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# DESIGN, CONSTRUCTION AND DYNAMIC ANALYSIS OF A LABORATORY-SCALE FRP COMPOSITE FOOTRBIDGE

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**Summary**

Pedestrian loading on flexible structures such as footbridges, grandstands and lightweight floors is an area, which is receiving significant attention from the research community of late. Of particular interest is the interaction between the pedestrian loading and the structural response of the loaded structure. This interest has been instigated by several noteworthy examples of high-profile structures, which have vibrated considerably under dynamic pedestrian loading under specific conditions. From a structural engineer's perspective, recent developments in design and construction materials have led to lighter, longer spans than previously achieved, which may contribute to increased susceptibility to particular dynamic loads.

Separately, fibre reinforced polymer (FRP) composites represent the greatest innovation in structural materials in the recent past. These materials offer advantages over traditional materials such as steel, concrete and timber, which include improved durability performance, flexibility of design, improved quality assurance in production, potential for use of recycled materials, etc. However, perhaps the most significant advantage for civil engineering structures is the increased strength to weight ratios offered in comparison to more traditional materials.

These materials are growing in popularity in innovative structures and are gaining growing acceptance among designers internationally. One of the major barriers to increased use is the lack of design guidance on the use of these materials in load-bearing structures.

The authors are currently researching pedestrian-induced loading on flexible structures and also the use of FRP materials in construction. This paper describes the amalgamation of these two discrete research interests by detailing the design and dynamic analysis of a laboratory-scale FRP composite footbridge. The bridge was specifically designed to have a natural frequency within the range excitable by human walking. It will be used to investigate the interaction between loads produced by walking and running pedestrians and the vibration of the structure which they are traversing.

**Keywords:** pedestrian loading; human-structure interaction; vibration serviceability; spring-mass-damper; structural damping; natural frequency

## 1. Introduction

Vibration serviceability of lightweight or long span structures has emerged as a critical design consideration in recent times. There have been several high-profile incidents of structures such as footbridges undergoing excessive vibration, when subjected to loads from, say, crossing pedestrians. Advances in construction technology, structural materials and ever-increasing structural analysis capability has facilitated longer spans and lighter structures than achievable heretofore. Footbridges, in particular, fall into this category, along with stadium grandstands and even office floors. In many of these long-span structures, where the imposed static actions due to pedestrians are relatively small, might exhibit dynamic behaviour marked by closely-spaced natural frequencies and/or frequencies very close to the values perceived by human beings [1].

As a result of this trend, particularly for these types of structures, serviceability performance becomes increasingly more critical than in heavier construction. Due to their relative flexibility and associated low natural frequencies, the types of transient loading applied to these structures often elicits unexpected dynamic responses.

Some high profile examples of structures exhibiting excessive dynamic behavior resulting from applied loads include the Millennium Bridge, London [2], the Singapore Airport's Changi Mezzanine Bridge [3], the Clifton Suspension Bridge in Bristol, UK [4], and the Pedro e Inês Footbridge in Portugal [5]. Even more recently, in New York, the Squibb Park Bridge in Brooklyn closed in 2014 and remains closed pending remedial work to reduce the vibrations induced by pedestrian loading [6]. While the actual response of the aforementioned bridges varied, the common factor between them all was the vibration response caused by pedestrian loading.

In general there are two approaches within design guidelines towards dealing with footbridge vibration serviceability. The first approach requires the designer to avoid designing footbridges that have specific natural frequencies and is referred to as a '*Frequency Tuning Approach*'; i.e., the bridge is designed to avoid certain frequencies. While the second allows footbridges to be designed within specific frequency ranges as long as the dynamic response of the bridge is within acceptable limits for bridge users, and may be considered as a '*Vibration Limit Approach*'; i.e., the dynamic response of the bridge to a dynamic load model is analysed.

In the vibration limit approach, prediction of the structural response induced by crowds is determined by estimating the response caused by a single pedestrian and multiplying by a particular enhancement factor. This approach has been shown to be not only conservative, but quite inaccurate in many cases.

Moreover, many of the models employed for simulating the individual pedestrian-induced loading simplify the actions of persons crossing the footbridge to (moving) loads [7]. This approach disregards the fact that people are mechanical systems and, therefore, does not account for the interaction between the crowd and the structure that is supporting them [8].

