A FINITE ELEMENT BASED METHODOLOGY FOR STRUCTURAL ANALYSIS OF MS LINER SYSTEM IN SPENT SUB ASSEMBLY STORAGE BAY

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ABSTRACT

Nuclear Power Plant (NPP) structures for storage of Nuclear wastes are lined with metallic liners over the inner concrete surface due to stringent requirements of containing radio active fluids and preventing leakage of the fluids to the external environment through the possible cracks in the concrete. Under the action of the various static and seismic loads, the integral liner deforms with the concrete surface. The liner design, involves, determination of forces generated in the liner plates, the supporting embedded parts for the liner plates, and the connection (jointly called as the liner system), to maintain the integrity of the liner system under the deformed profile. This paper deals with the methodology adopted for the structural analysis of the liner system, adopting sub-modeling technique. The approach adopted for determination of forces in different elements of the liner system, and their design to maintain the integrity of the liner system is outlined. The analysis and design issues and solutions adopted are discussed with an illustrative example and the solution adopted for a Nuclear Power Plant structure under construction in India.

INTRODUCTION

Metallic liners for concrete are widely used in NPPs for containing radio active fluids and preventing leakage of the fluids to the external environment through the possible cracks in the concrete. This liner is reinforced by means of stiffeners, generally T-sections running along the length and breadth of the liner plate. These stiffeners are embedded into concrete by means of anchors. (Figure 1). With this arrangement the liner system (Liner plate, stiffeners and anchors, and the inter-connections), behaves integral with the concrete surface, and deforms with the concrete surface, under action of various loading conditions.

This paper presents a three-stage approach for analysis of the liner system using the sub-structuring technique. The deformations in the concrete structure are obtained from the results of the global analysis of the concrete structure using a centre line model. A refined FE model of the liner with the various stiffening elements at their locations is modeled, with the intent of transfer of the global model concrete deformations appropriately to enable determination of liner plate stresses and the stiffener forces. Finally the anchor forces are determined so as to maintain the integrity of the liner system with concrete based on which the different connections are designed.

The methodology is elaborated with examples from the work being done for Prototype Fast Breeder Reactor (PFBR), under construction, at Kalpakkam, in India. The Nuclear Island Connected Building (NICB) is a large Reinforced Concrete Building of size 92.6m x 83.2m x 72m height consisting of eight buildings connected monolithically. The Fuel Building (FB) is one of the buildings forming part of NICB housing the Spent Subassembly Storage Bay (SSSB) to store spent fuel submerged under water. This is a lined pool of about 18 x 6 x 9m Ht. The analysis and design of the liner system in this pool is chosen as an illustrative example.

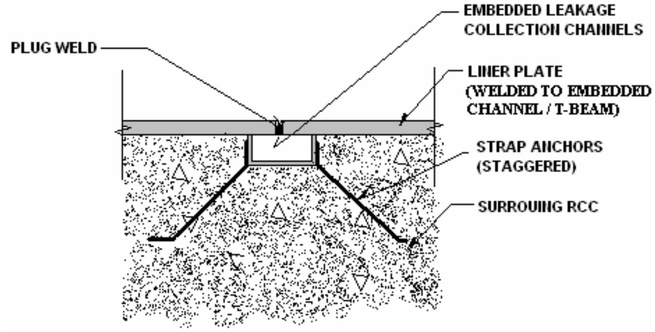

Figure 1 - Components of Liner System

UCTURAL BEHAVIOUR OF LINER SYSTEM

The liner plate is provided over the top of base slab and over the inner surface of the concrete walls. Stiffeners (T-sections / channels) are embedded in concrete using anchors. The liner plate is welded to these stiffeners. These stiffeners act as interface elements between the liner plate and concrete surface. Hence there will be compatibility of strains in the concrete below the liner plate and the liner. These displacements transferred to the liner plate induce in-plane and bending stresses in the plate. The stiffeners stiffen the liner plate, eliminating local instabilities (buckling), and resulting excessive deformation in between the anchor points. Differential strain, if any, will be transmitted to the anchors as pull out forces. These forces are dependent on the stiffness of the liner plate, stiffeners, and the spacing of the anchors.

