Research, Development and Testing of Multiple Span - Multiple Use Horizontal Lifelines from the Designer's Perspective.

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International Fall Protection Symposium

Wuppertal, Germany, 15 -18 September 1998

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Abstract

Our planet spins around at one revolution per 24 hours. This can be difficult to sense, but we do experience one effect which we call day and night. There are other associated phenomena which can be difficult to sense, gravity being a classic example. It is a force of attraction between objects which we cannot feel, hear, smell or see, but if we drop an object we observe its effects as the object falls and strikes the ground. Falls from a height are propelled by the same effect, and as such they represent one of the most critical dangers that industry has to face in its everyday operations. Gravity cannot be isolated, minimised, or segregated from workers in the same way as other occupational hazards are, so engineered controls must be devised to protect workers at height from falls. Such controls are known as Fall Protection, an abridged term for "protection from falls from a height".

A horizontal lifeline (HLL) is one type of fall protection system which provides a continuous attachment for a safety harness in the horizontal plane. In the case of a multiple span system, (Figure 1), it typically consists of a mounted cable or rope which runs the length of the area to be protected, and is attached to the building or structure by intermediate anchors at preset intervals, and by two extremity anchors. If a person falls whilst attached, they will be arrested in a similar manner to the way in which an aircraft catches the arrester wire, when landing onboard an aircraft carrier, Fuller et al (1980).

Attention to ergonomic design is paramount in order to facilitate the work of personnel connected to the system, and to protect them from injury during and after an accidental fall. Various design features are discussed. The dynamic response of a HLL to a fall is a complex event, and to date has only been successfully modelled using sophisticated real time based software. This has been specially developed and verified from the results of extensive dynamic testing.

Figure 1 - HLL Installation under bridge

The question of the number of attached users, their all up mass, the consequences of simultaneous, near simultaneous, and staggered interval falls is discussed in the light of research carried out. The paper describes the use of two and four anthropometric dummies in dynamic fall simulations and some results of high speed photography are presented. The question of the compatibility interaction between a HLL and an attached self retracting lifeline is also discussed.

1 Introduction

This paper is a brief review of the design approach that was employed to produce the Sayfglida® HLL concept from first principles to market, and some of the solutions that emerged from that approach, including subsequent developments. D Riches was the senior engineer during the period 1989-1993 and headed the design team of Barrow Hepburn Sala Ltd, responsible for the Sayfglida® project. L J Feathers gave comprehensive support as the research and development manager, and was responsible for a great deal of the Sayfglida® innovation.

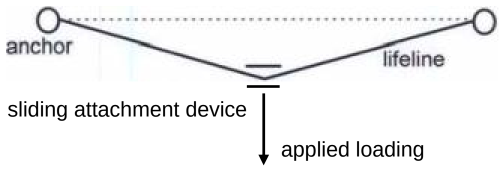
Designing fall arrest systems (FAS) is a very demanding activity because great care has to be exercised when analysing the moral, legal, technical and commercial aspects, before making a decision. And often, the first three aspects require significant attention before the latter can be properly realised, with all the attendant pressures. The designer has to be painstakingly conscientious, and must be able to work with a clear conscience, because fundamentally the task is not to protect limbless wooden dummies from colliding with a test house floor, but is to prevent the death of a real person. Any design mistake not revealed during an inadequate test programme can result in someone's death. In the UK, the legal responsibilities for product research, design, test, manufacture, installation, and user information are given stark emphasis in Section 6 of the Health and Safety at Work Act (1974).

2 Important Lessons

Previous HLL development work had been inherited from other engineers within BH Sala, but disappointing test results had taught four important lessons. The first was that welding and stress relieving heat treatment can be difficult processes to reproduce consistently, and poor welds can be prone to sudden brittle fracture, especially when the welded area is within a dynamically applied load path. A well known example of this phenomenon is the Liberty ships which suffered major fractures, including some which broke completely in two, ASEE (1946).

The second lesson was that a complex design may give excellent performance in the design laboratory, but if it cannot be consistently reproduced by production tooling within the tolerances required, then the design solution is not a solution at all.