This interaction between pedestrians and the flexible structures upon which they are walking has been identified as crucial to better simulation of pedestrian-induced loads. Some approaches to account for this interaction include modelling the pedestrians as moving single degree of freedom spring-mass-damper (SMD) systems [9] and inverted pendulum models [10]. However, calibration of these models has proven difficult.

In particular, the exact contribution of crossing pedestrians to both the stiffness and damping characteristics of a coupled bridge-pedestrian system is unknown. In order to study the nature of this interaction, the authors have designed and constructed a laboratory-scale fibre reinforced polymer (FRP) composite footbridge. This paper describes the design, construction and dynamic analysis of this bridge.

## 2. Design Approach

The footbridge described herein was designed to be accommodated in the structures laboratory in AIT. In addition to the spatial restrictions imposed by its location, a number of other constraints had to be considered early in the bridge design.

### 2.1 Footbridge Constraints

A number of constraints were placed upon the final footbridge, as follows:

#### *2.1.1. Maximum Bridge Span*

The span of the bridge was limited to the available space in the structures laboratory in AIT. The maximum span achievable was 11m, including access and egress platforms. This permitted a maximum clear span for the bridge of 8.0m.

*2.1.2 Desired Dynamic Performance*

In order to further our understanding of the nature of the interaction between pedestrians and flexible structures, the structure must be excitable by pedestrian loading. This requires the structure in question to have a first vertical natural frequency of close to the pedestrian walking range of 1.6Hz to 2.4Hz. As this is to be a lightweight bridge, the mass of the pedestrians would influence the frequency of the overall pedestrian-structure system, so slightly higher natural frequencies of the empty structure would be acceptable.

Further, it is desirable to be able to alter the natural frequency of the bridge so that the effect of resonant response could be directly measured. In order to do this, it was decided to design the bridge so that the clear span could be altered – thus varying the natural frequency.

*2.1.3 Material Selection*

In order to achieve the required dynamic performance, within the spatial constraints imposed, a number of potential structural materials were examined. Conventional materials such as reinforced concrete, steel and timber were considered but eliminated as they would not be able to achieve the required performance. Instead, it, it was decided by the design team to utilise FRP composite structural members in the bridge as this would allow study of both pedestrian-induced vibrations and the structural performance of non-conventional structural materials.

*2.1.4 Instrumentation*

Finally, and crucially, it must be possible to measure the forces exerted by pedestrians directly on the bridge. To this end, it was decided that a force plate would be embedded in the bridge at midspan. In addition to the force plate, the bridge was to be mounted with accelerometers at midspan and 2/3 span to record the vibration response.

**2.2 Design & Construction Process**

The major design decision was to utilize FRP composite materials for the primary structural members. Due to the specific requirements of this bridge in terms of exact dynamic and static properties, the authors opted to fabricate the main beams themselves, affording them complete control over the members' structural properties. Samples of glass fibre reinforced polyester (GFRP) were prepared, using the hand layup method. These samples were tested in order to determine their structural performance and sections were thus optimized to provide the desired characteristics. I-beam sections were then fabricated by joining flat plate sections as described in [11].

The bridge was designed to consist of two main beams, with regular cross bracing, all constructed from GFRP. This provided a grid, which supported a plywood deck. There is a recess provided at midspan to support an AMTI Accugait Force Plate. Access and egress (walk-on, walk-off) platforms are provided at each end of the bridge.

The span of the bridge can be adjusted by positioning of the supports, with a range of spans available from 6.5m to 8.0m. This would allow the natural frequency of the bridge to be easily altered. The structure can also be made effectively rigid through the use of intermediate supports. This provides for a direct comparison between pedestrian loading on rigid and flexible structures.

Finite element modelling of the bridge in ANSYS estimated the natural frequency of the empty structure to be 3.98Hz for a span of 6.5m and 2.97Hz for a span of 6.5m. As the presence of a pedestrian on the bridge was likely to lower the natural frequency, these values were deemed suitable for the study of human-structure interaction. The FE model was further updated following the static and dynamic analysis to yield optimum comparison with the measured values. Further details of the design are provided in [11]. Figure 1 shows various stages of the bridge construction, while Figure 2 shows the completed structure.