BASIS OF METHODOLOGY - SUB -MODELING

The approach involves transfer of displacement profile at the surface of the elements of global FE model, on to the elements of a sub model developed for analysis of liner, involving modeling of liner plate and stiffeners.

The concrete elements of the global FE model are formed relatively coarser, so as to reduce the number of DOFs of the global model in the sub-model. The liner system of stiffeners and liner plate panels is modeled with a relatively finer mesh as compared to the concrete model. The stiffeners are to be modeled at their locations, and, the liner panels in between the stiffeners are modeled fine enough to represent the variations in stresses due to boundary displacements.

In order to transfer the displacement profile from coarser concrete mesh onto a finer liner mesh, sub modeling technique is utilized. Each node pertaining to the stiffeners of the liner system (which are the interface nodes between concrete and liner system), are mapped on to an element of the coarser concrete mesh (by location), by means of shape function of shell element used for modeling the concrete structure. The coarser concrete element is mapped on to a parent element of size unity, and based on the coordinates of the nodal location of the finer liner mesh, the transformed iso-parametric coordinates of the liner nodes are determined in the parent coordinate system. Using this transformation, the liner nodes are mapped on to corresponding coarser elements of concrete mesh.

Use of iso-parametric elements enables use of the same shape functions for transferring the displacements of the concrete mesh on to the liner nodes. For each liner node pertaining to the stiffeners, the element onto which it is mapped, is determined, and based on the displacements of the boundary nodes of the element, the nodal deformation of the liner mesh's node is determined.

As the concrete structure is modeled on the centerline, the displacements are transformed to the surface considering a linear deformation profile across the thickness of the concrete element, using the deformations and the nodal rotations. The nodal rotations at the surface nodes are considered to be same as those obtained at the centerline of the elements.

The displacement transformation, based on sub modeling technique, is represented mathematically, as given below,

$$\begin{Bmatrix} u \\ v \\ w \end{Bmatrix} = \sum_{i=1}^{8} N_i \begin{Bmatrix} u_i \\ v_i \\ w_i \end{Bmatrix} + \sum_{i=1}^{8} N_i \frac{rt_i}{2} \begin{bmatrix} a_{1,i} & b_{1,i} \\ a_{2,i} & b_{2,i} \\ a_{3,i} & b_{3,i} \end{bmatrix} \begin{Bmatrix} \theta_{x,i} \\ \theta_{y,i} \end{Bmatrix} \quad - \quad (1)$$

where u,v and w represent the displacements in node of finer liner mesh.

u_i, v_i and w_i represent the displacements in node i of concrete element, on which the liner node is mapped. The summation is done over the results obtained for the eight nodes of the concrete's shell element.

r represents the thickness coordinate

t_i represent the thickness at node i

{a} = unit vector in s direction (Natural coordinate s)

{b} = unit vector in-plane of element and normal to {a}

$\theta_{x,i}$ = rotation of node i about vector {a}

$\theta_{y,i}$ = rotation of node i about vector {b}

The shape functions used in above equation could be evaluated using equation 2 as,

$$u = \frac{1}{4}(u_I(1-s)(1-t)(-s-t-1) + u_J(1+s)(1-t)(s-t-1) + u_K(1+s)(1+t)(s+t-1) + u_L(1-s)(1+t)(-s+t-1)) + \frac{1}{2}(u_M(1-s^2)(1-t) + u_N(1+s)(1-t^2) + u_O(1-s^2)(1+t) + u_P(1-s)(1-t^2)) \quad - \quad (2)$$

which represents, $U = N_1 U_1 + N_2 U_2 + \ldots N_8 U_8$

THREE STAGE METHODOLOGY:

Stage-1 (Analysis of Integrated FE Model)

Structural analysis of an integrated FE model of NICB (Global model), in which the beams, columns, walls and slabs, and the base soil are idealized, is performed. Floor slabs are modeled as pure diaphragm elements essentially to simulate the in-plane stiffness. However, lined panels, are modeled as thick shell elements with both in-plane and out of plane DOFs. The stiffness of liners is not considered in strengthening the concrete system, as per the provisions of AERB code [2]. The deformations in the concrete structure are obtained from the results of the global analysis of the concrete structure at the nodes located on the element centerlines.

