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Structural analysis and safety assessment of submerged floating tunnel prototype in Qiandao Lake (China)

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Abstract

This article presents the structural analysis and the safety assessment of the submerged floating tunnel (SFT) prototype, which is designed to be built in Qiandao Lake (China). Based on the principle of bending stiffness equivalence, a homogenized equivalent single-layered-tube model is established. The effective beam bending stiffness and the corresponding Young's modulus are deduced. By using lamination theory of composite mechanics, the equivalent local bending stiffness of the SFT prototype panel is calculated and the corresponding modulus is obtained. The moduli deduced via the two approaches are nearly equal. Then, the strength analysis of the SFT prototype under the actions of water wave, water current and earthquake is carried out. The reliability of the SFT prototype is assessed through the comparison of the obtained stresses with the design values.

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Keywords: submerged floating tunnel (SFT); SFT prototype; strength analysis; safety assessment; structural analysis

1. Introduction

Submerged floating tunnel (SFT), also named Archimedes Bridge, is a kind of transportation passage floating and submerged within water to bridge water banks, which takes the advantage of buoyancy and is tethered to the foundation and the shores. As an innovative transportation technology, SFT will become attractive competing with traditional transportation passages with its economical and environmental advantages [1]. However at present, there is still not any actual SFT being built in the world. In recent years, the Sino-Italian Joint Laboratory of Archimedes Bridge (SIJLAB) has made efforts in the design of the first SFT prototype in Qiandao Lake of China and has performed relevant simulations and experiments [2–6]. A description on structural analysis of the SFT prototype in Qiandao Lake is given in a recent paper [4]. It is noted that the tube structure of the SFT prototype is complicated with three layers (sandwich structure), and particularly the external layer is an alveolate-shaped aluminium extrusion shell as shown in Figs. 1 and 2. In the analyses of the dynamic response under the loadings of water current, water wave, seismic action, etc., the tube structure of the SFT prototype has to be simplified. In the present paper, two approaches are used to obtain effective Young's modulus. One is based on the global beam bending stiffness

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equivalence and the other, on the equivalence principle of local panel bending stiffness. Based on the effective material properties of the equivalent structure, the maximum stresses of the SFT prototype under water wave, water current and earthquake are calculated and the strength analysis of the prototype is performed based on the resultant forces obtained in Refs. [2, 4].

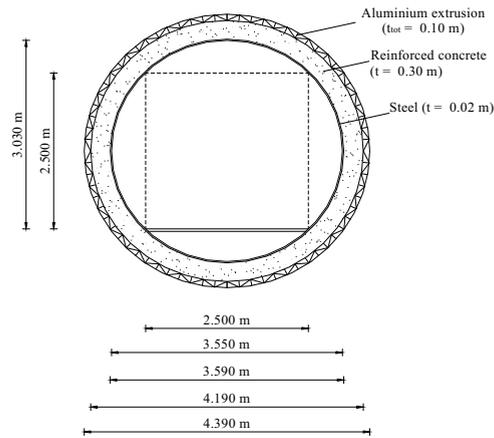


Fig. 1. Cross section of SFT prototype showing three-layered structure [2]

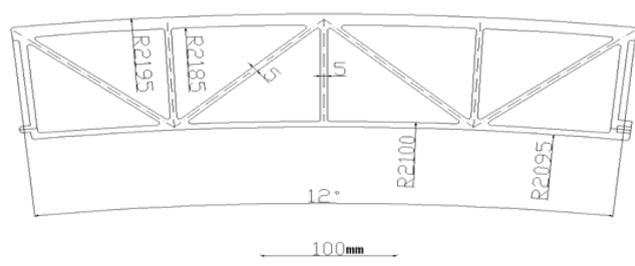


Fig. 2. Profile of the aluminium alveolate layer and its detailed structure [2]

2. Homogenization of the three-layered structure of the SFT prototype

Two approaches are used to homogenize the three-layered structure of the SFT prototype. One is according to the equivalence principle of global bending stiffness, in which the tube structure is regarded as a beam. The other is based on the local bending stiffness equivalence, in which a local zone of the tube structure is regarded as a piece of cylindrical panel subjected to bending deformation. The effective Young's moduli obtained via the two approaches are with a little difference.