*Figure 1. Construction of the Laboratory Scale FRP Composite Footbridge*

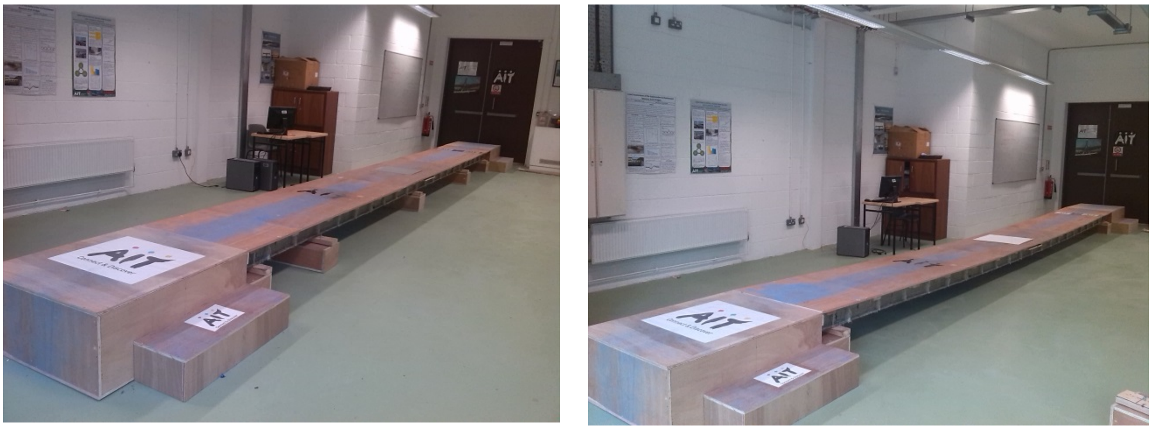


*Figure 2. Completed Laboratory Scale FRP Composite Footbridge*

### 2.3 Instrumentation & Analysis

The bridge is unique in terms of assessing pedestrian induced loads as it has a force plate mounted at mid-span. This allows for direct measurement of pedestrian forces in three orthogonal directions. The surface of the force plate is flush with the surface of the bridge deck so it is undetectable to crossing pedestrians. Accelerometers are mounted to the underside of the bridge at both mid-span and 2/3 span in order to capture the dynamic response. The spatial characteristics of the pedestrian footfall are captured through the use of grid paper (which also covers the position of the force plate) and chalk dust – a technique proven to be effective by others [12], [13], [14], including earlier work by the authors [15]. Video recording of all tests is also carried out.

The bridge is designed for the investigation of human-structure interaction and walking trials have been carried out but their results are beyond the scope of this paper.

## 3. Static Analysis

Results from the finite element modelling of the bridge predicted a static deflection under self-weight of 35mm for the 6.5m span, rising to 77mm for the 8.0m span. While these deflection values are relatively larger, they are necessary to achieve the low natural frequency of vibration. Measured static deflections were 35mm for the 6.5m span and 75mm for the 8.0m span, showing excellent agreement with the FE model.

Secondly, an 80kg static mass was placed at the mid-span of the bridge and the static deflections were recorded. These were measured as 45mm and 95mm for the 6.5m and 8.0m spans respectively. Again, they compare very well with the FE model predictions of 47mm and 99mm.

## 4. Dynamic Analysis

### 4.1 Natural Frequency

Of interest in this structure is the fundamental natural frequency, which is associated with the first vertical bending mode. Measurement of the vibration response was carried out for the free vibration response of the bridge, following an impulse load applied at mid-span. The work reported herein does not consider any ambient or pedestrian-induced vibration. The response is capture by the accelerometers and the natural frequency is derived from Fourier transform of the measured accelerations. Figure 3 shows the free vibration response for the 8.0m span under its own self-weight, together with the associated Fourier Transform results.