Stage-2 (Determination of liner stresses)

This stage involves usage of sub modeling technique, for the determination of forces in liner plate and the stiffening beam elements. The step wise methodology adopted is as follows,

a) The concrete area over which the liner is provided is modeled (in the global model) using a relatively coarser mesh. The displacements are obtained at the nodes of the concrete elements based on the global model analysis.
b) Sub-model: The liner is modeled with a refined mesh using plate elements and stiffener elements. The nodes of the FE mesh formed, corresponding to the stiffeners is determined. The stiffeners act as interface points between the liner and the concrete surface. These are hence the nodes over which the displacement profile of the concrete surface is to be transferred.
c) Using the transformation principles outlined above, the displacements of the concrete surface are transferred to the nodes corresponding to the stiffeners of the liner model.
d) The sub model of liner thus formed is then analyzed for the displacement profile applied, and the stresses in the liner plate and the forces in the stiffener elements are determined.

Stage 3 (Determination of Anchor Point Forces)

This stage of analysis involves determination of pullout forces in the anchors. The shear forces generated by the liner, in the plane of the slab, are considered to be resisted by the embedded portion (surface) of the stiffener sections. The equilibrium forces at the anchor points are determined, so as to maintain the integrity of the liner system with concrete.

Any relative displacement between two anchor points in the slab will cause the portion of liner in-between the two points to be strained. Based on the strain generated in the liner, and the stiffness of the liner plate and the stiffeners, reaction forces get generated in the anchor points. Determination of these reactive forces in different directions, design of the embedded elements to resist these reactive forces generated, and transfer them into concrete are thus performed.

Since a small lined portion of concrete of the entire integrated structure is considered for the liner analysis, the deformations obtained in the concrete portion will have two components, viz, a) the rigid body displacement of the portion of concrete considered, and b) the relative deformation profile obtained within the portion considered. The portion of nodal displacements of concrete that causes rigid body deformation of the lined area, will not cause any stress in the liner system, and hence will not cause any reaction in the anchor points, whereas, the relative displacement part will cause reactions at the anchor points.

For determination of the anchor forces, two sub stages are considered in the third stage of analysis, which are explained as below,

a) Sub stage 1: In this sub stage, the displacement profile is applied on the refined FE mesh of the liner, as in the second stage. Since only the displacements are applied, without any internal forces, nodal in-equilibrium forces will be obtained in different nodes of the model. These in-equilibrium forces will be a representative of the relative displacement obtained in the liner model, since the rigid body displacement part will not cause any in-equilibrium forces in the nodes.

b) Sub stage 2: In this sub stage, the in-equilibrium forces contributing to each anchor node are summed to determine the anchor forces. This summation is performed, by performing an equilibrium static analysis of the liner model, in which the anchor nodes are arrested, and the in-equilibrium forces, as obtained from the first sub stage are applied on the model. The reactions obtained at the anchor points are determined based on the equilibrium analysis, which gives the forces for which the anchoring elements are to be designed.

DESIGN OF LINER SYSTEM COMPONENTS

The liner-plate system consisting of the following sub-components are designed using the stresses / reactions evaluated as indicated above.

- Liner plate
- Embedded Stiffener section (T section (ISNT 50) / Channel-Section (ISMC 75)
- Anchors
- Welded junction between liner-plate and Stiffeners.
- Welded junction between Stiffeners and Strap anchors

Design of the SS Liner Plate

The second stage analysis results in the in-plane forces and the bending moments in the liner plate resulting in in-plane and bending stresses / strains at the nodes of the liner. The membrane components of the stresses in x and y directions (in-plane), which are uniform across the liner cross-section, are to be combined with the flexural stresses evaluated at the top and bottom planes of the liner in respective directions. These are evaluated as per the different load combinations in line with provisions of AERB code [2], to obtain the combined stresses and strains in x and y component directions. The principal stress/strain components (in a 2-D domain) are obtained at top, middle and bottom positions for different load combinations. The combined principal values are then compared with the stress and strain limits for normal and abnormal combinations, as specified in Table 8.1 of AERB/SS/CSE-2 [2]. As specified in AERB code, for normal design combinations, the stress limits are checked in case of tension, and strain limits are checked in case of compression. In case of abnormal design combinations, strain limits are checked under both tension and compression.

