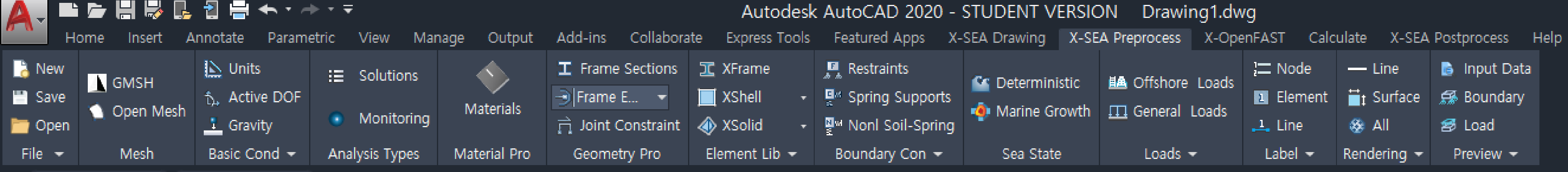
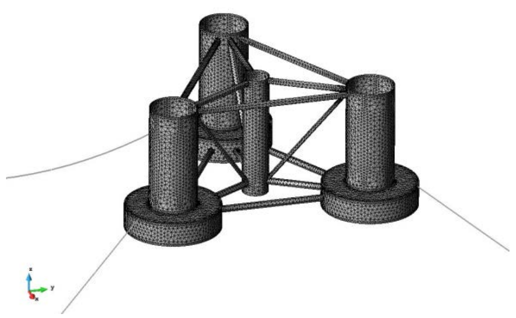


Application: Offshore Wind Turbine Structural Engineering

X-Wind

Part 1: X-SEA (Analysis and Design of Offshore Structure



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2020-0612

Introduction of X-SEA

Introduction

- The current version of X-SEA includes the results of extensive research and development base on finite element program XFINAS, which was originally developed in Imperial College, London.
- The X-SEA is an integrated finite element structural analysis software that provides for the nonlinear dynamic analysis and design of offshore steel and concrete structures, including oil and gas and wind farms.
- The X-SEA provides a high-performance graphics of AUTOCAD Interface with interactive and visual environment for the analysis and design of offshore structures.
- The power of X-SEA is further enhanced by its speed and 64-bit capability with **Multi-core Parallel Direct Sparse Solver** using INTEL PARDISO.
- For the design of offshore wind turbine structure, coupled dynamic analysis of the **OpenFAST** (NREL, USA) **and X-SEA** can be combined with X-SEA environmental load.
- Post-processing of integrated analysis results for Fatigue Limit State analysis (FLS) and Ultimate Limit State (ULS) analysis (GH Bladed & OpenFAST).

PARDISO Solver: Results

$$[K]\{x\}=\{f\},\ \{x\}=\ ?$$

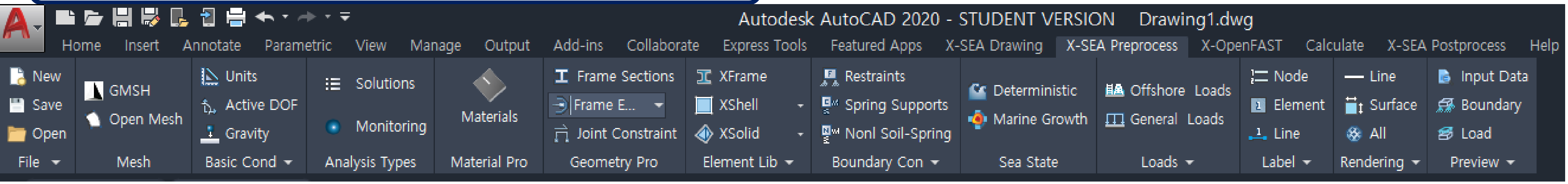
- The newly restructured X-SEA using 64 bit PARDISO package is very fast, high performance, robust and memory efficient software for solving large sparse symmetric and unsymmetric linear systems of equations on shared memory multiprocessors.
- The 64 bit system of X-SEA is extremely faster than 32bit X-SEA shown in the table.
- The degree of freedom of model is almost unlimited by the efficient memory management system.