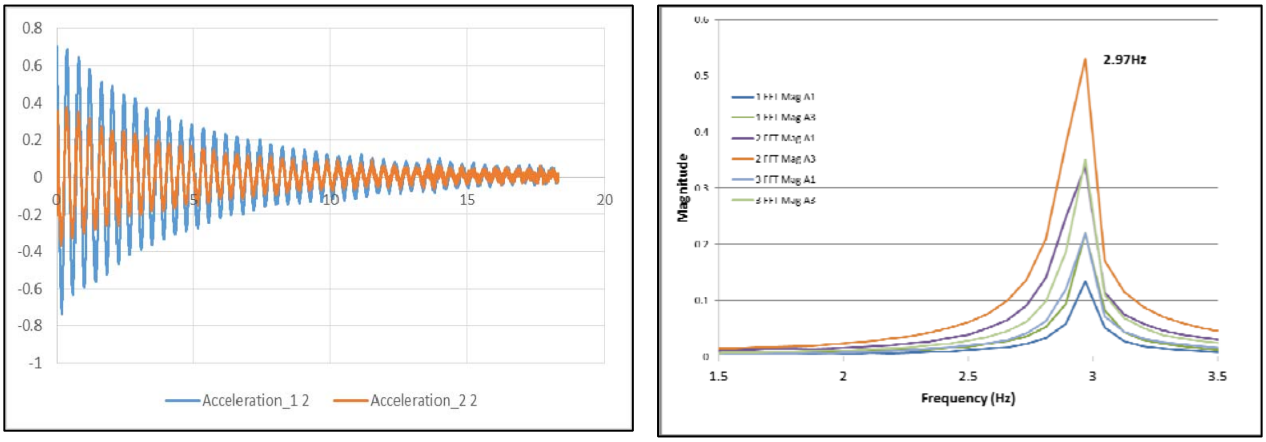



*Figure 3. (a) Acceleration response of 8.0m span under self-weight (b) FFT of acceleration traces for 8.0m span under self-weight*

The measured natural frequency of the empty bridge, for the 8.0m configuration was 2.97Hz, compared to 2.73Hz predicted by the FE model. For the 6.5m span, the values were 3.98Hz and 4.08Hz respectively. When an 80kg static mass was placed at mid=span of the bridge, the measured natural frequency for the 8.0m span reduced from 2.97Hz to 2.19Hz, as expected. For the 6.5m span, the frequency reduced from 3.98Hz to 2.94Hz. This reduction in natural frequency is expected and is crucial when considering the effect of pedestrians on a flexible structure, where the mass of the pedestrians is significant in terms of the modal mass of the structure they are traversing.

### 4.2 Damping

The structural damping present in the bridge was measured through determining $\delta$, the logarithmic decrement, associated with the free vibration response. Values for $\delta$ can then easily be converted to the more commonly used parameter of $\xi$, the damping ratio. As the footbridge is relatively lightweight and flexible, initial assumptions were that the structural damping is low, with values less than 5% being used in the finite element models. The measured response showed a damping ratio for the empty bridge of 1.45% for the 6.5m configuration, with a value of 1.30% for the 8.0m clear span. When the 80kg mass was placed at mid-span, the values increased to 1.48% and 1.80%, representing an average increase in structural damping of just under 16%.

Table 1 presents a summary of the static and dynamic responses of the bridge for each span from 6.5m to 8.0m and offers a comparison with the estimated values from the updated finite element model. In general, the values are within 5% of the model predictions and all are within 8.1%.

## 5. Influence of Stationary Humans on Dynamic Response of Footbridge

It has been extensively theorized that the presence of humans on a flexible structure not only alters the mass of the human-structure coupled system, but may also contribute to changes in the stiffness and/or damping properties of the system.

As part of this study, the dynamic response of the bridge with human test subjects present was also measured in order to assess the influence of the humans on the dynamic properties of the now coupled system.  While full walking trials have been carried out, this paper presents the results of static and dynamic testing of the bridge when occupied by stationary human test subjects. In this case, two individuals took part in the testing, with individual masses of 80kg each. The work has been approved by the Research Ethics Committee of AIT and both test subjects were fully informed of the nature and purpose of the tests and signed informed consent forms.

