Confinement Effectiveness in Concrete Structures

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Abstract: From the beginning of the 19th century, confined concrete is a popular topic among researchers. This is because, the ductile behaviour and strength of the concrete increases, when it is confined. Hence confinement effect is considered in seismic design of concrete structures. To find the strength enhancement due to confinement, various models have been proposed. Some of these models are Mander's model, Shah's model and modified L-L model. These models were developed for concrete confined by spiral reinforcement, (the spiral reinforcement was anchored to the main reinforcement bars). Almost all the experiments in the past on concrete confined with spiral reinforcement were carried out anchoring the spiral reinforcement to the main reinforcement bars. In the present study experiments were carried out without fixing the spiral to the main reinforcement bars. The obtained experimental results were compared with the available models. It was found that modified L-L model was very close to the results obtained. Some applications that could use the confinement effect, such as increasing the column load carrying capacity in post construction stage and using spiral reinforcement to increase shear resistance in beams and flat slabs (punching shear) were discussed. Then the experimental results by using spiral as shear resistors were given and it was compared with the confinement effectiveness of the spiral. Areas identified for the future works have also been highlighted as recommendations for future work.

Keywords: Confinement, Spiral reinforcement, punching shear

1. Introduction

From the beginning of the nineteenth century there has been lots of emphasis given on confinement effect in concrete structures. Confinement increases the ductility and strength of compressed concrete and also confinement effectiveness is used in seismic design to increase the performance of buildings during earthquakes. The confinement is provided in plastic hinge region of the columns and piles using transverse reinforcement (spirals). This transverse reinforcement could give confinement, so the buckling of longitudinal bars and shear failure could be prevented.

The confinement induced by this transverse reinforcement is passive in nature, where confining pressure is induced by the transverse dilation of concrete resulting from principal axial strains. It is shown in Figure 1. Steel that is used as transverse reinforcement has got enough stiffness, so variable confining pressure is induced [5]. The axial and transverse behaviour of the concrete and stiffness determines the variable passive confinement provided.

It is also to be noted that the axial stress strain behaviour of unconfined and confined concrete

differ significantly. The test axial stress strain curve is shown in the Fig. 2 [8].

Figure 1 - Confining pressure

To determine the effect of confinement in addition to steel, materials such as fibre reinforced polymer were also used. Nowadays there is a perception among the researchers to go and find new materials to provide confinement.

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Figure 2 - Unconfined and confined strength vs. axial strain

Already many tests had been done to determine the confinement effectiveness of these new materials (Glass Fibre Reinforced Polymer and Carbon Fibre reinforced Polymer, etc). But the properties of these materials were obtained using accelerated test. So the long term behaviour of these materials are uncertain. But reinforcing steel is a very old material and its long term properties are well understood. So providing confinement with steel bars compared to the newer material will be a reliable and better option. Lots of researchers developed models to predict the strength of confined concrete by spiral reinforcement. Richart et al. was the first to study about the strength of concrete confined by hydrostatic pressure or by spiral reinforcement [8].

Richart et al. carried out tri axial compressive tests of concrete specimens under hydraulic confining pressure and concluded that the strength of the concrete with active confinement from lateral (fluid) pressure was almost same as for concrete with passive confinement pressure induced by closely spaced circular spirals that causes an equivalent amount of lateral pressure. Richart et al. showed at the early stages that the strength of concrete confined by an active hydrostatic pressure can be represented by the formula [8],

$$f'_{cc} = f'_{co} + k_1 f_1 \dots\dots\dots 1$$

f'_{cc} - The maximum concrete stress under the lateral fluid pressure f_1

f'_{co} - The unconfined compressive strength.

Richart et al. [12] also found that the average value of the coefficient for the test conducted was $k_1 = 4.1$. This model was used for long

period of time. Balmer in 1949 found that k_1 varied between 4.5 – 7.0 [8]. From that time onwards various investigators had come up with different models and found the ways to increase the confinement effect.

