DRIVEABILITY OF COMPOSITE PILES

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Abstract: Deep foundation has historically involved the use of traditional materials such as concrete, steel and timber. However, these materials suffered from strength degradation and its repair cost is significant especially if installed in harsh marine environment. A relatively new trend in piling industry is to use composites as substitute material. Composites present a novel solution without most of the traditional materials' shortcomings. The basic advantages of composites among other construction materials include lightweight, high strength-to-weight ratio, corrosion resistance, chemical and environmental resistance, and low maintenance cost. Apart from the mentioned advantages, composite materials face impediments since they do not have a long track record of use in piling system. To partially address the aforementioned barrier, this paper presents information on the driveability of composite piles which is one of the first steps toward understanding its behaviour during driving. Additionally, experimental impact test result conducted by the authors on fibre reinforced polymers (FRP) hollow pile is also discussed in this study. Result from the impact test on laminate confirms that longitudinal specimen exhibited higher energy absorption capacity compared to the transverse specimens. The performed axial impact test on pultruded section revealed that degradation of stiffness increases with increasing incident energies and impact cycles. Generally, literature showed limited information on full-scale driving test and needed field tests to carefully assess and verify the driving performance of the composite piles to be used in developing reliable design procedures.

Key words: Composite piles, pile driving, fibre reinforced polymers (FRP), impact behaviour.

1 INTRODUCTION

Traditional pile materials such as concrete, steel and timber suffered strength degradation and their repair cost is significant especially if installed in harsh marine environment. Problems associated to these traditional pile materials include deterioration of wood, corrosion of steel and degradation of reinforced concrete making its service life reduced. A relatively new trend in deep foundation industry is to use composites as a substitute for traditional materials in piling system. FRP composites present an alternative solution without most of the traditional piles' performance shortcomings. The basic advantages of composites among other construction materials include lightweight, high strength-to-weight ratio, corrosion resistance, chemical and environmental resistance and low maintenance cost (Sakr, El Naggar, & Nehdi, 2005).

Composite piles have been available in the North American market since the late 1980s, though their use has been limited mainly to marine fendering applications. To date, a number of load bearing composite piles were already used in bridge rehabilitation including Route 40 Bridge over the Nottoway River in Sussex County, Virginia and Route 351 Bridge project in Hampton, Virginia (Pando, Ealey, Filz, Lesko, & Hoppe, 2006). In Australia, application of composites in deep foundation is still in its infancy. There are however few appliance of composites undertaken but with only limited information. For instance, pultruded tubes were applied as FRP pile in an elevated walkway along the shoreline of Tweed Heads, New South Wales (Fig. 01).

Apart from the mentioned advantages, composite materials face impediments since they do not have a long track record of use in piling system. Iskander, Hanna and Stachula (2001) identified five potential areas that should be overcome for composite piling to be accepted in a widespread basis. First, economic necessity requires composite piles to be cost competitive on a life cycle basis. Second, mechanical and physical properties should be defined and a long term performance should be verified under field conditions. Third, design methods for predicting driveability and capacity should be developed. Fourth, design and testing standards should be developed, and fifth, several composite piles should be instrumented, installed, load tested, and monitored.

FIGURE 01: Application of composite pile.

This paper presents information on the driveability which is one of the first steps in the recognized areas toward understanding the behaviour of composites piles. Included in this study are published literatures related to composite pile's driveability. Additionally, experimental result on impact tests conducted by the authors on FRP pultruded tubes will also be incorporated in this paper.

2 COMPOSITE PILE TYPES AND MATERIALS

Review of the available literature shows that currently there are five common types of composite piles which are considered as potential substitutes (Pando et al., 2006). These include plastic encased steel pipe core piles, structurally reinforced plastic piles, concrete-filled FRP piles, fibreglass pultruded pipe piles and fibreglass reinforced plastic piles.

2.1 Steel Pipe Core Piles

Steel pipe core piles were the first composite piles introduced to the U.S. market (Iskander & Stachula, 1999). This pile consists of two layers, an inner steel layer and thick outer plastic shell. The inner layer provides the structural strength while the outer shell is used to protect the steel from corrosion. The outer shell is often made from high-density polyethylene (HDPE) which consists of recycled plastic materials (i.e. plastic milk jugs and juice containers). These piles were first installed in April 1987 at Berth 120 in the Port of Los Angeles.