The third lesson was that improvements to one design aspect can have adverse effects on another. The sliding attachment device for the connection of the worker's lanyard had been designed with an unconventional profile. It was decided to statically load this component, together with the HLL rope in the manner in which it would be loaded in a fall arrest occurrence, ie perpendicular to the HLL, (Figure 2):



At a loading of 15 kN, the device cut completely through the wire rope, indicating that the interaction under load between device and rope constituted a serious weakness. The profile had been contributory to the cutting action. The fourth lesson, also from the above test, was that when individual components are combined together in a system, the strength of the whole system may be different to the individual strengths of each component. It is entirely unsatisfactory to test each component in isolation without carrying out a system performance test.

3 System Approach

This development was curtailed, and a new project, (Sayfglida®), was commenced from first principles. It was decided to establish a list of basic system design requirements and a list of components, Riches (1997), and a study of patents and other relevant literature was made. The influence of previous Canadian research work upon the authors cannot be overemphasised, Sulowski and Miura, (1983).

The approach that was taken, was to make the person for whom the protection was required the most important part of the system. Then to work up through the system and make all other considerations secondary to this. This might seem to be an obvious approach, but it can be overlooked. It is relatively easy to focus on component design, selection of materials, performance, and meeting the standards criteria, but crucially all FAS should be founded on the ability to facilitate the work of the people connected to the system, and to protect them from injury during and after an accidental fall. The users must not be forgotten.

The proposed means of connecting the worker to the HLL was by energy absorbing lanyard, rated to give an applied arrest force of 3.5 ± 0.5 kN. This would have sufficient capacity to dissipate a fall factor 2 fall, with a maximum length of 2.0 metres. (Fall factor equalling the quotient of free fall over pre-fall lanyard length). This would allow for a situation when the HLL had to be installed near to the level of the walk way.

It was also realised that because the arrest force is applied perpendicular to the lifeline, it is amplified as it is transmitted throughout the system. This being the case, if the magnitude of the arrest force could be kept low, this would have the benefit of lower forces throughout the system.

The amount of fall momentum put into the system could be controlled by lanyard length, also by the height of the HLL above the walk way, which meant that strict control of these two parameters would be necessary during site design. A range of lanyard lengths would have to made available to suit specific circumstances. This started an underlying theme throughout the project, which repeatedly emerged at every stage; Sayfglida® would have to be designed as a complete FAS. Arrest performance would be governed by the time based interaction between energy absorbing lanyard extension, lifeline extension, intermediate support friction, harness extension and other supplementary forms of energy dissipation. To guarantee this interaction the Sayfglida would have to be controlled and marketed as a complete FAS, so that installation and user companies could be offered a fully tested component compatible design.

4 Single or Multiple Span?

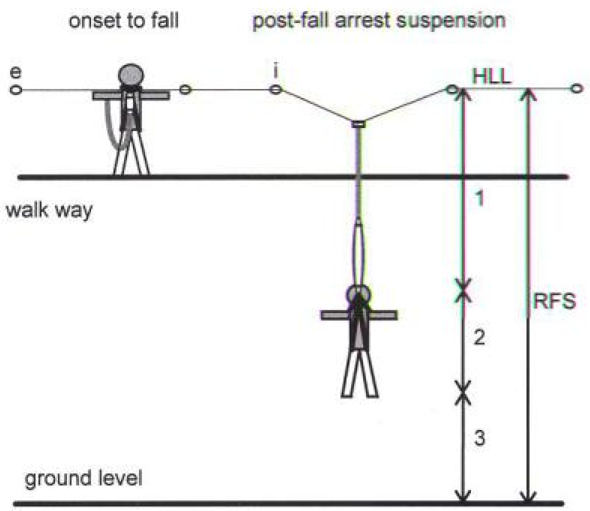
The advantages and disadvantages between single span and multiple span types had been analysed, Riches (1992), and it was decided to proceed with a multiple span design. As the number of intermediate anchors is increased the need for tensioning becomes less critical as the weight of the lifeline becomes increasingly supported. One of the design aims was to produce a tension - independent system, because it was known that some earlier types of HLL needed a precise tensioning set up. This could be difficult to achieve during installation, and if not done correctly could interfere with performance. Multiple span systems could also have corner units, designed to contour the HLL around internal and external corners, which a single span system could not do.