2.1. Effective structure of prototype based on equivalence principle of beam bending stiffness

Since the diameter of the SFT prototype is much smaller than its length, it may bend like a beam when subjected to actions of water wave, water current and earthquake. During bending of the tube, the plane of the cross section remains plane and the deformation of the cross section can be ignored. Therefore, the formula of global bending stiffness of the equivalent structure can be written as:

$$J^{eff} = E^{eff} I^{eff} = \sum_{i=1}^3 E_i I_i = \sum_{i=1}^3 J_i \quad (1)$$

where E_i and I_i are the modulus and the bending inertia moment, respectively, and $i = 1, 2, 3$ corresponds to the three layers of steel, concrete and aluminium alveolate. E^{eff} is the modulus of the effective material, which is a fictitious material, but is not necessarily any one of the three materials, and I^{eff} is the effective bending inertia moment of the homogenized effective structure, which is $I^{eff} = \pi / 64 \cdot (D^4 - d^4)$, where D and d are external and internal diameters of the SFT prototype. For the two layers of steel and concrete, it is easy to calculate the inertia moments, whereas for the alveolate-shaped aluminium layer, the calculation is a little complicated. The real (solid) cross section should be used to calculate the inertia moment I_{al} . It consists of four parts: outer and inner cylindrical skins, and straight and slant stiffening webs (or stiffeners). The inertia moments of the four parts are calculated one by one, and then summed up to obtain the total result. By omitting the tedious procedure, the result is given as $I_{al} = 0.79 \text{ m}^4$. The value of bending stiffness of the alveolate aluminium layer is

$$J_{al} = 5.56 \times 10^{10} \text{ N} \cdot \text{m}^2 \quad (2)$$

So, the right hand side of Eq. (1) equals to:

$$J^{total} = \sum_{k=1}^3 J_k = 33.5 \times 10^{10} \text{ N} \cdot \text{m}^2 \quad (3)$$

This is the effective bending stiffness of the SFT prototype as a beam. From Eq. (1) we can calculate the effective modulus E^{eff} , since I^{eff} is easily obtained as follows:

$$I^{eff} = \pi / 64 \cdot (D^4 - d^4) = 10.4 \text{ m}^4 \quad (4)$$

Then, the effective modulus E^{eff} reduces to:

$$E^{eff} = 3.22 \times 10^{10} \text{ Pa} \quad (5)$$

If the aluminium layer is omitted [2], the bending stiffness of the two-layered tube is:

$$J_{Total} = J_{con} + J_{st} = 29.69 \times 10^{10} \text{ N} \cdot \text{m}^2 \quad (6)$$

In the same way, for the one-layered structure of steel, the bending stiffness and the effective modulus is also calculated. The results are summarized in Table 1.

Table 1. Effective modulus and bending stiffness for three types of structure

Structure type	3-layered structure	2-layered structure	1-layered structure
	Steel/Concrete/Aluminium	Steel/Concrete	Steel
Effective modulus, Pa	3.22×10^{10}	4.06×10^{10}	21.0×10^{10}
Effective bending stiffness, $\text{N} \cdot \text{m}^2$	35.25×10^{10}	29.7×10^{10}	7.5×10^{10}
Internal diameter / External diameter, m	3.55/4.39	3.55/4.19	3.55/3.59

2.2 Effective bending stiffness based on local bending stiffness equivalence

In order to deal with the local bending problems, the homogenization methodology for local bending deformation needs to be developed. For instance, when the prototype tube is subjected to a collision of an object, say a sinking boat, it will undergo local bending deformation. To obtain the effective bending stiffness, the composite lamination theory [7] is utilized.