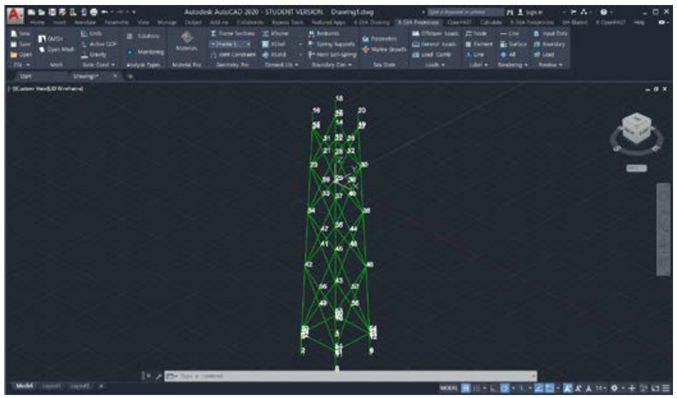
Meshes	Elements	CPU Time (sec) in 64bit	Result (m) Analtical Sol:1.264	Non-dimension
2x2	4	0.19	1.211	0.95807
4x4	16	0.22	1.251	0.98972
16x16	256	1.05	1.262	0.99842
32x32	1,024	2.94	1.265	1.00079
48x48	2,304	5.2	1.265	1.00079
64x64	4,096	7.95	1.265	1.00079
96x96	9,216	16.97 (133.63 Sec in 32 bit)	1.265	1.00079
128x128	16,384	29.17	1.265	1.00079
196x196	38,416	74.11	1.265	1.00079
256x256	65,536	131.52	1.265	1.00079

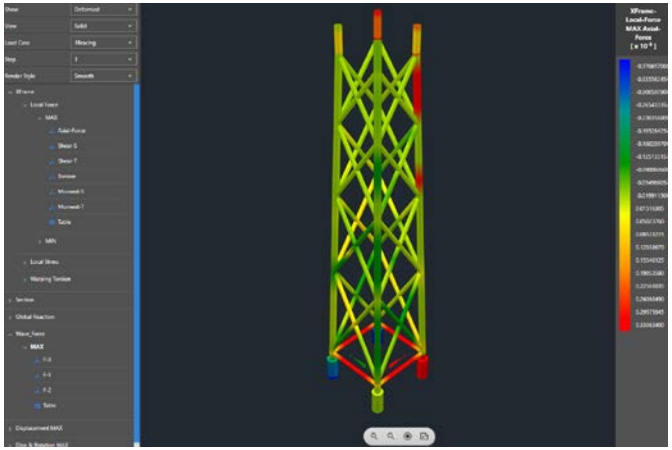
CPU Time: Square plate under uniform Pressure