The multiple span design created the problem of how to allow the unrestricted passage of the worker and energy absorbing lanyard past the intermediate anchors, without the need for repeated disconnection and reconnection to the system. This was solved by the design of the intermediate anchor bracket and the Sayflink, a profiled slotted tube which also provided the means of attachment for the energy absorbing lanyard. These items are reviewed later in the paper.

5 Installation Problems

It was decided to visit previously installed HLLs, to study their effectiveness. HLL installation companies were also asked for their opinion on what qualities a new product should possess. It was acknowledged that apart from structural integrity, the installation process contributes to the performance of the system. Poor installation means poor protection, irrespective of the merits of the system. The main problem discovered was that the methods of calculating intermediate and extremity anchor forces and arrest force/distance for a simulated fall was something of an inaccurate affair. Calculations had to be done because each HLL had a different configuration, as it was tailor made to the work place geometry. Assumptions were being made in calculations to make the analysis simple, but the likely degree of error was not known in the solution.

Installation companies needed calculations to predict, within a certain degree of accuracy, the response of a HLL installation to a simulated fall. Such a calculation would be based on the specific HLL configuration needed to solve the particular problem on site. This would provide the criteria necessary for anchor selection, ie the loads on extremity, intermediate and corner anchor positions, and would tell them where the anchors should be positioned, in regard to allowing sufficient free space for the fall arrest to take place in, eg Figure 3:



key:

e = extremity anchor i = intermediate anchor

1 = lanyard length + energy absorber operation + "V" deflection

2 = harness stretch + distance between harness attachment point and feet

3 = safety clearance

Recommended Free Space (RFS) = 1 + 2 + 3

Anchor height above ground level must be equal to or greater than RFS

6 Computer Modelling

After considering the mathematical analysis of the multiple span HLL, with the inclusion of corner arrangements, and finding that the equations generated were insolvable using manual methods, it was decided to proceed with the writing of a computer program. This program would not be based on the limited accuracy of energy balance methods used in earlier analyses, but would use a time stepping finite element analysis. This would allow staggered falls to be analysed, (a second faller falling after the first, after some time interval). A more detailed account of the software development is reported in Drabble and Brookfield (1998).

7 Rating

The function of a HLL is to transfer the faller's momentum into the system, and so it is necessary to limit the fall momentum to that which can be sustained by the system, at an acceptable factor of safety. The fall momentum is directly proportional to the faller's free fall velocity and mass. The free fall velocity can be controlled by limiting the free fall distance, and this was discussed in section 3. The all up mass (AUM) of connected workers can also be limited. AUM is the sum of the masses of the worker, clothing and all equipment carried. Anthropometric data, eg Bolton et al (1971), which surveyed 2000 aircrew, gives the 99th percentile male mass as 96.5 kg with the range measured being 51-109 kg. Pheasant (1990) gives the 95th percentile male mass as 95 kg. In view of this and marketing requirements it was decided to limit the Sayfglida® to a rated mass of two workers of 120 kg AUM. This was subsequently increased to 2 x 136 kg for the American market.

8 Lifeline Selection: Rope

Because of other considerations, rope was chosen for the lifeline. However, rope is designed primarily to be loaded in tension, and not to be loaded in bending about an abrupt radius, as in the case of the "V' shaped rope deflection which arises in multiple span HLLs as a result of a fall arrest impact, (Figure 3). This bending occurs at the points where the rope passes over the intermediate anchors and through the sliding attachment device.

Static tests to destruction (Figure 4) had been carried out on an earlier type of multiple span system, and had revealed that the bending interaction between the rope and the intermediate anchors was a major design weakness. The loading had been applied in the same direction as it would be applied in a fall arrest occurrence, ie perpendicular to the lifeline. The failure mode in all these tests was at the point where the HLL rope passed through the intermediate anchor.