A condition, where the surface of liner plate is not exposed to weather, is considered for checking the allowable limits. The limiting values of stresses and strains of the liner plate, as given in AERB code, AERB/SS/CSE/2 [2], are furnished in Table 1 and 2 below.

Design of Embedded stiffener beams (Channel / T – Section)

The embedded stiffener beams support the liner plate panels at intervals. These are designed for the element end forces and moments obtained from the second stage analysis. The design for the combined effect of bending moment and axial force and that of shear and axial force are checked to be within limits as per AERB code, AERB/SS/CSE/2 [2].

The allowable stresses adopted for design of section is as per that given in Table 2, corresponding to carbon steel material. Since the beam is totally embedded in to concrete, it is considered to be laterally supported throughout, and hence the same allowable stresses are applicable for axial and bending tension and compression.

Apart from shear and bending stresses on the embedded beam sections, they are also subjected to bearing of face of their embedded flange with adjacent concrete. Any differential axial membrane strain that gets generated in the liner plate causes a shear force to be transferred to the embedded leg of the stiffener and a bearing stress between the face of the embedded leg and adjacent concrete. The bearing and shear stresses as determined above are checked to be within limits.

Design of MS Anchors

The anchoring arrangement consists of strap anchors provided along the stiffeners, embedding them into the base concrete. They are subjected to pull out force transmitted from stiffeners and liner plate, as elaborated in stage 3 analysis. The anchor design is performed considering a condition where any one of the anchors is pulled out. The anchors are designed for the forces transferred, using allowable stresses as per AERB/SS/CSE-4 [3].

Table 3 gives the allowable stresses in anchors under different design conditions as per the code,

Table 1: Limiting values of stress and strain adopted for design of liner plate

Design Condition	Compression		Tension	
	Membrane	Membrane + Bending	Membrane	Membrane + Bending
Normal design condition	*E*u / 30	*E*u / 20	Sm	Sm
Abnormal design condition	*E*u / 20	*E*u / 10	*E*u / 10	*E*u / 10

Where *E*u represents ultimate strain in liner plate and
Sm represents the permissible axial stresses, as given for Stainless steel material in Table 2.

Table 2: Permissible Design Stresses Adopted (in MPa)

Design Condition	Material	Axial Tension / Compression	Bending Tension / Compression	Shear
Normal design condition (without temperature)	Carbon Steel	(0.6*250) = 150	(0.66*250) = 165	(0.4*250) = 100
	Stainless Steel	(0.6*170) = 102	(0.66*170) = 112.2	(0.4*170) = 68
Abnormal design condition (without temperature) and Normal design condition (with temperature)	Carbon Steel	(0.6*250*1.5) = 225 (<=0.9*250)	(0.9*250) = 225	(0.4*250*1.4) = 140
	Stainless Steel	(0.6*170*1.5) = 153 (<=0.9*170)	(0.9*170) = 153	(0.4*170*1.4) = 95.2

Table 3 Permissible Design Stresses for embedded anchors (in MPa)

SL No	**STRESS PARAMETER**	**STRESS VALUE**	
		DESIGN CONDITION	
		NORMAL	ABNORMAL
1	Tension	0.55*fy	0.87*fy
2	Bond (with concrete)	0.25*0.7*sqrt(fck)	0.40*0.7*sqrt(fck)

Welded junction between liner-plate and Stiffening beam

A continuous stretch of plug weld for a length equal to the center to center spacing of anchors (Refer figure 1), will be subjected to the same set of vertical forces that are transmitted to the anchor, and set of horizontal shear forces transmitted by bearing of embedded beam with concrete. The stresses in the weld are checked with the requirements of AERB code [2].

Welded junction between Stiffening beam and Strap anchors

The pullout forces transmitted to the anchors are evaluated as explained above in the design of MS anchors. Since these forces are transmitted through the fillet weld between the strap anchor and the stiffening beam, the weld is designed for the same set of forces. The stresses caused in the weld are checked against their limits as per AERB code [2].

EXAMPLE PROBLEM (Design of Liner Plate for Spent Sub assembly Storage Bay (SSSB) of NICB)

Figure 2 shows 3-D FE model of the SSSB pool. The pool is about 18m long x 9m wide, with height of about 9m. The inner surface of the pool is lined, since it contains radio active water permanently stored in it. The pool is connected to the adjacent portions of the building by means of two slabs at intermediate levels, and one slab at the top. The pool is supported at the base, by means of stub columns along the periphery of the pool, and wall on one of the peripheries. General arrangement of the SSSB pool is furnished in figure 3.

