

Figure 5. – (a) Sectional plane of SFT model, (b) 3D finite element model of SFT (Kim JH et al, 2015)

The governing equation of motion for the entire structure can be formulated as:

$$(\mathbf{M}_s + \mathbf{M}_a)\ddot{\mathbf{U}}_s(t) + \mathbf{C}_s\dot{\mathbf{U}}_s(t) + \mathbf{K}_s\mathbf{U}_s(t) = -(\mathbf{M}_s + \mathbf{M}_a)\mathbf{I}_f\ddot{\mathbf{U}}_g(t), \quad (4)$$

where subscript 's' and 'g' denote the superstructure and supporting ground. Mass, damping, and stiffness matrices are denoted by  $\mathbf{M}$ ,  $\mathbf{C}$ , and  $\mathbf{K}$ , respectively. The relative value of structure acceleration, velocity and displacement are denoted by  $\ddot{\mathbf{U}}_s$ ,  $\dot{\mathbf{U}}_s$  and  $\mathbf{U}_s$ , respectively. The hydrodynamic force applied on the structure due to the relative motion of fluid can be obtained using Morison equation (Dawson TH, 1983).  $\mathbf{M}_a$  is the added mass coefficient matrix. No incident wave or current were considered in this study and thus the water particles acceleration and velocity become zero. For the external force on the structure due to seismic ground motion is calculated by the multiplication of total mass and ground acceleration. Furthermore, the influence of ground accelerations  $\ddot{\mathbf{U}}_g$  on the structural degrees of freedom is decided by the influence matrix  $\mathbf{I}_f$ .

The continuum mechanics based 3D beam finite elements (Yoon and Lee, 2014) and taut cable elements are used to model the tunnel and mooring cables, respectively. Beam element and discretization of applied cross-section of tunnel is illustrated at Fig. 6.

We studied a 10km span length SFT, which has the outer diameter of tunnel cross-section 15.7m. Mooring cables are installed with uniform spacing ( $d=100\text{m}$ ) and its diameter is 0.15m. The tunnel cross-section is a composite structure consisting of outer steel and inner concrete (Long et. al, 2009). The equivalent Young's modulus considered is 34 GPa for tunnel, and that of cables is 210 GPa. We consider two cases of cable angles  $\theta$  from the seabed: 45 and 60 degrees.

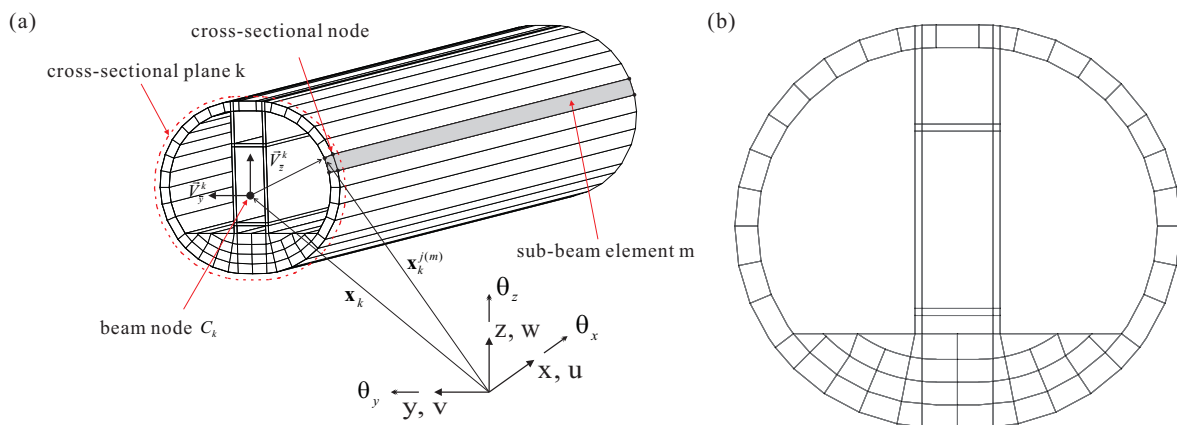


Figure 6. – (a) 3D beam finite element, (b) tunnel cross-section discretization (Kim JH et al, 2015)

Water depth  $h$  is 120m and the depth from the water surface to the center of tunnel ( $H$ ) is 40m. For the input seismic motion, El Centro and Kobe earthquakes are selected for the input seismic acceleration. The input seismic ground motions are assumed be homogeneous.

