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Stability Study of Arches Vaults and Domes Built by Compressed Stabilized Earth Blocks

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Abstract:
We base this paper on the building principles of Compressed stabilized earth bricks, a distinguished technique of earth construction. Objective of this research resides in maximizing the use of Earth as a construction material and replacement of steel, reinforced concrete cement as much as possible (less than 6-7% in most cases). The institute's continuous avant-garde attempts are opening new doors in Sustainable construction – eco-friendly and energy saving technologies.
The structural principles corresponding to the use of Earth as major construction material differ vastly from the everyday construction techniques using RCC etc which have been mastered to their capacities in many a aspects by the Earth Institute. We will discuss our learning and research under Ar. Satprem Maini's guidance in relation to the construction techniques and principles of Arches, Vaults and Domes using compressed stabilized earth blocks.
The attraction of humans to Dome roofs, arches and vaults goes back to the beginning of settlement. Starting from simple conical huts and circular domes, man has come to build over 40-50 basic types of arches, vaults and domes.
The main principles of stability of this type of construction are based on the horizontal thrust forces, Weight loads and line of thrust in case of arches and an addition of hoop forces in case of domes. We discuss 2 methods to study any arch's stability: Catenary Method and the Funicular method. Architects have been using the catenary form for a stability test for years. The most prominent example would be of Antoni Gaudi's use of chains and links and gravity (makings of a catenary) in his designs.
The funicular method has been modified for this specific Earth Construction technique of the Institute. The Funicular study of an Arch (section) shows its exact stability profile and can easily specify the counter solution for future structural problems against common loads. It is the essential step for the Optimization method developed for unstable arch profile made for such construction. Optimization method has been especially developed for constructions without centrelines of arches, vaults as well as domes, despite their structural differences. The lightest arch's optimal section is taken and half of the arch is considered, with the thickness increasing from the top towards the bottom. Once an optimized profile is achieved, masonry pattern is defined, specific to the kind of earth blocks that are being produced in the laboratory.
We draw from personal practice and the study of real time projects structured on this method which is being used successfully in many parts of the world and is one of the most cost effective, Eco-friendly and energy saving methods of construction.

1. Compressed Stabilized Earth Blocks (CSEB)

A compressed earth block is made using stabilized or raw soil with small amounts of moisture and may or may not be mixed with a stabilizer. This composition is compressed in a steel press- manually or motorized. They have been in existence since 19^{th} century in simple forms.

Stabilizers allow buildings to be higher and walls to be thinner. They will have more strength against compression and better water resistance. Using cement as stabilizer, curing of blocks go on for 20-28 days after the manufacturing. Post curing, bricks can be left to dry and will be used during construction like normal bricks with Soil as cement mortar. Thus, these bricks are known as Compressed Stabilized Earth Blocks (CSEB)

Soil composition for CSEB: Different composition is required for different stabilisers: For cement as a stabiliser, soil needs more sand content (50% than clay content (20%). Whereas for lime as a stabilizer, coil needs more clay (35%) than sand (30%). Gravel and silt content remain 15% and 15-20% respectively.

According to these specifications, adding of gravel or sand to the soil available can be done to improve its quality. The procedure to stabilize available soil is as follows to get the desired results when soil is wet. Stabilisation is not required when soil is not exposed to water.

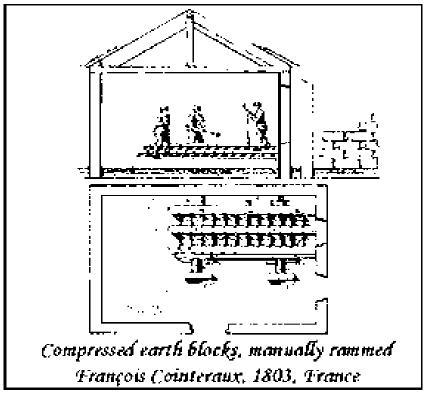

Figure 1

	PRINCIPLE	ACTIONS
Mechanical	Compacting soil	• Density of soil and mechanical strength are maximized along with the resistivity against water, decreasing permeability as well as porosity.
Physical	Addition or removal of aggregate to improve soil texture	• Sieving removes particles of coarse nature mixing different soils to obtain appropriate texture. Clay for binding and gravel/sand to strengthen.
Chemical	Achieving the desired quality by adding chemicals.	• Chemicals added shall bind the earth together.