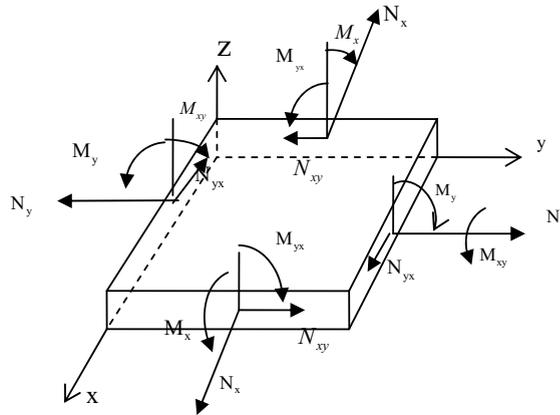


Fig. 3. In-plane force resultant and bending moment

According to lamination theory of composite mechanics, the constitutive relationship of a laminated composite panel is given as (also refer to Fig. 3):

$$\begin{Bmatrix} N_i \\ M_i \end{Bmatrix} = \begin{bmatrix} A_{ij} & B_{ij} \\ B_{ij} & D_{ij} \end{bmatrix} \begin{Bmatrix} \epsilon_j \\ \kappa_j \end{Bmatrix} \quad i, j = 1, 2, 6 \tag{7}$$

where N_i is the matrix of in-plane force resultant, M_i is the matrix of bending moment, ϵ_j is the matrix of in-plane strain, κ_j is the matrix of bending curvature, and A_{ij} , B_{ij} and D_{ij} are the matrices of tensile stiffness, coupling stiffness and bending stiffness, respectively, whose formulas are as follows:

$$A_{ij} = \sum_{k=1}^n (\bar{Q}_{ij})_k [z_k - z_{k-1}] = \sum_{k=1}^n (\bar{Q}_{ij})_k t_k = \sum_{k=1}^n A_{ij}^k \tag{8}$$

$$B_{ij} = \frac{1}{2} \sum_{k=1}^n (\bar{Q}_{ij})_k [z_k^2 - z_{k-1}^2] = \sum_{k=1}^n (\bar{Q}_{ij})_k t_k (\bar{z}_k) = \sum_{k=1}^n B_{ij}^k \tag{9}$$

$$D_{ij} = \frac{1}{3} \sum_{k=1}^n (\bar{Q}_{ij})_k [z_k^3 - z_{k-1}^3] = \sum_{k=1}^n (\bar{Q}_{ij})_k \left(t_k \bar{z}_k^2 + \frac{t_k^3}{12} \right) = \sum_{k=1}^n (A_{ij}^k z_k^2 + I_{ij}^k) \tag{10}$$

where $(\bar{Q}_{ij})_k$ is the constitutive matrix of the k^{th} layer, $t_k = z_k - z_{k-1}$ is the thickness of k^{th} layer, and $\bar{z}_k = \frac{1}{2}(z_k + z_{k-1})$ is the coordinate of center plane of k^{th} layer (refer to Fig. 4). For the present case, there are three layers. At first, the origin of the referential coordinate is assumed at the interfacial plane between concrete and aluminium alveolate layers. The coordinate of physical neutral plane has to be determined. In the determination of the coordinate for the physical central plane, the following formula is used.

$$z_c = \frac{B_{ij}}{A_{ij}} = \frac{\sum_{k=1}^3 B_{ij}^k}{\sum_{k=1}^3 A_{ij}^k} = \frac{\sum_{k=1}^3 E^k S^k \bar{z}}{\sum_{k=1}^3 E^k S^k} \tag{11}$$

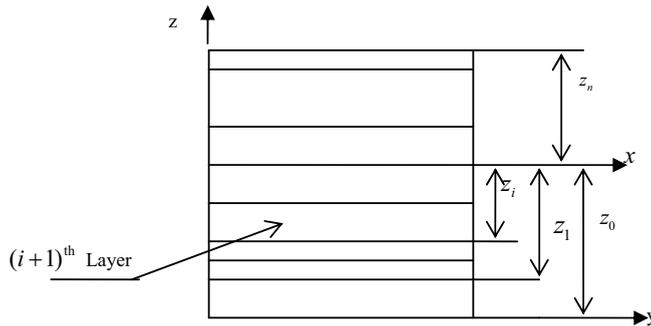


Fig. 4. Coordinate of laminated composite

The values of B_{ij}^k and A_{ij}^k for the three layers are calculated and the results are shown in Table 2.