To find the effective lateral confining pressure on the concrete section by spirals, Mander et al. [8] assumed that the maximum transverse pressure from the confining steel can only be exerted effectively on that part of the concrete core where the confining stress has fully developed due to the arching action. Based on this the lateral confining pressure inserted by the spirals were found out and it is given by,

$$\rho_s = \frac{A_{sp} \pi d_s}{(\pi/4) d_s^2} = \frac{4A_{sp}}{s d_s} \dots\dots\dots 2$$

$$k_e = \frac{1 - \frac{S'}{2d_s}}{(1 - \rho_{cc})} \dots\dots\dots 3$$

$$f' = \frac{1}{2} k_e \rho_s f_{yh} \dots\dots\dots 4$$

f' - The lateral pressure exerted by the spirals

A_{sp} - Area of the transverse reinforcement bar

ρ_s - Ratio of the volume of transverse confining steel to the volume of confined concrete core

f_{yh} - Yield strength of the transverse reinforcement

A_{sp} - Area of transverse reinforcement bar

S' - Clear vertical spacing between spiral or hoop bars

d_s - Diameter of spiral between bar centers.

To determine the confined concrete compressive strength f'_{cc} , a constitutive model involving a specified ultimate strength surface for multi axial compressive stresses is used in this model. When the confined concrete core is placed in triaxial compression with equal effective lateral confining stresses f'_1 from spirals or circular hoops, it can be shown that the confined compressive strength is given by

$$f'_{cc} = f'_{co} \left(-1.254 + 22.254 \sqrt{1 + \frac{7.94 f'_1}{f'_{co}}} - 2 \frac{f'_1}{f'_{co}} \right) \dots\dots\dots 5$$

Ahmad and Shah[1] did some experiment work and based on that gave an equation for f'_{cc} using regression analysis for normal weight concrete specimens reinforced with spirals of yield

strength of 413 MPa. Li et al. [6] modified and extended the confined concrete constitutive model proposed by Li et al. [7], which was originally developed for concrete confined by CFRP, to concrete confined by steel reinforcement. To find the lateral effective stress by confinement they adapted the Mander's model. They assumed that the mechanism of confined concrete is similar to the mechanism of soil under tri-axial loading, the stress relationships of confined concrete can be derived from tri axial relationships. According to Mohr-Coulomb failure envelope of the soil under confined stress (σ_3) and axial stress (σ_1) could be expressed as follows:

$$\sigma_1 = 2C \tan(45^\circ + \varphi/2) + \sigma_3 \tan^2(45^\circ + \varphi/2) \dots 6$$

By using the above constitutive model for confined concrete, the compressive strength of confined concrete (f'_{cc}) can be calculated as follows.

$$f'_{cc} = f'_c + f'_1 \times \tan^2(45^\circ + \varphi/2) \dots 7$$

$$\varphi = 36^\circ + 1 \times (f'_c/35^\circ) \leq 45 \dots 8$$

$$\sigma_1 = 2C \tan(45^\circ + \varphi/2) = f'_c \dots 9$$

f'_1 is same as in the Mander's model

σ_1 - Axial stress

C - Cohesion of the soil or rock

σ_3 - Lateral confining stress

φ - Angle of internal friction of the material

Pallewatte [9] also proposed a behaviour oriented model to find the strength enhancement due to confinement effectiveness. He introduces the concept of Confinement effectiveness index (α) which is defined as the spatial average confining stress developed at the peak strength of the core (σ_v) to the potential confinement capacity ($\frac{1}{2}\rho f_{yh}$). This is introduced because potential capacity is attained when all lateral steel reaches yield condition. Confinement effectiveness index (α) is given by the equation 10.

Pallewatte [9] identifies three important parameters that the confinement effectiveness is depended on. They are ρ_s (Ratio of the volume of transverse confining steel to the volume of confined concrete core, Ratio of lateral tie spacing and the least lateral dimension of the core and the contribution of the flexural stiffness of lateral reinforcement arms.

$$\alpha = \frac{1}{1 + K^* + K_o(s/d)^{\gamma}} \dots 10$$

K^* - Limit uniformity factor

K_o - Uniformity factor

K^* is the Limit uniformity factor that represents the condition when spacing of the lateral reinforcement becomes zero.

$$K^* = \frac{0.7 \left[\frac{\rho f_{yh}}{f_{co}} \right]^2}{F_r} \dots 11$$

ρ - Ratio of lateral steel to that of the confined concrete core

F_r - Parameter based on the geometric properties of lateral reinforcement.