Introduction of X-SEA: Autocad Pre&Postprocessor

Preprocessor: Ribbon Menu in Autocad



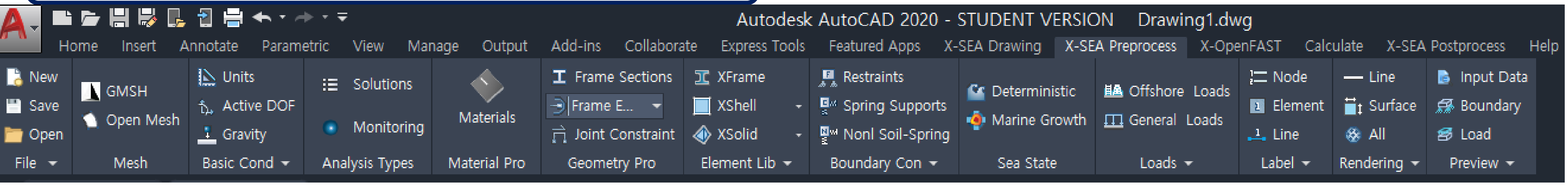


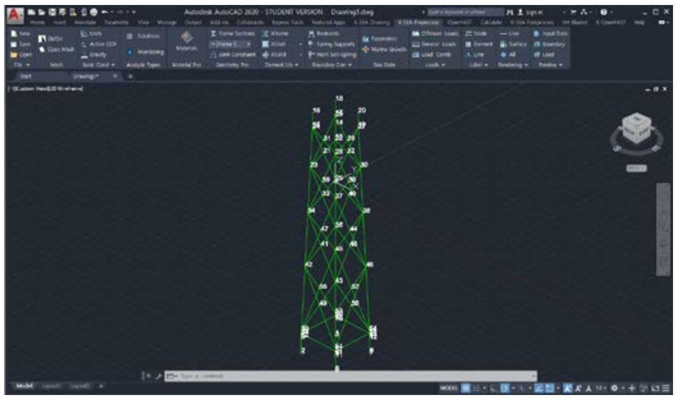


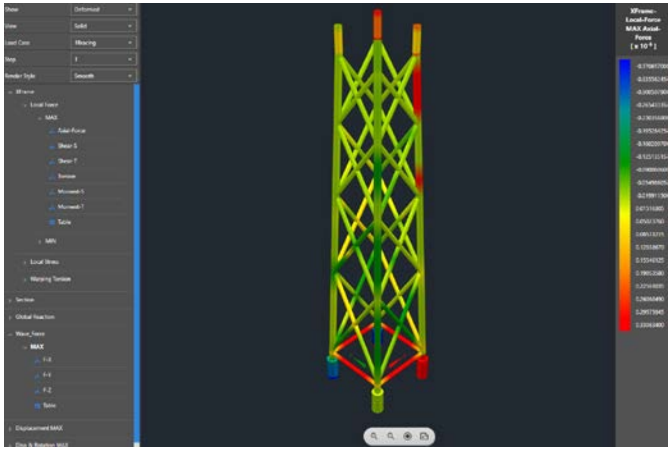
- AutoCAD (Autodesk, Inc. USA) becomes most popular and user-friendly CAD software which is used by the world-wide engineer. AutoCAD does not only have powerful, perfect graph drawing and editing ability but also allows users to carry out a FEA(Finite Element Analysis).
- User can draw and modify the three dimensional (3D) model of the offshore structure on the screen of AutoCAD 3D. By using same AutoCAD 3D model, X-SEA analysis does not need export/ import operations which is generally used in commercial FEM software.
- Pre/postprocessor of X-SEA has integrated with AutoCAD using the "ADD IN" function of AutoCAD.
- Through interactive approach of AutoCAD, the finite element calculation make users obtain calculation results and report with visualization of postprocessing in AutoCAD environment.

tion of X-SEA: Autocad Pre&Postprocessor

Preprocessor: Ribbon Menu in Autocad







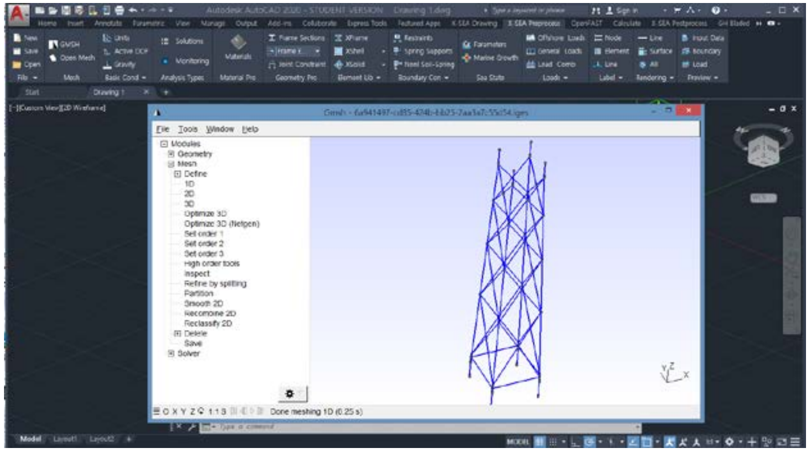
AutoCAD (Autodesk, Inc. USA)는 전 세계 엔지니어가 사용하는 가장 사용자 친화적인 CAD 소프트웨어이다. AutoCAD는 강력하고 완벽한 그래프 그리기 및 편집 기능을 갖추고 있을 뿐만 아니라 현 X-WIND에서 사용자가 유한요소 해석을 수행할 수 있도록 한다

사용자는 AutoCAD 3D 화면에서 해양 구조물의 3차원 모델을 생성한다. X-WIND는 동일한 AutoCAD 3차원 모델을 사용함하여 유한요소해석을 수행하며, 다른 상용 소프트웨어처럼 3D 데이터를 내보내거나 읽어들일 필요성이 없는 혁신적인 소프트웨어이다. /. import operations which is generally used in commercial FEM software.