2.2 Structurally Reinforced Plastic (SRP) Piles

Structurally reinforced plastic (SRP) piles are composed of extruded recycled plastic matrix reinforced with fibreglass rods or steel rebar. The outer surface of SRP piles is typically dense plastic and chemically treated with antioxidants and ultraviolet inhibitors to retard UV degradation. SRP piles are produced using continuous extrusion process which allows manufacturing of piles in a variety of lengths free of joints. Piles are available in diameters between 254 mm to 406 mm and are reinforced with 6 to 16 FRP or steel reinforcing rods of diameters ranging from 2.5 cm to 3.5 cm with a pile length of up to 32 m.

2.3 Concrete-filled Fibre Reinforced Polymer (FRP) Piles

Structurally Concrete-filled fibre reinforced polymer (FRP) piles are made of an outer FRP shell with unreinforced concrete infill. The main role of FRP shell is to provide a stay-in-place structural formwork for the concrete infill, acts as noncorrosive reinforcement, gives confinement to concrete in compression and protects the concrete from severe environmental effects (Mirmiran & Shahawy, 1996). On the other hand, the concrete infill offers the internal resistance in the compression zone and increases the stiffness of the member and prevents local buckling of the FRP tube (Fam & Rizkalla, 2001). Currently, concrete-filled FRP piles are adopted in a bridge rehabilitation projects in Virginia, USA (Pando et al., 2006).

2.4 Fibreglass Pultruded Pipe Piles

Fibreglass pultruded pipe piles are composed of outer fibreglass sheet fitted with a fibreglass grid to provide structural strength. The grid consists of two sets of orthogonal plates joined at four intersecting points and forms a tic-tac-toe pattern. The grid inserts are sometimes filled with HDPE, plastic lumber, or polyethylene foam fills. This pile was used in 1996 in a demonstration project at Berth 7 in Port Newark, NJ and in Tiffany Pier Project.

2.5 Fibreglass Reinforced Plastic Piles

Fibreglass reinforced plastic piles consists of recycled plastic matrix with randomly distributed fibreglass reinforcement. The dense solid outer shell is bonded to the peripheral surface of the inner plastic core which is foam-filled to reduce total weight. Trimax is currently the only manufacturer of this product consisting of high density extruded recycled polyethylene reinforced with approximately 20% fibreglass. Trimax lumber was used in the construction of the Tiffany Street Pier in New York City.

In Australia, there are two primary types of FRP piles being adopted. Wagners Composite Fibre Technology used pultruded sections and BAC Technologies Pty. Ltd. employed circular FRP hollow pile. Information on these two FRP piles will be described in the next section.

FIGURE 02: Pile driving rig for trial test.

3 FIELD DRIVING TESTS

Very few case histories are available with driving information of composite piles due to its novelty. There is however a small amount of study on field tests of composite piles to date. For instance, Mirmiran, Shao and Shahawy (2002) conducted an analysis and field test on the performance of composite tubes under pile driving impact. The authors found that driving stresses in filled tubes were comparable to that of the prestressed concrete pile. The empty tubes, however, were found to be susceptible to buckling and damage.

Baxter, Marinucci, Bradshow and Morgan (2005) studied the performance of composite piles under actual pile driving. Initial driving on composite piles runs smoothly until few embedment depths. However, at an approximate depth of 2m, steel pipe core pile's top began to deform or buckle and the pile barely moved. The pile was then extracted and visually inspected and found to have damage on the tip. On the other hand, concrete-filled FRP pile's cushion was broken at an approximately 4m of embedment until the concrete core at the top began to crack and finally wrecked.

Composite pile was also field-driven in an elevated walkway project located in Tweed Heads, Australia. This project utilized pultruded tubes that were manufactured by Wagners Composite Fibre Technology (WCFT) in supporting the superstructure. The tube was held by a steel frame and was driven by a 1ton diesel hammer as shown in Fig. 01. The 4m long pultruded tubes were driven to an embedment depth of 2.5 – 3.0m. Geometric and mechanical properties of the adopted tubes are given in the subsequent page. No geotechnical data was obtained on the site where the field tests were carried out.