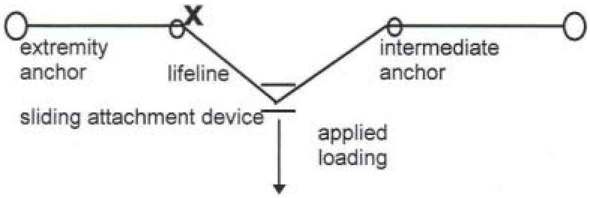


Figure 4 HLL Tensile Tests to Destruction

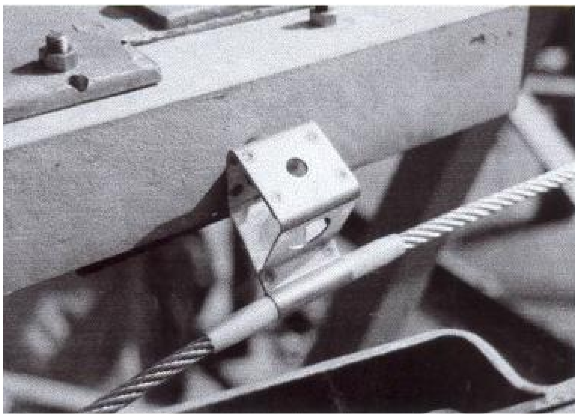
The tests revealed that a stress concentration had occurred at the bearing point of the rope on the intermediate support, and that this had weakened the rope strength by a factor of 32%. Consequently it was realised that the Sayfglida® design would need to pay close attention to detail in those areas.

The question of whether two attached workers could fall simultaneously was discussed within the design team, and whether or not the fallers could react against the HLL at the same time. It was realised that if the arrest force-time signatures overlapped in any way that there would be a summation of forces. In terms of time, the worst type of free fall expected would be in the region of 4.0 metres, which would take 903 ms. There would also be a time interval for the HLL to stretch into its V shape, and from fixed anchor data, it would take an energy absorber approximately 500 ms to dissipate the fall momentum. It was felt that there was a possibility of workers' force-time signatures overlapping. It was also realised that if there was a greater stagger in time between falling workers, that the second faller could have a greater free fall than the first, because the V deflection would have already occurred. It was also felt that if two workers were in the same subspan, because the task required two sets of hands, there was a strong possibility of a double fall, eg from a gust of wind, a swinging load, or a collapsing support structure. An accident was known about where two labourers had fallen through a roof together, whilst holding a high pressure water hose, Health and Safety Executive (1988). This would be a subject that would have to be evaluated during the dynamic test programmes, but since the very purpose of the system was to save life, it was felt both legally and morally that any safety system should be capable of sustaining what was foreseeable in terms of risk. Therefore all design considerations were based initially on a double simultaneous fall situation.

After completing the evaluation and study a 12 mm diameter 7x7 construction right hand lay 316 stainless steel rope was chosen for the lifeline. This would allow a HLL tension of up to 25 kN to be generated with a factor of safety (FOS) of 3. Allowing 25 kN in the HLL meant that the Sayfglida® would be able sustain a two person simultaneous fall, each at 120 kg all up mass, and each at a maximum arrest force of 6 kN if necessary. It would also allow the system performance envelope to be developed to allow an increased number of simultaneous users.

9 Deforming Bracket and the Sayflink

In order to minimise cable bending effects and stress raising points at the intermediate anchor-HLL interface, a number of features were designed into the intermediate support bracket, (Figure 5):



The bracket was designed to deform in response to a fall arrest force occurring in an adjacent subspan, in order to relieve stress at this point, to dissipate some of the fall energy, and to serve as a "tell-tale" fall indicator. The rope was held in the bracket by two nylon stabilizers, which prevented rope to bracket contact. Experience with earlier bracket designs, which had allowed the HLL rope to float and make contact with the bracket, had shown that wind vibration could cause serious rope damage. The stabilizers also acted as a solid lubricant, allowing the rope to slide through the bracket during a fall arrest, again minimising any stress concentration bearing point. A single hole for an anchoring bolt, to enable the bracket to swivel in the direction of the V deflection, completed the process of minimising bearing point stress.

The Sayflink, (Figure 6 below), was designed to give a smooth passing action through the stem of the bracket. The offset slotted tube, with helical converging edges, with a pivoting link, allowed the Sayflink to ride up onto the bracket stabilizer, and turn the slot into alignment with the bracket stem. The inside of the tube was venturi shaped to help relieve rope bearing stress whenever a Sayflink was called to be at the bottom of a V deflection.