| | **(a) Empty Bridge** | | | | | | | **(b) 80kg Mass at mid-section** | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Clear Span (m)** | **Measured Deflection (mm)** | **FE Predicted Deflection (mm)** | **Error** | **Measured Natural Frequency (Hz)** | **FE Predicted Natural Frequency (Hz)** | **Error** | **Structural Damping (%)** | **Measured Deflection (mm)** | **FE Predicted Deflection (mm)** | **Error** | **Measured Natural Frequency (Hz)** | **FE Predicted Natural Frequency (Hz)** | **Error** | **Structural Damping (%)** |
| **8.0** | 75 | 77 | -2.6 | 2.97 | 2.73 | -8.1 | 1.30 | 95 | 99 | 4.2 | 2.19 | 2.11 | 4.7 | 1.80 |
| **7.5** | 60 | 61 | -1.6 | 3.28 | 3.10 | -5.5 | 1.38 | 80 | 80 | 0.0 | 2.38 | 2.34 | 1.7 | 2.62 |
| **7.0** | 45 | 47 | -4.3 | 3.59 | 3.55 | -1.1 | 1.14 | 60 | 63 | 5.0 | 2.65 | 2.58 | 2.7 | 3.48 |
| **6.5** | 35 | 35 | 0.0 | 3.98 | 4.08 | 2.5 | 1.45 | 45 | 47 | 4.4 | 2.94 | 2.97 | -1.0 | 1.48 |

*Table 1. Results from Static and Dynamic Analysis of Bridge (a) Empty and (b) with an 80kg mass at midspan*

A number of test scenarios were employed as follows:

*Test Scenario 1: One Person Standing at Midspan*

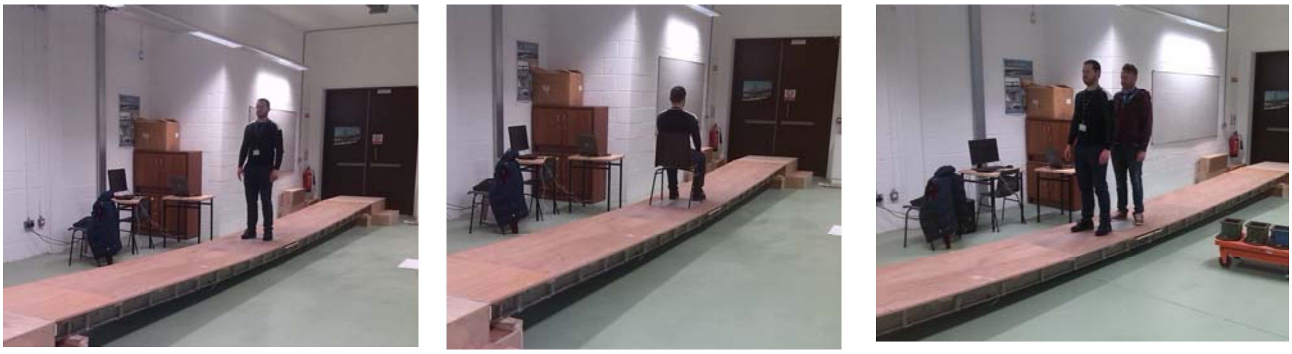
This involved one person (Mass = 80kg) standing at midspan of the bridge while the bridge was excited and the free vibration response was recorded.

*Test Scenario 2: One Person Sitting at Midspan*

This involved one person (Mass = 80kg) sitting at midspan of the bridge while the bridge was excited and the free vibration response was recorded. The purpose of this was to isolate the person's trunk to eliminate the stiffness and damping properties of his legs.

*Test Scenario 3: Two Persons Standing at Midspan*

This involved two persons (Combined Mass = 160kg) standing at midspan of the bridge while the bridge was excited and the free vibration response was recorded. Figure 4 shows each test scenario. In this paper, only the contribution form the person standing at midspan (Test Scenario 1) is reported.



(a) (b) (c)

*Figure 4. Test scenarios employed – (a) One person standing, (b) One Person and (c) Two Persons standing at midspan of the bridge*

### 5.1 Effect of Person Standing at Midspan on the Natural Frequency of the Bridge-Person System

As seen previously, the presence of an inert 80kg mass at the centre of the bridge span reduces the natural frequency of the first vertical mode shape from 2.97Hz to 2.19Hz (Table 1). When the pedestrian with a mass of 80kg stood at the centre of the span, the frequency further reduced to 2.11Hz. Therefore, although the pedestrian and the inert mass had the same mass, they both affected the natural frequency of the bridge slightly differently. This suggests that the person alters not just the mass of the coupled system, but also the stiffness. The natural frequency, therefore is not just contingent on the mass of the pedestrian, but also upon their stiffness contribution. This was further illustrated by the walking trials reported by the authors elsewhere [16]. This is important as it supports the approach of simulating pedestrians as moving spring mass damper systems, rather than point loads/forces.