Table 2. Coupling stiffness coefficient and tensile stiffness coefficient of three materials

Material	Steel	Concrete	Aluminium
Coupling stiffness coefficient B, [N·m]	0.13×10^{10}	0.144×10^{10}	0.004×10^{10}
Tensile stiffness coefficient A, [N]	0.42×10^{10}	0.96×10^{10}	0.177×10^{10}

By using Eqs. (8) and (9) and the data in Table 2, the total values of B and A are calculated to give $B = 0.278 \times 10^{10} \text{ N} \cdot \text{m}$ and $A = 1.58 \times 10^{10} \text{ N}$. Therefore,

$$z_c = \sum \frac{B^k}{A^k} = 0.175\text{m} \tag{12}$$

That is, the distance of the physical central plane from the concrete-aluminium interface is 0.175m. With the coordinate of the physical central plane, the bending stiffness D can be calculated by Eq. (10). The bending inertia moments of steel and concrete layers are readily obtained. For the aluminium alveolate layer, the bending inertia moment is sum of four parts, i.e. the upper and the lower skins, and the slant and the straight stiffening webs. Omitting the calculation details, the result is:

$$D_{ij} = \sum_{i=1}^3 E_i I_i = 223.3 \times 10^6 \text{ Pa} \cdot \text{m}^3 \tag{13}$$

By using this approach, we can get another effective modulus of the homogenized prototype. The formula is:

$$E^{eff} = \frac{D_{ij}^{com}}{I^{eff}} = \sum_{k=1}^3 \frac{E_k I_k}{I_{tube}} \tag{14}$$

where $k = 1, 2, 3$ corresponds to steel, concrete and aluminium layers, respectively. In the same way, the effective bending stiffness of a panel and the effective modulus for the case without aluminium alveolate layer are computed.

The results are summarized in Table 3. For comparison, the results of those based upon global bending equivalence are also included. From Table 3, it is noted that the difference of effective modulus between those obtained by global bending equivalence and local bending equivalence is only 5.6%.

Table 3. Effective bending stiffness and modulus in two approaches

Local bending equivalence effective stiffness of panel, Pa · m ³	Global bending equivalence effective stiffness of beam, N · m ²	Effective modulus by local bending equivalence, Pa	Effective modulus by global bending equivalence, Pa
	35.25×10^{10}	3.62×10^{10}	3.42×10^{10}
223.3×10^6 [#]	29.69×10^{10} [*]		4.05×10^{10} [*]

The effective stiffness of the local bending equivalence is bending stiffness in unit width. * Ignore aluminium.

2.3. Effective mass density

In dealing with dynamic problems, the homogenization of mass density of the prototype is performed. The effective mass density is simply the weighted average value of the mass densities for the three layers with their cross section areas as the weighted factors. By omitting the tedious procedure, the result is as $\rho^{eff} = 2.26 \times 10^3 \text{ kg/m}^3$. The weight per meter of the SFT prototype is calculated as $W^{SFT} / m = 115.8 \text{ kN/m}$. Since the buoyancy per meter equals to $\hat{W} = 148.3 \text{ kN/m}$, the ratio of buoyancy to weight is $BWR = 1.28$ and the residual buoyancy is $RB_k = 32.5 \text{ kN/m}$. With the consideration that the live load is $C_k = 10 \text{ kN/m}$, the remaining residual buoyancy is $\overline{RB}_k = 22.5 \text{ kN/m}$ and the ratio of buoyancy to weight reduces to $\overline{BWR} = 1.18$.