10 Testing, Testing

A dynamic test programme, Monks, (1991) and Drabble, (1995) was carried out at Nuclear Electric's Structural Test Centre, Cheddar Gorge, UK and at DBI Sala, USA. High speed photography, high speed video and stills were used to record the proceedings. Traditionally in the UK, simulations of falling workers to test the performance of FAS was accomplished by the use of anthropometric test dummies (ATDs). ATDs have their dimensions, mass distribution and anatomy arranged to be statistically representative of certain population groups. They are also used in other industries where human impacts are of concern, eg aircraft ejection and vehicle passenger restraint, Schultz et al (1996). Despite the fact that the fall arrest industry was going towards the use of limbless wooden shapes and solid cylindrical masses for use in testing, it was decided to test with 95th percentile 100 kg mass ATDs. Since Sayfglida® was a full FAS and the tests were meant to reflect how the system would be used and how it might react in practice, it was felt that ATDs would bring more relevance to the testing than other surrogates, as shown for example in Figure 7.

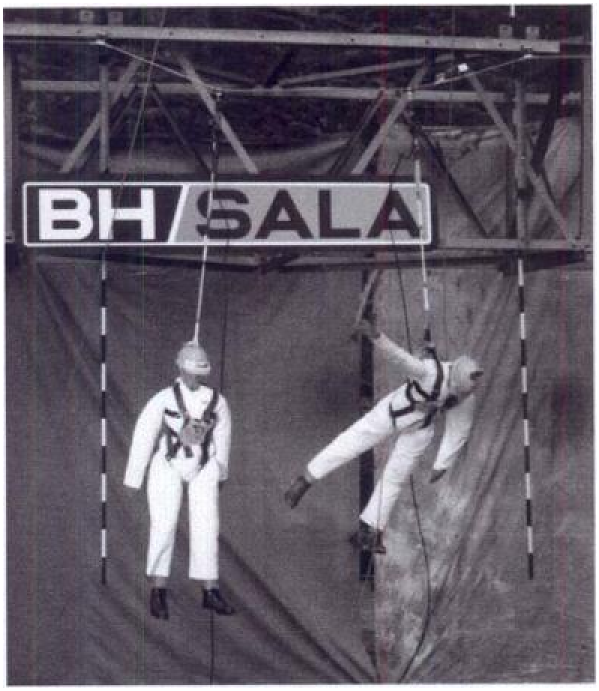


Figure 7: Dummy "George" catches his arm on the HLL on the way down during a "SIMREL"

The results were able to confirm the design, and the data was used to verify, and over time, to improve the accuracy of "Life", the name given to the computer software. The tests involved a variety of combinations. Single ATD releases were carried out in different subspans, with different types of energy absorbing lanyards and retractable lifelines as the connecting subsystem. Staggered 500 ms releases (STAGREL) of two ATDs examined the response of the system. These tests were carried out with two ATDs in the same subspan, two ATDs, one in each of a pair of adjacent subspans, and two ATDs in the extremity subspans. Simultaneous release (SIMREL) of two ATDs followed the same pattern with releases over the corner unit also. Variations included direct releases over intermediate brackets and different release points in subspans, eg mid subspan and quarter subspan.

Some results are reviewed as follows. A 500 ms STAGREL, with two ATDs in the same subspan had maximum lanyard tensions of 5.0 kN at 1000 ms after release and the second had 5.5 kN at 1490 ms after release. The HLL tension trace showed two distinct shadows of the lanyard traces, the first peaking at 10 kN at 1000 ms after release and the second peaking at 10.2 kN at 1490 ms after release. There was a small period of superimposition of 100 ms whereupon the second impact pulse rose to 4 kN before the first impact pulse had concluded. The second lanyard had a 17% increase in energy absorber extension over the first, indicative that the second A TD had fallen further than the first, because of the V deflection.

The same test was repeated but with a SIMREL. The maximum lanyard tensions occurred at 5.0 and 5.2 kN simultaneously after 1050 ms. The HLL tension trace showed superimposition, with the tension peaking at 17 kN at 1050 ms after release. The lanyard energy absorber extensions were identical.

A sequence of tests was conducted to investigate the effects of a four ATD SIMREL in the same subspan, (Figure 9).