K_o is the uniformity factor that accounts for the uniformity of confining stresses in the lateral direction when the spacing of the lateral reinforcement becomes larger than one.

$$K_o = \frac{7}{F_r} \dots 12$$

$$F_r = 1 + 350 \left(\frac{\emptyset}{L} \right)^2 \dots 13$$

$\emptyset$ - Effective diameter of the tie cross section

L - Linear span of a tie arm

For a circular section F_r is limited to 15. Confinement stress on a concrete core under passive confinement could be found as given in equation 14.

$$\sigma_v = \alpha \frac{1}{2} \rho f_{yh} \dots 14$$

Equation 15 is given to find the strength gain (Δf_c) over an unconfined concrete core

$$\Delta f_c = 6 \left[\frac{\sigma_v}{1 + 0.6 K_o \sqrt{(s'/d)}} \right]^{\frac{3}{4}} \dots 15$$

In the experiments done to validate these models spiral is connected to the longitudinal bars. So this could provide necessary anchorage to the spirals. But in practical, for some application there may be situations where there are no longitudinal bars. So there is nothing to provide the necessary anchorage. So it is important to know the strength enhancement due to spirals in such situations or in non-reinforced concrete structures.

2. Objective

To determine the confinement effectiveness with regard to steel, which is the widely used material in Sri Lanka, without connecting the spiral transverse reinforcement to the longitudinal bars and to find the appropriate model that fits closely with the experimental results, by comparing the values with the existing models to predict the confinement effectiveness on concrete. In addition, it was intended to identify the applications that could use the confinement effect. Also to identify whether confinement strength enhancement is related to the increase in shear strength due to spiral reinforcement as shear resistors in beams.

3. Experimental Details

3.1 Experimental Series 1

In order to achieve the above stated objectives, experiments were done in 2 series. In series one 9 cylinders were casted and they were divided into three sets. Each set contained 3 cylinders and named A, B, C. Set A (cylinders 1,2 and 3) contains cylinders without any confinement. Set B (cylinders 4, 5 and 6) contains cylinders confined with 20 mm pitch spirals and set C (cylinders 7, 8 and 9) contains cylinders with 40 mm pitch spirals. Spiral reinforcement were made using a lathe machine. It is shown in Figure 3. It was made from 5.8 mm diameter mild steel bar which has yield strength of 300 N/mm².

Cylinders were of 150 mm diameter and of 300 mm height. Initially cylinders were cleaned and mould oil was applied. Then spiral reinforcement was kept inside (longitudinal bars were not fixed inside the cylinder).

Figure 3 - Spiral manufacturing using a lathe machine

Then the concreting was done using Grade 25 concrete and the cylinders were allowed to cure in water after demoulding, till the test date (fortnight).

Then the cylinders were tested in compression using Amsler testing machine. The details of the cylinders and the test results were given in Table 1. The photographs taken after failures are given in Fig. 4, 5 and 6.

Figure 4 - Failure of cylinder 1

Table 1 - Test results of unconfined and confined concrete cylinders

Identification	Remarks	Diameter of cylinders (mm)	Breaking Load(kN)	Stress at Failure (N/mm ²)	Average of failure compressive strength (N/mm ²)
Cylinder 1	No spirals	151.5	25.0	13.6	15.3
Cylinder 2		151.7	30.3	16.5	
Cylinder 3		152.2	29.4	15.9	
Cylinder 4	20mm pitch	151.0	64.8	35.5	33.1
Cylinder 5		152.0	58.5	31.6	
Cylinder 6		152.0	59.5	32.2	
Cylinder 7	40mm pitch	152.0	42.3	22.9	23.0
Cylinder 8		152.5	39.1	21.0	
Cylinder 9		152.0	46.5	25.1

Figure 5 - Failure of cylinder 4

Figure 6 - Failure of cylinder 7

It is observed that the cylinders with 40 mm and 20 mm pitches gave about 50 % and 116% increment of strength respectively compared to the unconfined concrete cylinders. The theoretical values of the confinement were found from the Mander's model, Shah's model modified L-L model and Behaviour oriented model. These values are given in Table 2.