3. Strength analysis of prototype tube

3.1. Stress analysis of SFT prototype under actions of water wave and current

In reference paper Ref. [2], the horizontal and vertical forces caused by water wave and current are $F_h = 4.875 \text{ kN/m}$, $F_v = 4.860 \text{ kN/m}$ respectively. By using the afore-obtained results of effective bending stiffness, (J_{eff}^{total}) of three -layered SFT prototype and that without aluminium layer (J_{eff}^{st+con}), the bending stresses of the two cases were calculated. For simultaneous actions of F_h and F_v , the maximum bending moment is approximately equal to:

$$M_{max} = \frac{\sqrt{2}}{8} \times F_h \times l^2 = 8662.0 \text{ kN} \cdot \text{m} \quad (15)$$

The bending stress of SFT prototype composing three layers is obtained:

$$\sigma^{al} = \frac{E_{al} M R_{max}}{J_{eff}^{total}} = 3.88 \text{ MPa} \quad (16)$$

For the two-layered SFT prototype, which is not including aluminium layer, the bending stress is obtained as $\sigma^{con} = 1.96 \text{ MPa}$. If only steel tube stands for the load, the stress is given as $\sigma^{st} = 43.5 \text{ MPa}$. It can be seen that the SFT prototype is strong enough to bear the water wave and current actions.

3.2 Seismic analysis of SFT prototype

According to the SFT design report [2], the PGA of the quake is 0.3g (see EC8), the maximum tensile force subjected by SFT incurred by earthquake is: $F_{ten}=2.4 \times 10^3$ kN. This force will be distributed to the three layers in accordance with their tensile stiffness. By omitting the aluminium alveolate layer, the load acting on the steel shell is

$$F_{ten}^{st} = F_{ten} \times \frac{E_{st} S_{st}}{E_{con} S_{con} + E_{st} S_{st}} = 0.686 \times 10^6 \text{ N} \quad (17)$$

The load acting on the concrete layer is $F_{ten}^{con} = 1.714 \times 10^6 \text{ N}$. The calculated tensile stresses in steel and concrete layers are $\sigma_{st} = 3.06 \times 10^3 \text{ MPa}$ and $\sigma_{con} = 187.0 \text{ MPa}$ respectively. Noting that the design compressive strength of concrete ($f_{cd} = 11.3 \text{ MPa}$) and the design stress of steel S235 ($f_{yk} = 235 \text{ MPa}$) [2], the SFT prototype (neglecting aluminium layer) can be safe under this tensile load. If the aluminium alveolate layer is taken into consideration, the tensile force supported by the two layers of steel plus concrete will be lessened by 13%. The tensile stress of concrete will be 162.7 MPa and the stress in steel shell will be 2.66 MPa, which are still much larger than the design strengths of concrete and steel. Ref. [2] gives the maximum bending moment caused by earthquake is $M = 5.5 \times 10^4 \text{ kN} \cdot \text{m}$. If the aluminium layer is ignored, the bending stiffness of the two-layered tube is $J_{eff}^{st+con} = 29.69 \times 10^{10} \text{ N} \cdot \text{m}^2$. Then the bending stress is given as:

$$\sigma_{ben}^{st+con} = 29.27 \text{ MPa} \quad (18)$$

This stress will cause the concrete shell of the two-layered tube failure. If the three-layered SFT prototype sustains this seismic bending moment, the bending stress in the outer skin of aluminium alveolate extrusion panel will be:

$$\sigma_{earthqua}^{SFT} = \frac{E_{al} M R_{max}}{J_{eff}^{total}} = 24.65 \text{ MPa} \quad (19)$$

Because the characteristic value of aluminium alveolate is 240 MPa, the SFT prototype will be intact.

4. Strength analysis of prototype joints

According to Ref. [2], 144 bolts are used to connect two modules of the prototype, which are distributed along a circular line of 3.27m in diameter. The diameter of the bolt is 30mm.