A temperature of 55 degrees is considered for the fluid inside the pool, as a worst thermal condition. The differential deformation of the liner plate with respect to concrete surface is considered for analysis under thermal loads, as only this portion of the deformation will cause stress in liner plate and forces in anchors. Normal static and seismic forces are applied on the pool. The seismic and static deformations are obtained from the analysis of integrated model of NICB. Seismic strains caused in the liner plate are determined considering a pure shear mode of deformation of SSSB pool (with maximum shear deformation applied as displacement boundary condition at the top of the pool). Design results due to seismic deformations based on spectrum analysis, are enveloped with the results obtained based on above-mentioned shear deformation considerations, and the critical stresses are determined.

An increased deformation effect due to creep of concrete under sustained loads is obtained, by analyzing the integrated structure for the sustained loads, with reduced E value assigned for concrete, calculated to incorporate the creep effects. The equivalent reduction in E value is calculated based on provisions of code AERB/SS/CSE-1 [1].

The deformed shapes of the SSSB pool under seismic and thermal loading conditions are furnished in figures 4 and 5. These displacements were imposed on a refined FE mesh of the liner plate. A 3-d model of the liner plate, covering the entire pool was developed, and, the entire model was applied with deformation profile of the concrete pool.

Comparing the plate stresses obtained from different load cases, it is observed that Load cases due to seismic events, creep of concrete and thermal loads are predominant in affecting the liner system stresses. Maximum tension of 15 MPa and compression of -19 MPa are obtained under seismic load cases. Thermal loads produce a maximum tensile stress of 88 MPa. Long term Creep and drying shrinkage of concrete causes a maximum compressive stress of -85 Mpa. The stresses and corresponding strains were found to be within allowable codal limits. Hence the reinforcement provided for the pool was considered to be adequate.

The combined axial and bending stresses generated in the stiffeners are also found to be within limits. Considering the design of anchors, the shear resistance offered by the embedded portion of the stiffener, by means of bearing against concrete is considered. Hence the anchors are designed only for pullout forces and not for the shear forces. Based on the above design, a uniform distribution of anchors (25 x 6 strap anchors) along the stiffeners, at a distance of 600mm c/c is found to be adequate. However, as a precautionary measure, the design is also performed without considering the shear resistance offered by the stiffeners, as they are not extending into compression zone of the concrete. Based on the above design, a non uniform distribution of anchors is arrived at. Strap Anchors of size 30 x 8 mm flats (on either side of the stiffener) are required to be provided at 400 mm c/c in the end liner panels, and 25 x 6 thick flats at 600mm c/c (provided on either side of the stiffener) are found adequate in the middle panels. Reason for such a non uniform requirement is that, the anchor forces generated in the anchors for interior panels get nullified due to equilibrium attained between the adjacent panels, whereas, in case of anchors for edge panels, large in-equilibrium forces get transferred to the anchors.

The connections between the various parts are designed in line with the methodology mentioned earlier, for the forces as mentioned above.

CONCLUSION

A methodology has been developed to check the integrity of the entire liner system, involving qualification of all the sub-components of the system, and the connections involved, for a wide range of load cases that could be envisaged.

It is observed that, the anchors become a critical component in the design. An optimal distribution of the anchors is a non uniform distribution of anchors with more for the edge panels of the liner system and relatively lesser for the interior panels unlike the usual consideration of uniform distribution of anchors throughout the liner.

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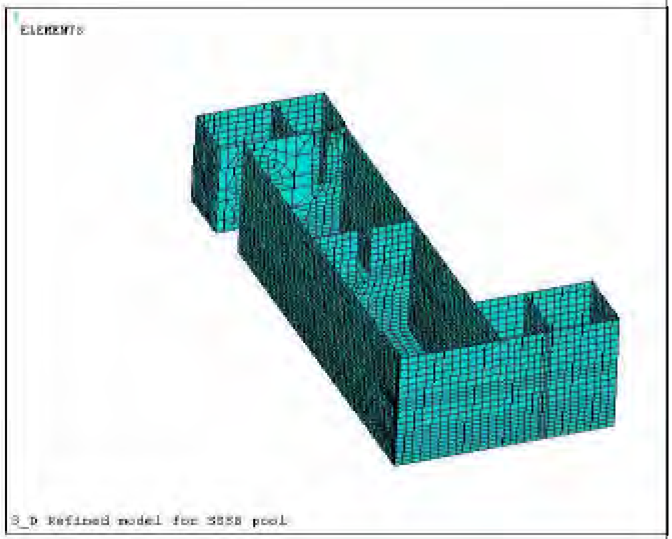