Table 2 - Theoretical values of confined compressive strength

Theoretical model	Compressive strength for 20mm pitch spiral (N/mm ²)	Compressive strength for 40mm pitch spiral (N/mm ²)
Experimental	33.1	23.0
Shah's model	22.1	17.8
Mander's	37.4	27.9
Modified LL	36.7	24.9
Behaviour oriented model	35.5	27

Then the experimental values were compared with the theoretical values (Table 3).

Table 3 - Comparison of experimental and theoretical values

Theoretical method	$\left(\frac{\text{Experimental}}{\text{Theoretical}}\right) \times 100$ (%)	
	20 mm pitch	40 mm pitch
Shah's model	129.1	150.0
Mander's model	88.5	82.4
Modified LL model	90.2	92.3
Behaviour oriented model	93.3	85.2

It could be seen that the values from the modified L-L model, Mander's model and behaviour oriented model were very close to the experimental results. The modified L-L model is closer to the experimental results when the cylinders are confined by 20mm and 40mm pitch spiral. It is almost 91 % of the total value. But Shah's model prediction is varying a lot, compared to the experimental results. This is because Shah's model is done for specific concrete (Normal weight concrete) and for specific strength of steel bars. This prediction is based on the regression analysis. So this is not suitable to predict the confinement strength enhancement where the concrete is confined by the materials with different properties. Also the lateral pressure k_1 was found and compared with the Richart [6] values. The k_1 values found from the experiment are given in Table 4.

Table 4 - K_1 values for experimental results

Number	Pitch size	K_1 values
Cylinder 4	20 mm	3.6
Cylinder 5	20 mm	3.2
Cylinder 6	20 mm	3.3
Cylinder 7	40 mm	3.0
Cylinder 8	40 mm	2.8
Cylinder 9	40 mm	3.3

It can be seen that for pitch size 20 mm k_1 value is in the range of around 3.2 - 3.6. For 40 mm pitch it is in the range of 2.75-3.3.

So depending on the pitch sizes the confinement effective co-efficient varies. For 20

mm pitch size spirals these values were around 18% less and for 40 mm pitch around 26% less compared to k_1 values proposed by Richart et al.

3.2 Experimental Series 2

To determine the enhancement of shear strength due to spirals, three small beams with a span of 0.77 m and cross section of 150mm X 150mm were casted and the beams were named as A, B, C. In Beam A only bottom reinforcement (2T16 bars) were fixed. In Beam B 40 mm pitch spiral as shear reinforcement and bottom bars (2T16 bars) were fixed. In Beam C 60 mm pitch spiral as shear reinforcement and bottom bars (2T16 bars) were fixed. It should be noted that the spiral reinforcement was not anchored to the main reinforcement (bottom reinforcement).

Table 5 - Cube Strength

	Cube Strength (N/mm ²)
Cube A	30.3
Cube B	28.8
Cube C	25.6
Average Strength	28.2

Figure 7 - Spiral as shear reinforcement.

The reinforcements were fixed inside the moulds and they were concreted using Grade 25 concrete. The arrangement of reinforcement inside a mould is shown in Fig. 7. Beams were allowed to cure in water till the test date (fortnight). Then they were white washed so the crack patterns could be clearly identified.

Then they were tested using Amsler testing machine. The testing arrangement is shown in Fig. 8. The experimental failure loads and the calculated shear stresses at failure are given in Table 6.

Table 6 - Failure Loads

Spiral pitch	Failure load (kN)	Shear stress (N/mm ²)
No spiral	54.94	1.49
40 mm	96.14	2.63
60 mm	94.17	2.60

According to BS 8110: Part 1: 1985 Table 3.9 shear strength of concrete,

$$V_c = 0.79 \left(\frac{100A_s}{b_v d} \right)^{\frac{1}{3}} \times \left(\frac{400}{d} \right)^{\frac{1}{4}} \times \left(\frac{f_{cu}}{25} \right)^{\frac{1}{3}} \dots \dots \dots 16$$

f_{cu} - The compressive strength of the concrete

A_s - The area of steel reinforcement

b_v - Width of the beam

d - Effective depth

Safety factor of 1.25 is not considered in this equation, although it is included in the code. This is because the actual shear capacity is considered, without applying safety factor. In order to identify the compressive strength of the concrete three control specimens (150mm x 150mm cubes) were casted. The compressive strength of the concrete at 14 days was found to be 28.2N/mm².