4.1 Effective thickness of reduced shell of bolts

The cross section area of the bolts is $s_{bolt} = \pi r^2 = 706.86 \text{ mm}^2$. The effective strength can be evaluated by using the reduced cylindrical shell, whose thickness is $h^{eff} = 144 \times s_{bolt} / (\pi \times d) = 0.0099 \text{ m}$, where $d = 3.27 \text{ m}$. The equivalent bending stiffness is:

$$J^{bolt} = 144 E^{st} s_{bolt} \frac{R_{mid}^2}{2} = 2.86 \times 10^{10} \text{ N} \cdot \text{m}^2 \quad (20)$$

For the fluid actions of $F_h = 4.875 \text{ kN} / \text{m}$ and $F_v = 4.860 \text{ kN} / \text{m}$ [2], the stress acting at the bolts is:

$$\sigma_{bolt} = \frac{E M R}{J^{bolt}} = 103.14 \text{ MPa} \quad (21)$$

It is obvious that under the actions of water wave and current the joint bolts are intact.

4.2 Strength analysis for seismic action

For the maximum tensile force of earthquake, that is $F_{ten}^{quake} = 2.4 \times 10^3$ kN [2]. The tensile stress of the bolts is

$$\sigma_{ten}^{bolt} = 23.58 \text{MPa} \quad (22)$$

For the maximum bending moment during earthquake, which is given in Ref. [2] as $M_{ben}^{quake} = 5.5 \times 10^4$ kN·m, the maximum stress in bolts is obtained

$$\sigma_{bolt} = \frac{E_{st} M_{ben}^{quake} R}{J_{bolt}} = 660.3 \text{MPa} \quad (23)$$

This stress is larger than twice of the value of characteristic yield stress f_{yk} ($= 235$ MPa) of S235 steel. The bolts will break under this seismic action. The maximum shear force incurred by earthquake given by Ref. [2] is equal to $Q = 2.75 \times 10^3$ kN, so the average shear stress supported by bolts is given in (24). This value is smaller than the shear strength of the bolts.

$$\tau = \frac{Q}{A_{bolt}} = \frac{2.75 \times 10^6}{144 \times 706.86 \times 10^{-6}} = 27.0 \text{MPa} \quad (24)$$

5. Concluding remarks

The present paper presents a structural property analysis and a reliability assessment for the SFT prototype to be built in Qiandao Lake (China). It consists of two parts: (i) Based on the stiffness equivalence principle, two homogenized equivalent single-layered tube models are established. It is worth noticing that for the homogenized equivalent single-layered SFT, its dimension (inner and external diameters) should not be changed, therefore the material mass density and Young's modulus will not equal to those of anyone of the three layers. (ii) By using the data of force resultants provided by Refs. [2, 4], the strengths of the SFT prototype are analyzed under the actions of water wave, water current and earthquake. The results indicate that for the actions of water wave and current, the SFT has large allowance of strength. However, under the seismic action, safety of the prototype (including the joint bolts) is not guaranteed. For some cases, the seismic stresses are much larger than the characteristic values of the relevant material.

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References

- [1] Ahrens D. Submerged floating tunnels –A concept whose time has arrived. *Tunneling Underground Space Tech* 1997; 12: 317-36.
- [2] Italian Team of SIJLAB. *Design report of the Archimede's Bridge Prototype in Qiandao Lake (P.R of China)*. Italy, 2007.

- [3] Chinese Team of SIJLAB. *Report of research and design for Archimedes Bridge Prototype at Qiandao Lake*. Institute of Mechanics, Chinese Academy of Sciences, 2007.
- [4] Mazzolani FM, Landolfo R, Faggiano B, Esposto M, Perotti F, Barbella G. Structural analysis of the submerged floating tunnel prototype in Qiandao Lake (PR of China). *Adv Struct Eng* 2008; 11 (4): 439-54.
- [5] Long X, Ge F, Wang L, Hong Y. Effects of fundamental structure parameters on dynamic responses of submerged floating tunnel under hydrodynamic loads. *Acta Mech Sinica* 2009; 35: 335-44.
- [6] Ge F, Long X, Wang L, Hong Y. Flow-induced vibrations of long circular cylinders modeled by coupled nonlinear oscillators. *Sci in China Ser G, Phy, Mech & Astro* 2009; 52: 1086-93.
- [7] Verson JR, Sierakowski RL. *The Behavior of Structures Composed of Composite Materials*. Boston: Martinus Nijhoff Publishers; 1975.