Figure 2 - 3-D FE Model of SSSB Pool

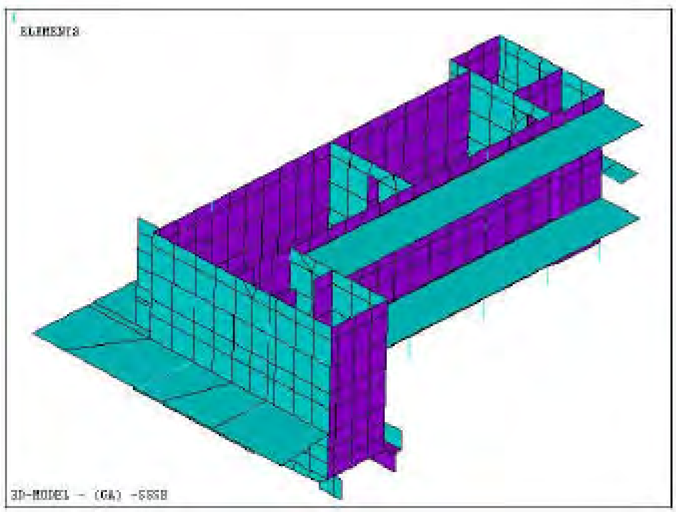

Figure 3 - General Arrangement of SSSB Pool (with surrounding concrete slabs and base columns)

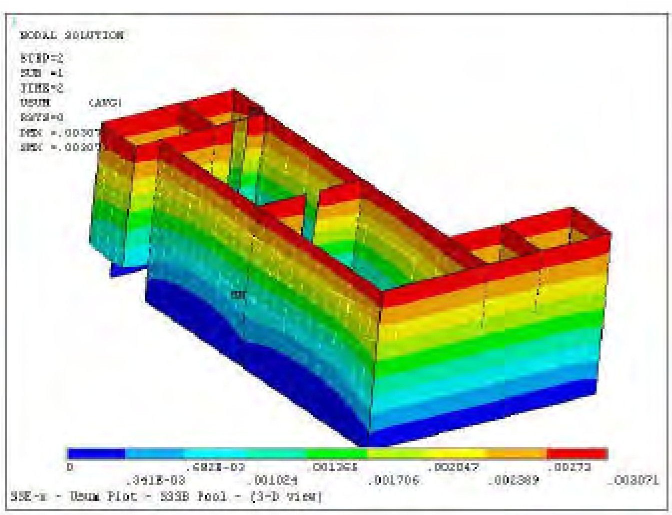

Figure 4 - Deformed shape of SSSB pool under Seismic load (SSE NS)

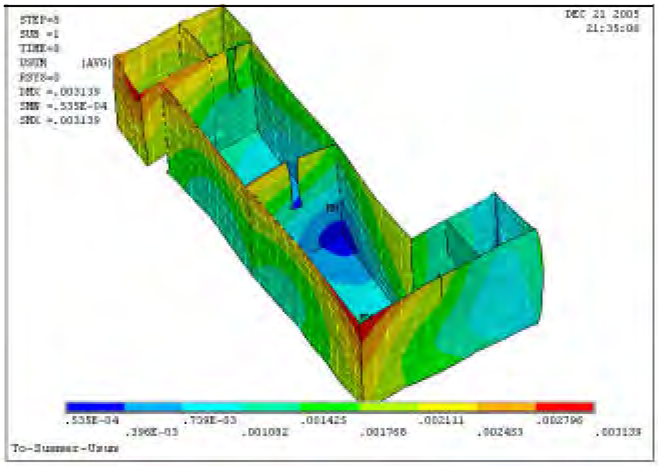

Figure 5 - Deformed shape of SSSB pool under Thermal loading

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