Table 1

2. Structural Principle

2.1. Arches & Vaults

Stability of Arches and vaults is attributed by thrust. Variation in the intensity and angle of Thrust or the line of force (resultant) characterizes the stability of an arch or dome. Here we talk of thrust as a resultant of load due to the arch's weight and the horizontal force or thrust.

Of these two, Horizontal thrust depends upon:

- Voussoir's weight
- Curvature of the arch- Less curvy the arch, more the thrust.

The HT is found on three spots in an arch – on the Springers and at the top. If HT is over limits it can be administered by changing the arch profile or by addition of support structures such as buttresses, truss rods, ring beams etc.

Line of force is a successive addition of the resultant forces acting at every point of the arch, i.e., the resultant of weight and HT.

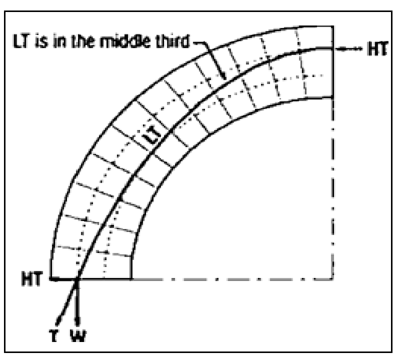

Figure 2

The condition of safe stability is that the Line of thrust shall be within the middle third portion of the arch section or vault.

T: Resultant force, thrust.
LT: Line of thrust.
HT: Horizontal Thrust.
W: Load due to weight of masonry and other loads.

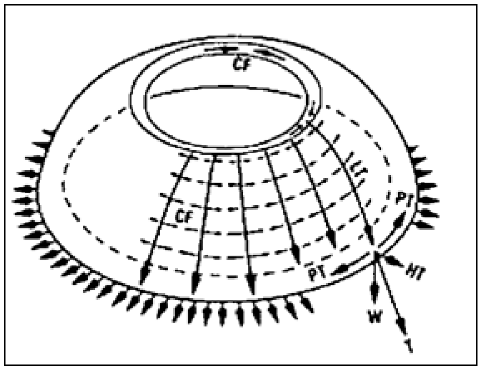

Figure 3

2.2. Domes

Dome's stability is also dependent on the attribute namely thrust which is the composition of weight and horizontal thrust of a typical arch section of its structure and hence, a line of thrust also corresponds to it. But domes don't fail as easily as arches or vaults. Design corresponding to a specific line of thrust which may fail an arch, may not fail a dome structure as another attribute, a more stabilizing force called Hoop force acts in a dome. Hoop forces are acting circumferentially in a dome for every horizontal ring in the dome. These forces allow a circular dome to be built without temporary supports, as the successive rings of the dome support each other. The resultant of these hoop forces creates a peripheral tension (PT) which acts on the wall beneath the dome.
LT: corresponding to an arch section.
CF or HF: Hoof force of each ring.
HT: Horizontal thrust.
W: weight load corresponding to an arch section.
T: Thrust for the arch section.
PT: Peripheral tension.

3. Stability Calculation

3.1. Catenary Method

The Catenary method of calculating an arch's stability has been in play since early 17th century. It was engineers and architects like Robert Hooke and Antoni Gaudi who applied the correlation of a chain's tensile stress and an arch's compressive stress. Antoni Gaudi's comprehensive studies of this method showed in application in his works of arches and vaults-always following the Catenary shapes.
This method is carried out by freely suspending a chain from two points on a white board to form the Catenary shape. Here the chain represents the centre-line of the arch section of the vault which is being analyzed. Now links of smaller chains are added to the main chain to represent the other loads on the vault-like that of masonry. This new curve is analyzed as the line of thrust-the ideal situation-but the intensity of these forces shall be obtained from the funicular method.
We try to determine how an arch shall be designed in order to bring its LT in the middle third, by adding weights –varying from 1-20 links- at different locations. We start by drawing the arch section on the board along with its middle third. Then we take a chain of length equal to that of the centre line which is equal to