BAC Technologies Pty. Ltd. (Queensland) tested a circular FRP hollow pile to determine its driveability behaviour and geotechnical performance. The pile has an outside diameter of 460mm and a wall thickness of 22mm. The 9.2m long FRP hollow pile, which is manufactured from resin infusion, was driven in Wilkie Creek (Dalby) by a single acting hammer. Fig. 02 evinces the actual set-up of the pile driving test with the driving hammer. The pile was successfully driven up to 6m. No geotechnical data on the site was acquired for additional analysis.

ANALYTICAL/PARAMETRIC STUDIES

Numerous studies have been performed on the driveability of composite piles. However, many of this studies are theoretical in nature and do not evaluate actual pile driving in the field. For example, Iskander et al. (2001) used WEAP to compare the driveability of short (60 ft), low capacity piles and long (90 ft) high capacity piles on a typical marine soil profile. The results indicate that the driveability of reinforced plastic (plastic lumber) piles, concrete-filled FRP piles, and timber piles was not a problem for the short, low capacity piles. However, the driveability (i.e. ease of installation) of these piles is very different for the long, high capacity piles.

Iskander and Stachula (2002) reverse-evaluated WEAP parameters (modulus of elasticity, damping and unit weight) by matching the results obtained during driving of the plastic lumber and FRP piles. Based on this analysis, the authors recommended the following parameters for the plastic lumber piles: an elastic modulus of equal to 2/3 of the manufacturer's reported composite modulus, the manufacturer's reported unit weight, and the pile damping factor of 9. Typical WEAP parameters published for traditional prestressed concrete piling provided a good match to measured results for the FRP piles.

Ashford and Jakrapiyanun (2001) analysed pile driving data using the wave equation as coded in the computer program WEAP87 for concrete-filled FRP pile, glass FRP pipe, steel pipe core pile and standard concrete and steel piles. Outcome of this study revealed that all piles are capable of being driven to 400 kN design capacity with a moderate size hammer. However, the impedance of piles composed solely of GFRP materials is significantly lower than all of the other piles reaching a limiting ultimate capacity (at refusal) of only 65-75% of the other pile analyses.

Mirmiran et al. (2002) used wave equation to analyse the transmission of stress waves through the length of the pile using computer program Microwave. Mirmiran and his colleagues concluded that no significant difference observed for the driveability of empty FRP tubes in different soil profiles. However, due to their low impedance, empty tubes can not attain more than 40-50% of the capacity of filled tubes. Additionally, No difference was observed in the driveability of concrete-filled FRP tubes and the prestressed concrete piles of the same cross sectional area and concrete strength.

4 IMPACT BEHAVIOUR OF FRP HOLLOW PILE

To date, information on the impact behaviour of composite piles is scarce and this area needs special attention. To better understand the behaviour of composite piles under impact loads, the authors conducted a laboratory-based impact test on the pultruded section. These include impact tests on laminate samples taken from the tube and axial impact test on the pultruded tube itself. It should be noted that this experiment is limited only on the behaviour of pultruded section and does believe that it can characterise the actual behaviour of FRP hollow pile. The objective of this study is to determine the effect of incident energies on the impact fatigue behaviour of pultruded section.

4.1 Materials

The tubes were manufactured by Wagners Composite Fibre Technology (WCFT) based in Queensland, Australia using pultrusion process. The 6.50mm tube wall, made from E-glass and vinyl-ester resin, is consisted of a laminate with fibre orientation in the form of [0/+45/0/-45/0/-45/0/+45/0]. Burnout of coupons showed an overall glass content of 79.80%. Tab. 01 & 02 shows the geometric and mechanical properties of the section taken from the manufacturer.

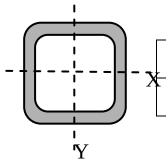

TABLE 01: Geometric properties*

Depth (mm)	Width (mm)	Thickness (mm)
125	125	6.50

TABLE 02: Mechanical properties*

Density (kg/m3)	Tensile strength (MPa)		Comp. strength (MPa)	
	Longitudinal	Trans	Longitudin	Trans
1970	650	41	550	104

Shear strength (MPa)	Modulus of elasticity (MPa)		Moment capacity (kN-m)	
	Longitudinal	Trans	X-axis	Y-axis
84	35,000	12,900	33.85	33.85