In the reference (Kim JH et al, 2015) the displacement time histories at tunnel center and the maximum displacement response envelopes through the span length are given for each seismic excitation. The displacement history appears the maximum transverse displacements of the tunnel are very similar for the two cable angle cases.

The peak ground acceleration (PGA) of Kobe earthquake is bigger than that of El Centro earthquake and the maximum magnitude of responses also shows the same trend. However, the locations of maximum displacement response are different. The maximum displacements calculated are much smaller than the total tunnel length, rarely exceeding 0.3 m.

## 5. CONCLUSIONS

In this presentation, we introduced our recent works on the analysis of fluid-structure interaction problems in ocean engineering. Numerical methods for hydroelastic analysis of very large floating structures, hydroelastic analysis of general floating structures, and hydroelastic analysis of submersed floating tunnels were presented. Their formulations were briefly reviewed and the numerical results were presented through representative numerical examples. Also, the results were compared with available experimental results and those in previous studies. The numerical methods developed here can be used be widely utilized in various ocean engineering practices, especially, for design of VLFS (Very Large Floating Structures), very large crude carriers, very large container ships and long submersed tunnels.

## ACKNOWLEDGEMENTS

This work was supported by the Basic Science Research Program through the National Research Foundation of Korea (NRF), funded by the Ministry of Education, Science and Technology (No. 2014R1A1A1A05007219)

## REFERENCES

- Jeon, H.M., Lee, Y., Lee, P.S., Bathe, K.J. (2015), "The MITC3+ shell element in geometric nonlinear analysis". *Computers and Structures*, **146**, 91-104.
- Jeon, H.M., Lee, P.S., Bathe, K.J. (2014), "The MITC3 shell finite element enriched by interpolation covers". *Computers and Structures*, **134**, 128–142.
- Kim JH, Yoon K, Lee PS (2015). "Hydroelastic analysis of long span submerged floating tunnels under seismic loads", ECCOMAS MSF 2015: The 2nd International Conference on Multi-scale Computational Methods for Solids and Fluids.
- Lee, P.S., Bathe, K.J. (2004), "Development of MITC isotropic triangular shell finite elements". *Computers and Structures*, **82**, 945-962.
- Lee, Y., Jeon, H.M., Lee, P.S., Bathe, K.J. (2015), "The modal behavior of the MITC3+ triangular shell element". *Computers and Structures*, **153**, 148-164.
- Lee, Y., Lee, P.S., Bathe, K.J. (2014), "The MITC3+ shell finite element and its performance", *Computers and Structures*, **138**, 12-23.
- Lee P.S., McClure G., (2007) "Elastoplastic large deformation analysis of a lattice steel tower structure and comparison with full-scale tests", *Journal of Constructional Steel Research*, **63**(5), 709-717.
- Yoon K., Lee P.S. (2014), "Modeling the warping displacement fields for discontinuously varying arbitrary cross-section beams". *Computers and Structures*, **131**, 56-69.
- Yoon, K., Lee, P.S. (2014), "Nonlinear performance of continuum mechanics based beam elements focusing on large twisting behaviors", *Computer Methods in Applied Mechanics and Engineering*, **281**, 106-130.
- Yoon K, Lee Y, Lee PS. (2012), "A continuum mechanics based 3-D beam finite element with warping displacements and its modeling capabilities". *Structural Engineering and Mechanics*, **43**(4), 411-437.
- Kim, J.G., Cho, S.P., Kim, K.T., Lee, P.S. (2014), "Hydroelastic design contour for the preliminary design of very large floating structures", *Ocean Engineering*, **78**, 112-123.
- Yoon, J.S., Cho, S.P., Jiwinangun, R.G., Lee, P.S. (2014), "Hydroelastic analysis of floating plates with multiple hinge connections in regular waves", *Marine structures*, **36**, 65-87.
- Kim KT, Lee PS, Park KC. (2013), "A direct coupling method for 3D hydroelastic analysis of floating structures", *International Journal for Numerical Methods in Engineering*, **96**(13), 842-866.

- Lee KH, Cho S, Kim KT, Kim JG, Lee PS. (2015), "Hydroelastic analysis of floating structures with liquid tanks and comparison with experimental tests", *Applied Ocean Research*, **52**, 167-187.
- Dawson TH. (1983), "Offshore Structural Engineering", *Prentice-Hall: Englewood Cliff*.
- Long, Xu., Fei, Ge., Lei, Wang., Youshi, Hong. (2009), "Effects of fundamental structure parameters on dynamic response of submerged floating tunnel under hydrodynamic loads". *Acta Mechanica Sinica*, **25**, 335–344.