$$\frac{A=\pi(R+1/2t)\alpha}{180}$$

Where, R=radius, α= angle of arch and t=thickness

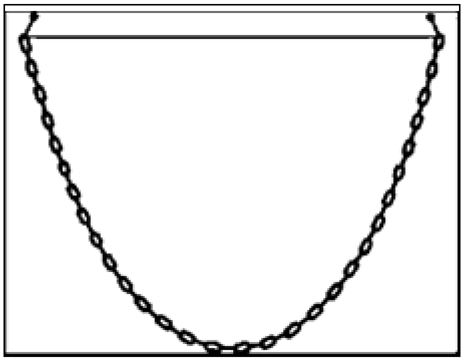

Figure 4

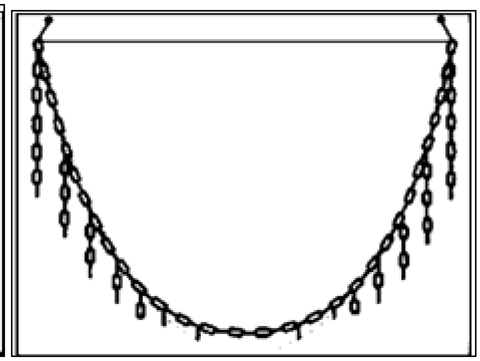

Figure 5

Hang this chain on the reversed drawing of the arch section, unless the desired arch is pure Catenary section, the chain will not be within the middle third. Now start the loading of the chain symmetrically by using the small chain links keeping then as evenly spaced as possible. Our aim is to get the chain inside the middle third of the section note that the chain, being the LT, must follow the pattern shown in the table.

Arch type	Entry of LT	Exit of LT
Segmental arch	Centre of arch	Centre of arch
Bucket arch	At 2/3 from arch intrados	At 2/3 from arch intrados
Semicircular arch	At 2/3 from arch intrados	At 2/3 from arch intrados
Egyptian arch	At 2/3 from arch intrados	At 2/3 from arch intrados
Catenary arch	Centre of arch	Centre of arch
Equilateral arch	Touched the intrados of arch	At 2/3 from arch intrados
Pointed arch	In intrados third of arch	At 2/3 from arch intrados
Corbelled arch	Centre of arch	Centre of arch

Table 2

Having done this, we now have the position of loads. Calculate the length of the segment on the scale of the arch drawing by:

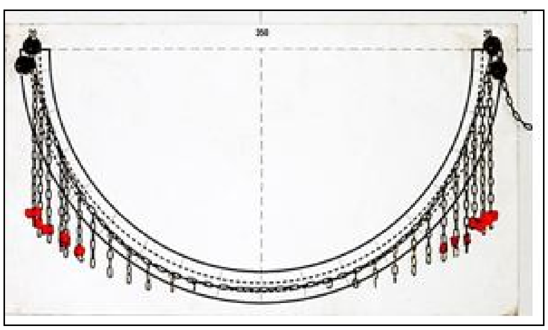

Figure 6

$$L = \frac{(\text{No. of links per segment}) \times (\text{length of chain}) \times (\text{drawing scale})}{\text{No. of links}}$$

Calculate the weight of each segment in kg/m by:

$$W(\text{segment}) = \frac{L \times t \times p \times (\text{Total no. of links per segment})}{(\text{No. of links per segment})}$$

The drawing of this arch is now reversed and these theoretical loads need to be stabilized by masonry. Height of this masonry is given by:

$$Height=\frac{Wload}{Width \times \varrho}$$

Where, ϱ is the volumetric mass in kg/m3

3.2. Funicular Method

3.2.1. Principle

This study is done by drawing half an arch section, divided along the curvature in small segments. On these segments, weights, Centre of gravity (CG), intensity of horizontal thrust are to be analysed and marked on the drawing. The line of thrust (LT) enters horizontally at the top of the arch and HT is the horizontal component at each segment. The force at the top of the arch is the balancing component between the two components of the arch profile and is needed to divide the arch in two parts. LT assumes its curve when HT meets the vertical line of CG, changing the resultant's angle consecutively in each segment. T keeps changing its angle till the last line of CG is accounted for and the ultimate resultant force obtained is the thrust T whose angle and intensity is calculated. The following method shall be followed to obtain the correct intensity of thrust and location of LT in the arch section.