* Note: Courtesy from Wagners Composite Fibre Technology

TABLE 03: Specimen dimension

Specimen ID	Width, b (mm)	Thickness, t (mm)
Transverse -A	6.58	6.40
Transverse -B	12.54	6.40
Longitudinal	12.48	6.30

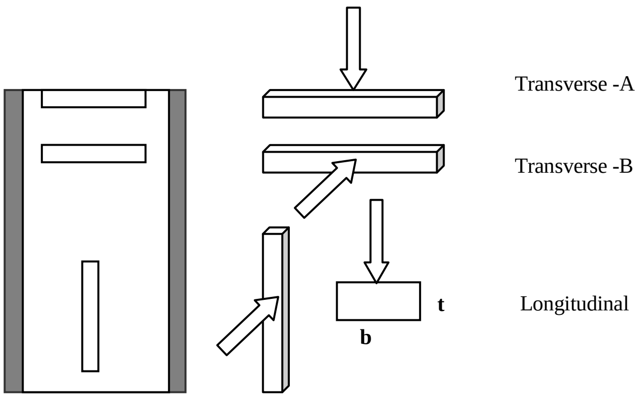

FIGURE 03: Specimen reference and direction of impact load.

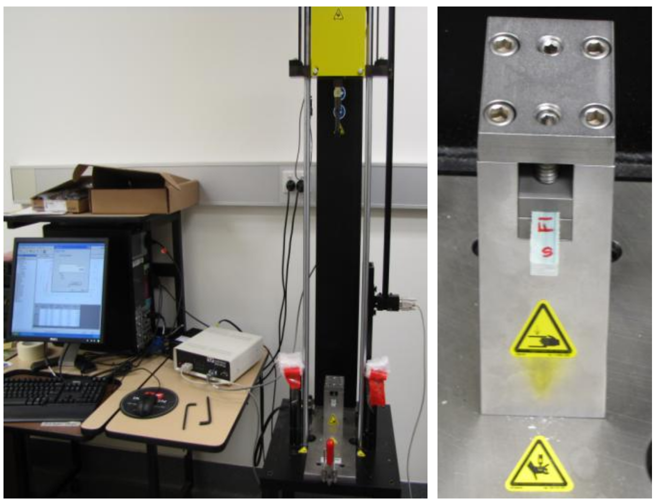

FIGURE 04: Testing set-up of Izod impact test.

TABLE 04: Summarised result of the average values obtained from each specimen

Specimen ID	Max impact load (N)	Max impact load/bt (MPa)	Max absorbed energy (J)	Max absorbed energy/bt Ea (kJ/sq.m)	Max total energy (J)	Max total energy/bt Et (kJ/sq.m)
Transverse - A	310	7.32	1.04	24.70	1.62	38.47
Transverse - B	670	8.31	3.53	44.00	4.27	53.20
Longitudinal	2,380	29.93	17.57	221.00	23.97	299.63

4.2 Impact Test on Laminate

4.2.1 Specimen and Testing Method

A total of 8 specimens per test were considered in the study. Tab. 03 depicts the average dimensions of the specimen used in the test. It should be noted that the specimen ID indicates the specimen reference and the direction of the applied impact load (shown in Fig. 03). The test was conducted under ISO 180:2000 (Determination of Izod Impact Strength). Impact tests were performed on Instron Dynatup impact testing machine with impulse data acquisition system. The drop weight testing machine consists of a drop tower equipped by a 15kg mass impactor which has a semi-cylindrical nose. The maximum falling height of the testing machine is 550 mm, which corresponds to maximum impact energy of 80.93 Joules. Fig. 04 illustrates the testing set-up and mounting of specimen on the impact machine.

