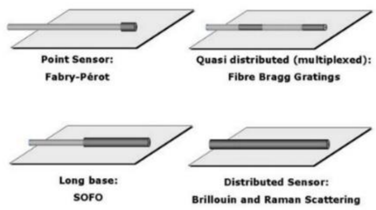


Figure 2.4 Structure of fiber optic sensor

Following this classification, optical sensors can be divided as follows:

- Point Sensor: measurements are made at one point,
- Multiplexed Sensor: allows to take measurements at multiple points along the sensor,
- Length base sensor (also called length measuring sensor): allows to obtain information on the basis of length measurement,
- Distributed Sensors: measurements are made over the entire length of the sensor, up to tens of kilometers.

In structural monitoring, both for new and old buildings, the reference can be represented by the material or by the entire structure (Inaudi et al. 1999). In the first case, the periodic control is based on the local properties of the material, by recording the response to structural loads, temperature variations and weathering. In this case, sensors equipped with a small measuring base are used ("Point Sensors" or "Multiplex"), which are able to provide a fairly constant stress condition, from a macroscopic point of view.

2.11.2 Utilization of OTDR-Based Fiber Optic Sensors for Crack Detection in Bridge Structures

The method of detecting cracks in concrete by utilizing a fiber optic sensor network based on OTDR technology has proven to be effective in conducting real-time and non-destructive structural monitoring, especially for infrastructure such as bridges and high-rise buildings (Zhao et al., 2020). Li et al. (2022) developed a method for identifying cracks in bridge structures using unmanned aerial vehicles (UAVs) equipped with image geometric correction, which allows for efficient and accurate crack detection.

Optical fiber-based sensor technology in the form of a sensor plate has been developed to detect cracks in concrete structures, without requiring initial information about the location of the crack, and can monitor multiple cracks at once in real-time using the OTDR (Optical Time Domain Reflectometry) principle (Vázquez-González, 2007). Bayu et al. (2016) developed an optical fiber-based sensor for pressure monitoring applications, focusing on increasing sensor sensitivity by varying the number of wire turns on the sensor.

Agus Rino (2017) in his thesis "Experimental Study of Long-Range Displacement Sensor Using Singlemode-Multimode-Singlemode (SMS) Structured Optical Fiber" developed an SMS fiber-optic sensor capable of measuring structural displacement with high sensitivity and a measurement range of up to 8 mm, making it an economical alternative compared to FBG sensors. Kumalasari et al. (2012) designed a fiber-optic displacement sensor applied to a bridge frame structure, with the aim of monitoring displacement in the metal bearing area in real-time and accurately.

van Zyl (2016) examined the role of artificial intelligence (AI) in the context of sustainability, and concluded that AI can act as both an enabler and an inhibitor depending on the sustainability indicators used. Hidayah et al. (2019) showed that increasing the number of turns in a pressure-based fiber optic sensor significantly increased the sensor's sensitivity to changes in applied pressure.

Hidayah et al. (2019) concluded that increasing the number of turns in a pressure-based fiber optic sensor is directly proportional to the increase in sensor sensitivity to changes in the applied pressure.

ITG Indonesia (2025) explains that various types of sensors such as strain gauges, inclinometers, piezometers, and fiber optic sensors are very important in monitoring soil conditions and building structures to ensure construction safety and reliability. Australia Indonesia Centre, "Development of fiber optic-based sensors for critical lines for road, rail, port, and bridge infrastructure," 2025.

Sofyan and Setyawan (2015) developed a fiber optic-based sensor for monitoring the weight of moving vehicles, which is expected to produce an accurate, cheap, and simple weighing system, and can be installed directly on the road without reducing driving comfort. Hidayah, Indaryanto, and Wibowo (2019) in their study examined the effect of variations in the number of turns on a pressure-based fiber optic sensor and found that a greater number of turns increased the sensor's sensitivity to changes in the applied pressure.

3. Results and Discussion

According to the observation results on the Fiber Bragg Grating (FBG) optical sensor, it is able to detect changes in micro-strain in real-time on the bridge structure. The monitoring results graph shows strain fluctuations in line with the dynamic load from traffic and changes in the environment. The FBG sensor installed at the critical point successfully recorded changes in the wavelength indicating the beginning of the formation of cracks, and is marked by a spike in strain at the Fiber Bragg Grating (FBG) optic is able to detect changes in micro-strain in real-time on the bridge structure. The monitoring results graph shows strain fluctuations in line with the dynamic load from traffic and changes in the environment. The FBG sensor installed at the critical point successfully recorded changes in the wavelength indicating the beginning of the formation of cracks, and is marked by a spike in strain above the threshold that has been determined by the thresholding method. Analyzing the data using MATLAB and LabVIEW software shows that there is a strong correlation between increasing local strain and the potential for structural cracks to form. Sensors mounted on steel and concrete elements are able to show sensitive responses to load variations, both static and dynamic. In addition, data processing using Kalman Filter and wavelet transform can filter noise and can clarify the signal of strain changes due to actual damage.

Comparisons with conventional methods such as visual and ultrasonic inspection show that optical sensors have advantages in terms of monitoring continuity, data accuracy, and remote monitoring capabilities through integration with IoT systems. These advantages provide significant benefits in predictive maintenance and rapid decision making before damage progresses further. However, the implementation of this system also requires attention to the protection of the sensor from harsh external environments and the need for special software to analyze the data. These factors can be challenges in large-scale applications, although the potential for development through nano-shielding and the integration of machine learning algorithms promises solutions to improve the accuracy and automation of crack detection systems.

3 Conclusion

This study proves that the Fiber Bragg Grating (FBG) optical sensor is an effective technology that can be used to detect early cracks in bridge structures. With the ability to monitor micro-strains in real-time and advantages in resistance to electromagnetic interference and multiplexing capabilities, this sensor is able to provide accurate monitoring data. The experimental results show that the FBG is able to record changes in strain that reflect the development of cracks due to mechanical and dynamic loads. System integration with analytical software and IoT networks strengthens the efficiency of remote structural monitoring. Although there are still many challenges in terms of sensor protection and the complexity of data analysis, this technology has very promising prospects in intelligent and sustainable bridge maintenance systems. The widespread application of optical sensors has the potential to revolutionize traditional approaches to infrastructure management, improve safety, and extend the service life of bridges. In the future, further development is needed in the aspects of sensor protection and the integration of artificial intelligence for data analysis to optimize overall system performance.

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