3.2.2. Method

- One half of the arch at the largest possible scale is drawn according to the span. Dividing it into segments which of equal length than calculate the weights (kg) of all segments. Their area can be approximated to trapezoids. Weight of segment would be =me X t x w x p, where me = median of the trapezoid (m), T = thickness (M), P = volumetric mass (kg/m3), W = width if the arch (m) – if the study is for a vault, the width is taken as 1 metre.
- Then define the centre of gravity (CG) of each segment while drawing the arch centreline .The CG will be centred on the median of the segment. The vertical lines of the CGs and reference all segments than add all the weights to know the total weight (kg), of half the arch.
- Evaluate the horizontal thrust, HT' which is not the actual force acting in the arch.HT' is related to the weight of the half of the arch, According to the shape ,HT' can be evaluated as:
  - Segmental arches: HT' = W
  - Bucket arches: HT' = W
  - Semicircular arches: HT' = W/2
  - Egyptian arches: HT' = W/2
  - Catenary arches: HT' = W/2
  - Equilateral arches: HT' = W/2
  - Pointed arches: HT' = W/2 or W/3

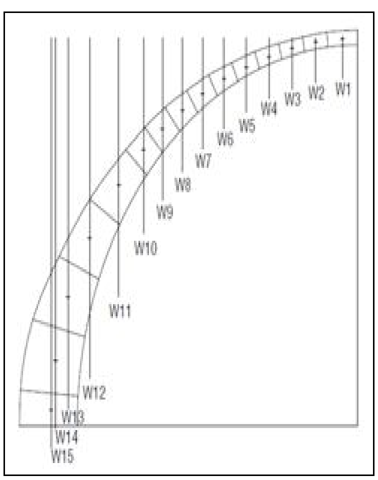

Figure 7

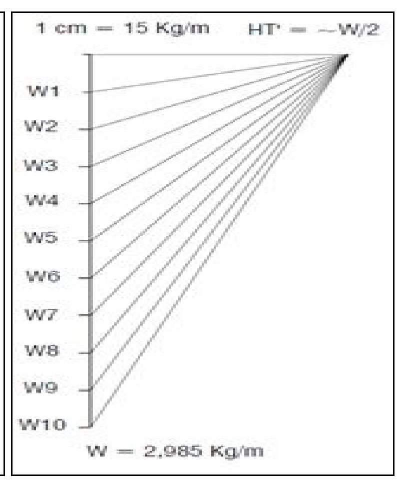

Figure 8

3.2.3. Start the Funicular Diagram

Report all weights and HT' on the diagram than trace the resultant forces by joining HT' and various weights. Transfer the resultant forces of the diagram, one after the other, onto the section of half the arch. Draw the line of HT' and let it enter the arch according to this pattern for the typical arches

- HT’ remains horizontal till it encounters the vertical line of the first segment.
- Draw the first resultant of the thrust , T’1 from the first vertical line:
- Transfer the resultant of HT’ and W1 from the diagram.
- The resultant forces of the diagram onto the section of the arch. The various resultant forces will define a theoretical line of the thrust, LT’, which is not the actual one acting in the arch.
- The last resultant force is not the actual thrust. It is a theoretical one, named T’.
  Extend the line of T’ to meet the line HT’. The intersection point is named I.
  This point is the “pivot of stability” of the arch which closes the funicular diagram.
- Joining the point I and the exit point of the thrust on the Springer of the arch:
  Follow the pattern for typical arches, shown in the table of the 9^{th} step in the previous page. This will be the real direction of the thrust, T.
  Transfer T onto the funicular diagram. It starts from the total weight, down the diagram, to cross the HT’ line. The intersection of T and this will define the actual horizontal thrust HT.
- Draw on the funicular diagram all the resultant forces by joining HT and the various weights. This will define a new diagram which shows now the actual forces in the arch.