4.2.2 Test Results and Discussion

Fig. 05 & 06 show the comparison of impact load and total energy versus displacement. Both specimens demonstrated splintering break failure as evidently shown in Fig. 05. This type of failure is common for brittle materials like composites and usually initiated by unstable cracking and followed by splintering (total rupture). Zhou (1995) also observed such failure mode on the impact behaviour of a composite laminate. This study characterized the damage effect of impact on laminate made from polyester resin reinforced with glass fibre. Longitudinal specimen demonstrated a higher impact load per unit area (bt) compared to transverse specimens due to a much greater stiffness. This was also the findings of the study conducted by Canteli, Arguelles, Vina, Ramulu and Kobayashi (2002) on a composite laminate in which the impact load increases with increasing material stiffness. On the other hand, specimens transverse A and B showed an almost identical impact behaviour trend and its peak impact loads are comparable (see Tab 04 and Fig. 05). Fig. 06 shows the behaviour of the specimens under total energy. Relationship between the total energy, rebound energy and the absorbed energy was discussed in the work of Belingardi, Cavatorta and Paolino (2008). It is interesting to note that all specimens attained its maximum total energy after the impact load's initial dissipations (i.e. impact load approaches zero). After the specimen reached its peak total energy, it started to damp the energy until total dissipation. Longitudinal specimen generated a remarkable total energy compared to the other specimens. Both specimens showed less rebound energy which implied that the impact energy was mostly absorbed by the specimen and most pronouncedly on transverse specimens. Contrary to impact load curve, specimens transverse A and B showed a visible difference on its total energy capacity as seen in Tab. 04 and Fig. 06.

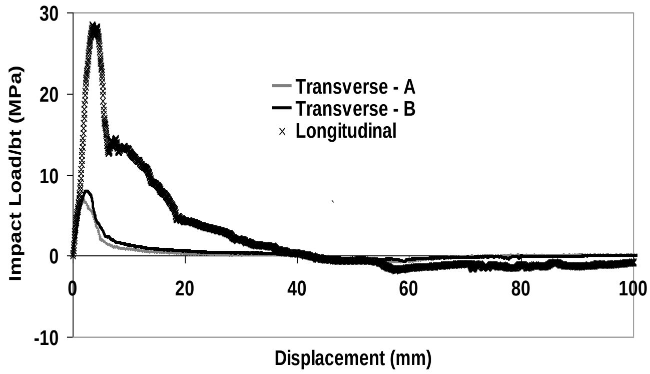

FIGURE 05: Impact load per unit area versus displacement curves

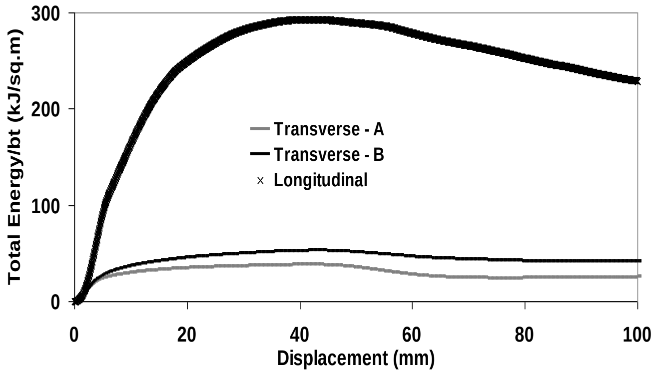

FIGURE 06: Total energy per unit area versus displacement curves

4.3 Axial Impact Test on Pultruded Tube

4.3.1 Specimen and Testing Method

No standard was published to suit this type of set-up and test; however, impacting test apparatus under AS 4132.3 (1993) was adopted except some modification on the set-up of the specimen. The 500mm long tube was supported by a steel frame mounted on the solid base (i.e. concrete pavement). Testing set-up and impact apparatus are shown in Fig. 07. Impact test was performed using an un-instrumented free-fall-dart testing apparatus with a total mass impactor of 14.72 kg. The falling height of the testing apparatus is 3.2, 2.7, and 2.2 m, which corresponds to incident energies of 460, 390, and 318 J respectively. The section was impacted up to maximum impact cycles of 75 impacts. The specimen was instrumented with 2 uni-directional strain gages mounted on the mid-height of the pultruded section. This distance is normally sufficient, as it is away from the direct mass impact. An LMS data acquisition device and a personal computer were used to capture the strain traces using a samplerate of 500 Hz. Post processing was done with LMS Test.Xpress software. Fig. 08 shows a typical strain traces in a scope mode generated from LMS data logger.

4.3.2 Test Results and Discussion

Fig. 09 illustrates the cumulative axial strain – impact number relationship for the three energies used. It should be noticed that for both energies, they exhibited similar behaviour with increasing number of impacts. Apparently, bilinear behaviour was demonstrated by the composite tubes adopted in the study with a clear transition of strain values between 40 – 50 impacts. At this impact loading regime, the composite tube underwent strain hardening or changing of peak force with increasing number of impacts.