Here Beam B and beam C have a different pitch of spirals as shear reinforcement, but shear stress at failure is almost the same.

Figure 8 -Testing arrangements for beams

The reasons for this is, there crack inclination angle were different and it was found that in both beams failure plane cut equal number of links.

4. Discussion

4.1 BS 8110: Part 1: 1985 codes specification about the shear strength and the experimental shear stress at failure

Shear capacity of the concrete depends on,

- ❖ Concrete strength
- ❖ Dowel action
- ❖ Aggregate interlocking
- ❖ Depth of the structural element.

Figure 9 - Shear failure of the beam 1

BS 8110: Part 1: 1985 code specifies the shear strength of concrete. From equation 16, the shear capacity of the beam A has to be 1.44 N/mm² (without considering the safety factor of 1.25). The beam failed in shear as shown in Fig. 9. The shear stress at failure is 1.49 N/mm². So the actual shear stress at failure was slightly higher than the BS code predicted.

4.2 Increment in shear carrying capacity due to spiral reinforcement.

It is evident from experimental results (Table 5) that there is an increase in shear carrying capacity for beams that are reinforced with spirals. For beam B, there is a 1.14 N/mm² shear strength increase compared to the control specimen.

Kamal Jafaar [3], during his experiments found that spiral reinforcement as shear resistors, also could increase the shear carrying capacity of the beams. But the extent to which the strength increases is not determined yet. This increment could be due to two reasons.

1. Due to the confinement effect of spirals.
2. Due to the direct tension induced in spiral because of the shear force

4.3 Prediction of increase in shear carrying capacity due to confinement effect

Karayannis et al. [4] did experiments about the shear capacity of beams with continuous spiral transversal reinforcement. They constructed three beams. The first specimen had common stirrups and the second one transversal reinforcement and the third one with spiral transversal reinforcement with favourably inclined legs. Each transversal reinforcement is made of similar spacing.

From the results and behavioural curves they concluded that the specimen with continuous spiral reinforcement showed high shear strength behaviour than the beam with closed spirals. With continuous spiral shear reinforcement showed respectively 15% and 17% higher shear strength than the beam with closed stirrups. So this enhancement would have occurred because of the increase in concrete shear strength due to the confinement effect.

For the experimental series 2, the cubic strength of the concrete was 28.2 N/mm². It was converted to cylindrical strength (Euro code specifies that to change the cubic compressive strength to cylindrical compressive strength, the cubic strength has to be multiplied by 0.8). Then by using the modified L-L model the increase in compressive strength due to confinement was calculated. Then it was converted into cubic strength. It was assumed that the multiplication factor to change the confined cylindrical strength into cubic strength is similar to that of unconfined concrete.

From the equation from BS 8110: Part1: 1985 the increased shear strength of concrete was calculated (due to increase in compressive strength due to confinement). The cover concrete was also assumed to be in confined stage. It was around 0.183N/mm². But the experimental increment was very high. It was around 1.28 N/mm². So this shows that there are other factors of spiral which contribute to the shear enhancement.

4.4 Prediction of increase in shear carrying capacity when the spiral is in direct tension

The shear carrying capacity of the spiral, when it is in direct tension could be predicted using discrete method or average integration method [2].

not have adequate anchorage length at certain locations, especially close to the top and bottom reinforcement.

2. This method of calculation of shear strength of the spirals adapts the principal of truss analogy. But actually there may not be an imaginary truss formed, when spirals are used as shear link without connecting it to the longitudinal reinforcement bar.

Figure 10 - Spiral reinforcement and the failure surface

In Fig. 10, height of points from bottom of the spirals to the points where the spiral reinforcement and failure surface intersects is shown.