ARCH TYPE	ENTRY OF HT’	EXIT OF LT’
Segmental arches	Centre of the arch	Centre of the arch
Bucket arches	At 2/3 from the arch intrados	At 2/3 from the arch intrados
Semicircular arches	At 2/3 from the arch intrados	At 2/3 from the arch intrados
Egyptian arches	At 2/3 from the arch intrados	At 2/3 from the arch intrados
Catenary arches	Centre of the arch	Centre of the arch
Equilateral arches	Touches the intrados of the arch	At 2/3 from the arch intrados
Pointed arches	In the intrados third of the arch	At 2/3 from the arch intrados

Table 3

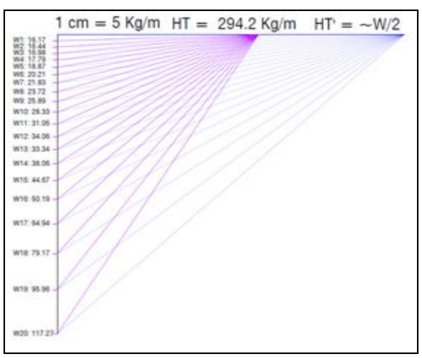

Figure 9

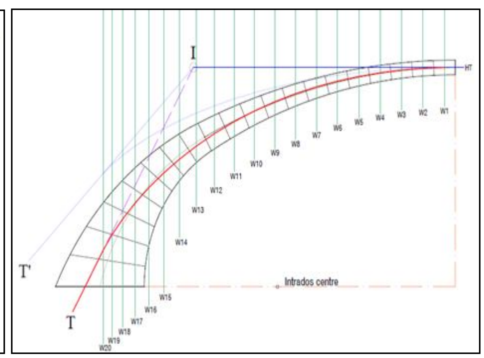

Figure 10

- The line of thrust should remain within the middle third.

3.2.4. Study Done by Hand on a Drawing Table

Only W is accurately known, as it was calculated at the beginning. T and HT cannot be calculated and are measuring on the drawing. Thus it is essential to draw the diagram at the largest possible scale and as precisely as possible, so as to convert with the scale their intensity with the minimum of error.

As T and HT are not calculated but approximated from the drawing, their intensity should be indicated with ±

T should be measured first as it is the longest force. The intensity of HT and T should be sounded and be slightly adjusted to get a triangle which is not too far from Pythagoras Relationship: T2 = W2 + HT2

Transfer all the resultant forces of the actual funicular diagram onto the section of the arch. This will define the actual line of the thrust, LT

3.3. Optimisation Method

3.3.1. Aim

The optimisation method is done when a centre line is not used for building arches and vaults and can also be adapted for domes-when not inside a building. Funicular method is the first step of optimization method. The basis of this method lies in the principle that LT should be in the middle third of the section thrust should be smaller for a light section.

Simple way to optimize arch is to reduce HT but it may result in extra weight as load is required on the haunches and a heavier arch ultimately exerts more HT thus it is more effective to focus on the arch's lightness.

3.3.2. Principle

Half of the arch section is drawn such that apex has the least thickness and it increases along the curvature. We need to find the apex's thickness and this study is done to achieve an appropriate section in accordance to the arch's span and shape. After the funicular method yields a light section, masonry pattern can be defined.

3.3.3. Method

This method starts with the Catenary method. It integrates also the Funicular method and other particular studies.

3.3.3.1. Defining the drawing the arch section

Draw half of the desired arch using a large scale (1/5 to 1/10) which fits on the tracing paper and define the arch's bottom thickness in relation to the span:

- 1/12 for 3 to 4 m span = 25 to 30 cm
- 1/15 for 5 to 6 m span = 30 to 40 cm
- 1/20 for 7 to 10m span = 40 to 50 cm

Define the minimum thickness at the top of the arch:

- 7 cm for the span between 3 to 6 m
- 9 cm for span between 6 to 10 m
- 11.5 cm for spans between 10 to 15 m
- 21 cm for spans between 15 to 25 m

Draw the centreline and the three thirds of the arch once the thickness have been defined. Calculate the angles of the various radiuses, if the arch is segmental or has several centres, average thickness (t) of the arch = (bottom thickness + top thickness)/2 and then the length (in m) of the arch centre line:

Centre line= $\pi(R+1/2t)\ \alpha$

Where, R= intrados radius (m),

180T= average thickness (m),

A=Angle of the arch

Note - that the centreline of the arch is not exactly the line of thrust as LT moves around the centreline .Nevertheless, this approximation is sufficient for the study.