Literature suggested two explanations for the changing of peak force phenomenon. In a series of repeated impact tests run on carbon/epoxy composite laminate, Wyrick and Adams (1988) commented the initial increase in the peak force as the result of the compaction process at the impacted surface. When impacted at low-energy levels, the fibre and matrix near the impact surface were damaged minimally, if any, and the compaction process provided a harder surface with greater local fibre and matrix concentration for the next impact. The second explanation was proposed by Liu (2004) who observed that even if delamination developed very early in an impact event, indentation and local matrix cracking were the dominant damage modes responsible for the generation of maximum peak force. However, the second explanation may not be valid for the present study since no local matrix cracking happened in the location of the strain gages.

Two significant distinctions were clearly observed between the published and the present study. Firstly, for the former studies, the peak force sustained by the composite increased initially until the maximum force was reached while the latter study does not reached its maximum peak force due to non-perforation. Finally, for the above-mentioned researches, after reaching the maximum peak force, rapid decrease of peak load happened due to complete perforation of the plate. Fig. 09 clearly exemplifies that the tube stiffness does not diminish impact after impact and its degradation happened after reaching its transition point as compared to the behaviour of impacted laminate. It can be observed that the difference in accumulation of strains for this kind of tube is insignificant for the first few impacts (i.e. up to 5 impacts) under different incident impact energies. For both tubes adopted, the point of transition (as discussed previously) lies exactly on impact number 45 and apparently indicating that its occurrence is independent on the incident energies applied. Although undoubtedly that reaching the transition point has nothing to do with the applied energy, it is still not imperative to expose if this would be the same case with the applied impact mass.

5 CONCLUSIONS

This paper presented the driveability and the recent application of composite piles in Australia. Result from the impact test on laminate confirms that longitudinal specimen exhibited higher energy absorption capacity compared to the transverse specimens. Outcome of the axial impact test on pultruded section revealed that degradation of stiffness increases with increasing incident energies and impact cycles. No maximum peak strain can be observed from the test as compared to the full-perforation test conducted on composite laminate plates. Only limited data was obtained on full-scale driving test and needs more field tests to carefully assess and verify the driving performance of the composite piles to be used in developing reliable design procedures.

FIGURE 07: Testing set-up and drop impact test apparatus.

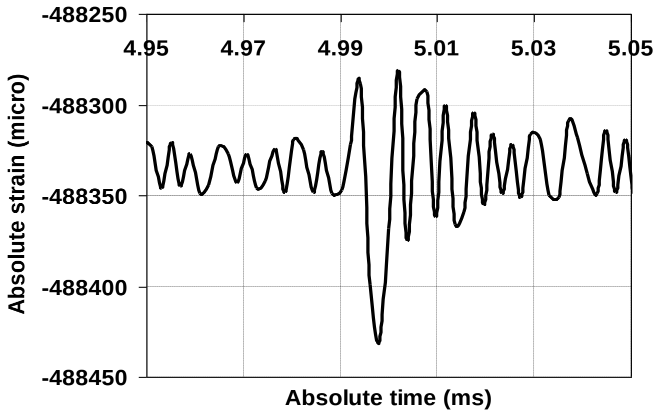

FIGURE 08: Typical strain traces recorded by LMS data logger.

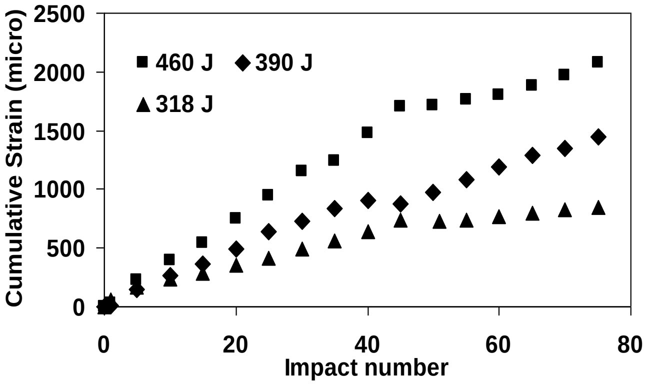

FIGURE 09: Cumulative strain vs. impact number relation.

6 ACKNOWLEDGEMENTS

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