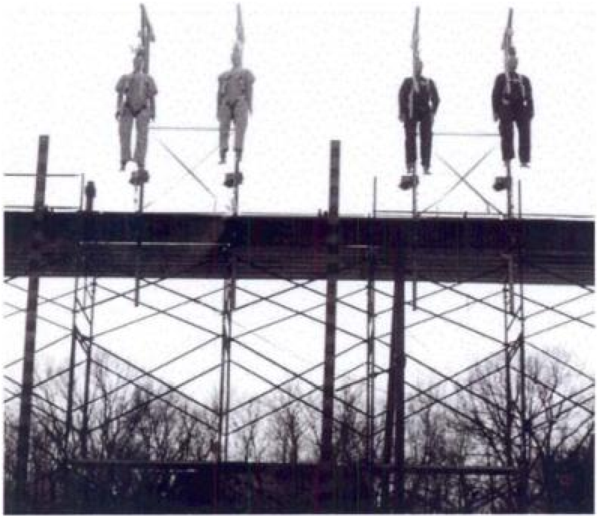


Figure 9 - Four ATDs awaiting SIMREL

The Sayfglida® for this test had two "in-line" energy absorbers, one at each cable extremity. Energy absorbing lanyards of 2.0 m length were used as the connecting subsystem, and the ATDs were released so that each experienced a four metre free fall. All the lanyard tensions peaked between 4.0-5.0 kN and at between 1050 and 1075 ms after release. The HLL tensions showed the superimposition of forces and rose to 24 kN at around 1075 ms after release. The in-line energy absorbers controlled the HLL tension to a level of 20 kN for 80% of the arrest time.

In all the tests carried out it was noted that the downward deflection of the cable (V effect), with the ATD in static post fall arrest suspension, was smaller than the dynamic dimension, ie under the maximum load condition - a response which would be necessary to build into the recommended free space calculations.

11 Attaching Retractable Lifelines

These devices rely on the velocity of a falling person to activate a clutch, which engages a brake to give the arrest resistance. Under normal use the clutch remains disengaged. It was known for some time that one of the most important aspects of designing such a device was that the phenomenon known as "ratchet pawl bounce" had to be avoided. Once the locking pawls of the clutch are engaged in the brake, it is important that they stay in the brake, or else if they come out, the worker will free fall again until such a time when the pawls can re-engage. This can be repeated several times. This "bounce out" can occur when certain parts of the load path are not stiff enough, ie when it behaves like a spring. One device when dynamically tested with a normal fixed point anchor, with no free fall, and with a 75 kg test mass, showed by the force time trace that it required 5 attempts before the locking pawls would finally engage, ie it bounced 5 times. This was due to the wrong choice of materials in the clutch and brake assembly.

There had also been reports of accidents with these devices when attached to a cantilevered beam, ie the anchor in effect was acting like a spring. Furthermore, it was known that some manufacturers had prohibited the use of their retractable lifelines when combined in use with single span HLLs.

It was decided to test some retractable lifelines in combination with the Sayfglida® to see if ratchet pawl bounce could be reproduced. HLLs are like big vibrating springs in response to a dynamic loading, and the stiffness and response of this spring depends upon a number of factors inherent to the particular configuration of the HLL in question. It was difficult from the impulse traces and high speed photography to see if bounce actually occurred in any of the tests.

Since attaching retractable lifelines to HLLs would give a greater range of movement for the worker in both the horizontal and vertical plane, it was decided to develop the Sayfglida® accordingly. The Life software would need developing to be able to model the interaction between retractable lifeline and HLL, and it was decided to develop a special retractable lifeline for use with HLLs. This would have a pawl locking mechanism to prevent bounce.

12 Conclusion

This paper has attempted to review the design approach employed to produce the Sayfglida® HLL, and has discussed some of the design features and how they were arrived at. This included the computer software simulation and some of the results of static and dynamic testing. The design and control of multiple span multiple use HLLs is very complex, and many of the issues written about in this paper require further input. However one must never lose track of the fact that the principles behind such designs must focus on the person to be protected.

13 Acknowledgements

The authors wish to thank Barrow Hepburn Sala Ltd for allowing access to the technical files that were produced by Messrs Riches and Feathers during their employment as the design authority responsible for the Sayfglida® HLL system. Also thanks to Mr Frank Drabble whose analytical contributions made it possible to simulate the outcome of falls on a multiple span HLL for the first time, to the Nuclear Electric test team at Cheddar Gorge, and to the engineering team who gave their support to Sayfglida® at BH Sala, Deiniolen, N Wales 1989-1993.

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