3.3.4. Funicular Study

- The arch has now different thickness from top to bottom
- Lt should enter in a different way for some arches according to the following pattern:

Arch type	Entry of LT	Exit of LT
Segmental arch	Centre of arch	Centre of the arch
Bucket arch	Now at the centre of the arch	At 2/3 from arch intrados
Semicircular arch	Now at the centre of the arch	At 2/3 from arch intrados
Egyptian arch	Now at 1/3 from the intrados	At 2/3 from arch intrados
Catenary arch	Centre of arch	Centre of arch
Equilateral arch	At the intrados of the arch	At 2/3 from arch intrados
Pointed arch	In intrados third of arch	At 2/3 from arch intrados
Corbelled arch	Centre of arch	Centre of arch

Table 4

- The first diagram may not get LT within the middle third.
- The thickness has to be adjusted along the extrados curve and / or bottom of the arch.
- Adjust the segment width:

Increase the thickness, and thus the weight, where LT is towards the intrados.

Decrease the thickness where LT is towards the extrados. In many cases, when LT is not in the middle third at a point, the problem has to be solved either before or after, because the arch is either too thin or too thick before or after this point.

Thickness is minimal near the apex. Therefore, if LT is close to the extrados at the upper portion, the width should not be reduced but kept as such and sometimes even increased, according to the arch type (i.e. Egyptian arch)

- Note that increasing the bottom thickness may increase the total weight of the arch and therefore will not give the most optimized arch.
- It is better to try optimizing the thickness along the extrados curve and only in the last resort to increase the bottom thickness.

- Calculate the new weights and centre of gravities for all segments, and redo the stability study with the funicular method to check if the line of the line of thrust is now within the middle third.
- It might be necessary to redo the previous step a few times
- Adjust the thickness of some segments.
- Calculate their weights
- Redo the funicular diagram until LT remains in the middle third.
- It is necessary sometimes to move the exit of LT, so as to get it in the middle third of the arch.
- Lt exits in the certain way, depending on the type of the arch.
- This condition has been obtained by research and it is a safe limit. But it can be changed shows that LT 1 exits as required, but it is outside the middle third towards the top.
- Elsewhere it is safely in the middle third.
- The exit of Lt can change as LT2 and then the line of thrust remains everywhere in the middle third of the arch.

This principle can also be applied with the entry of LT by moving a little bit the entry of LT up or down the theoretical entry; it might be possible to get it in the middle third everywhere. Once Lt is within the middle third, the arch stable but it could still be optimized further. The aim is now to minimize the thickness of the bottom of the arch.

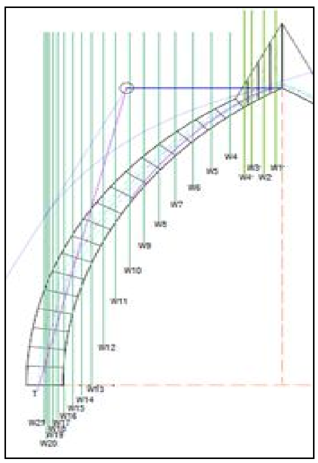

Figure 11

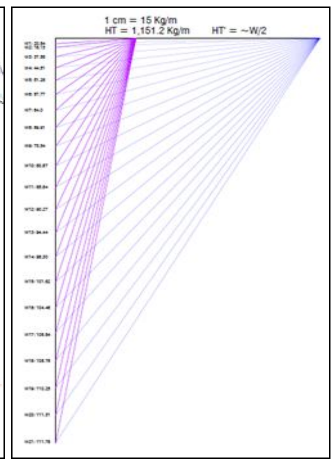

Figure 12

The minimum thickness on the springer is obtained when LT touches sometime the limits of the middle third, while remaining in it. When this is achieved, the arch is as light as possible .it has been fully optimized and the stability study is over, this step is optional, as the arch was already stable.

4. Conclusion

In the field of earth construction, the undergoing research on CSEB blocks and their building techniques is an ever developing contention. Eliminating the use of cement being the ultimate goal and perfecting this sustainable material is being undertaken at the Auroville Earth Institute. Our study covers the designing of and stabilization of arches, vaults and domes built with CSEB blocks. These structures can be found abundantly in Auroville and many other parts of the world, which are not just aesthetically surpassing but also structurally sound.

5. Acknowledgement

We are highly obliged by the first hand guidance provided by Ar. Satprem Maini, Director Auroville Earth Institute, and his surpassing knowledgeable experience in the field of Earth architecture.

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