The angle of the failure surface was taken from the failed beam B. Shear capacity of spiral reinforcement using discrete method was given as

$$V_s = A_{sp} f_{ysp} \sin \alpha \sum_{i=1}^n \sqrt{1 - \left(1 - \frac{a_i}{r_{sp}}\right)^2} \dots\dots\dots 11$$

V_s - Shear capacity

A_{sp} - Area of both legs of each spiral links

a_i - Distances locating the position at which a crack intercepts a spiral

r_{sp} - Inner radius of the spiral

α - Inclination angle of the transverse reinforcement

Using equation 11, the increase in shear carrying capacity due to the spiral reinforcement was calculated [2]. It was around 2.05 N/mm². But experimental results show only a 1.14 N/mm² of increment in shear capacity, which is 57.5 % of the expected value. So the experimental results is low compared to the expected, the reasons could be,

1. This may be because, although the spiral reinforcement is said to be having self anchorage mechanism, in actual case it may

4.4 Cube strength vs. cylindrical strength

Euro code specifies that to get the cylindrical strength of the concrete, cubic strength has to be multiplied by a factor of 0.8. But in experimental series 1, for unconfined cylinders average cylindrical compressive strength is 15.3 N/mm². But the average cube strength was found out to be 21.29 N/mm². So cylindrical strength is 0.72 times the cube compressive strength. In Sri Lanka currently BS 8110: Part 1: 1985 is used. But according to British Standards Institute it is a withdrawn code. So it is time for us to change to Euro code. So it is necessary to determine the correct ratio of cylindrical strength to cube strength of concrete that is specific to the materials of Sri Lanka.

5. Applications

Since the confinement due to spirals, without fixing it to the longitudinal bars also very effective, this technique can be used in several applications.

1. To increase the strength of concrete columns during the post construction stage, reinforcement similar to a spiral arrangement using steel bars or high tensile steel wire could be fixed and then to hide the reinforcement it could be plastered. In present situation to increase the strength of column steel jacketing as well as concrete jacketing is used. Instead of

this these wrapping the steel reinforcement around the column and then simply plastering it also can be considered as an option. The possible arrangement is shown in Fig. 11.

Figure 11 - confining column by steel reinforcement

2. Confined compressive strength of concrete is higher than the concrete without confinement, due to this the shear strength of the concrete could also increase. In BS8110: 1985: Part 1 relates the compressive strength of concrete to the shear strength. This could be used to prevent punching shear failure in flat slabs. So confinement effect could be used to increase the shear carrying capacity of thin flat slabs.

BS 8110: Part 1: 1985, clause 3.7.7.5 depicts the shear reinforcement in the form of spirals may be provided in slabs over 200 mm depth to increase the shear resistance. It does not guide us to provide shear links for thin slabs (less than 200mm) because it is practically difficult to fix the links. Other than shear links there are various methods of shear resistance available. Some of the options are shear band and stud rail shear resisting systems. But they are patented. Already the research done at university of Moratuwa had proved that there is an increase in shear carrying capacity when spirals are used as shear resistors [11]. But the contribution by the confinement effect for the increase in shear capacity is still not determined.

6. Conclusion

From Table 1, there is a significant increase in compressive strength when the concrete cylinders are confined by spiral reinforcement. The result of the experiment closely fits the modified L-L model which is developed by Li et al. So this model could be used to predict the confinement strength enhancement, but with a safety factor of 0.8. This is because experimental

values obtained were slightly less than the theoretical values, which is based on the modified L-L model.

Experimental Series 1 was carried out without fixing the longitudinal reinforcement bars inside the cylinders. So the spiral reinforcement is not anchored to the longitudinal reinforcement. The results prove that even without anchoring the spiral reinforcement to the main bars, there is a significant increase in compressive strength. So this could be applied at situations where the strength need to be increased, but the lateral reinforcement is not possible to be connected to the main reinforcement.

These days' people are keen in using new material to provide confinement in concrete structures. But long term impacts of these materials are still questionable. But steel is a well known material and its long term properties are well known and the continuous transversal spiral reinforcement gives a reasonable increase in concrete strength. So it will be reliable to use steel to confine the concrete.

Based on the results from experimental series 2, there is an increase in shear carrying capacity when the spiral reinforcement is used instead of shear links. This increment could be due to the confinement effect and due to the direct tension force induced in spiral.

7. Recommendations for future works

1. Columns to be casted and to be strengthened by lateral reinforcement. Then the strength enhancement due to the lateral reinforcement should be identified. After construction of the column, lateral reinforcement could be fixed to the column as shown in Figure 11. Then it could be plastered to hide the reinforcement.

2. A detailed experimental work to be done to find the component of increment in shear stress due to confinement effect of the spiral. Slab panels or beams with spiral as reinforcement should be casted by varying the diameter of the spirals, bar diameter and the pitch of the spirals. This will sheds more light in design calculations.

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