### 5.2 Effect of Person Standing at Midspan on the Structural Damping of the Bridge-Person System

The logarithmic decrement values (and hence the structural damping ratio) were shown to be heavily influenced by the presence of a human on the bridge. While an 80kg inert mass caused a 19% increase in damping, a person of the same mass standing caused an increase of 157%. In terms of the magnitude of structural damping, it increased from 1.30% for the 8.0m span empty structure to 2.91% for the same span, with one person standing at the centre of the bridge. Figure 5 presents the results for the logarithmic decrement of the bridge under the various loading conditions, considering the data from the three accelerometers. Again, this strengthens the argument for considering pedestrians as moving dynamic systems coupled with the overall bridge.

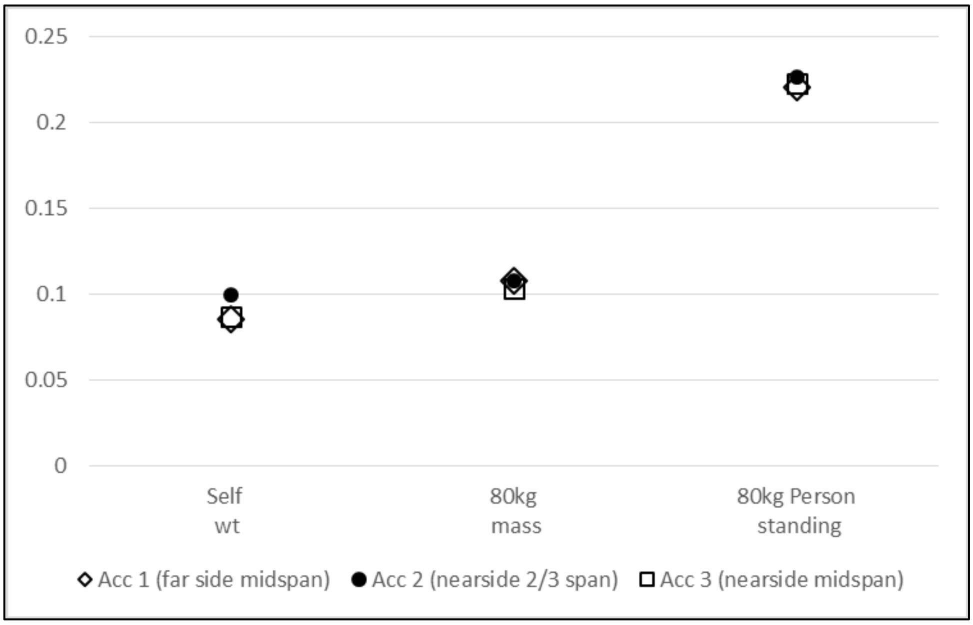



*Figure 5. Logarithmic Decrement for Empty Structure and Test Scenarios involving inert mass and humans at midspan.*

## 5. Conclusions

An 11m long glass fibre reinforced polymer composite laboratory scale footbridge has been constructed in AIT to investigate human-structure interaction. This paper described briefly the design and construction of this bridge and presented the result of the static and dynamic analysis of the completed structure under a number of loading conditions pertinent to the investigation of human-structure interaction. The measured static and dynamic response of the empty structure correlated well with the results obtained from a finite element model and show that the bridge is suitable for studying pedestrian-induced vibrations as it has a natural frequency of 2.97Hz, when empty, which reduces to 2.19Hz with an 80kg mass at midspan, yielding natural frequencies in the range excitable by crossing pedestrians. The structural damping increased from 1.5% to 1.8% with the addition of the 80kg inert mass.

Moreover, the dynamic properties were further altered by the presence of a human test subject of equivalent mass (frequency = 2.11Hz; damping ratio = 2.91% - an increase of 157%). The person had a greater influence on the natural frequency and a considerably greater impact on the structural damping. Both of these support the idea that pedestrians contribute to the stiffness and the damping of the coupled bridge-structure system and must be considered as such when attempting to simulate pedestrian loading on flexible structures.

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