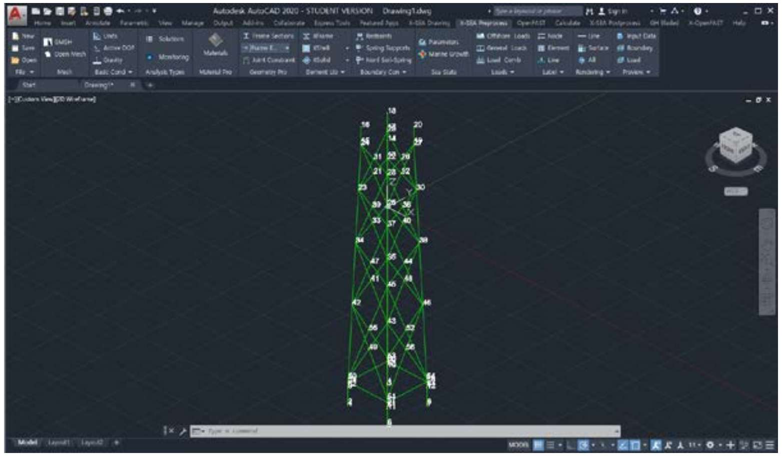
1. X-WIN의 프리/포스트 프로세서는 AutoCAD의 "ADD IN" 기능을 사용하여 AutoCAD와 통합되었습니다.
2. AutoCAD의 대화식 접근 방식을 통해 유한요소해석을 통해 사용자는 AutoCAD 환경에서 후처리 시각화를 통해 계산 결과와 보고서를 얻을 수 있다.

GMSH: Mesh Generation in X-SEA AutoCAD

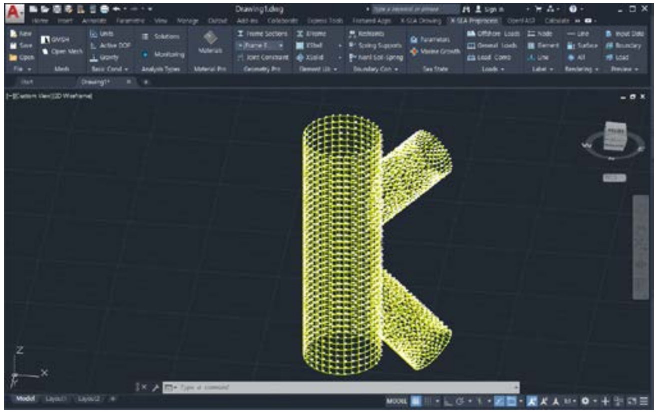
One-, two-, and three-dimensional mesh models were created using GMSH (https://gmsh.info/). GMSH is an open-source 3D finite element grid generator with a built-in CAD engine and post-processor. Its design goal is to provide a fast, light, and user-friendly meshing tool with parametric input and advanced visualization capabilities.



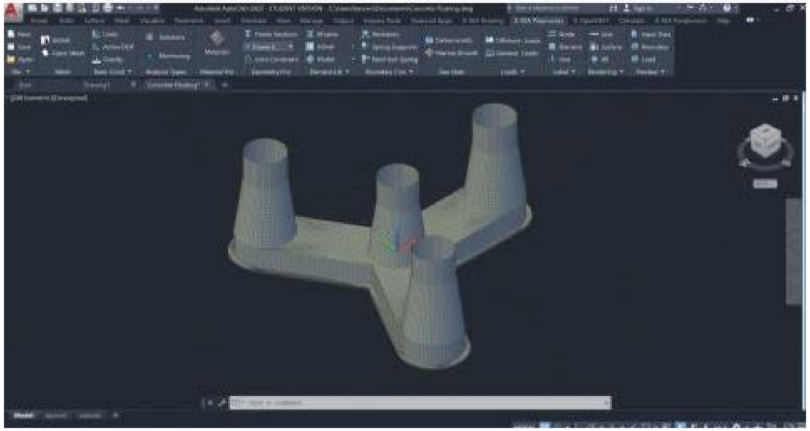
Pop-up Window of GMSH



Open Mesh in AutoCAD Screen



K joint of jacket structures



Mesh generation of concrete floating offshhore

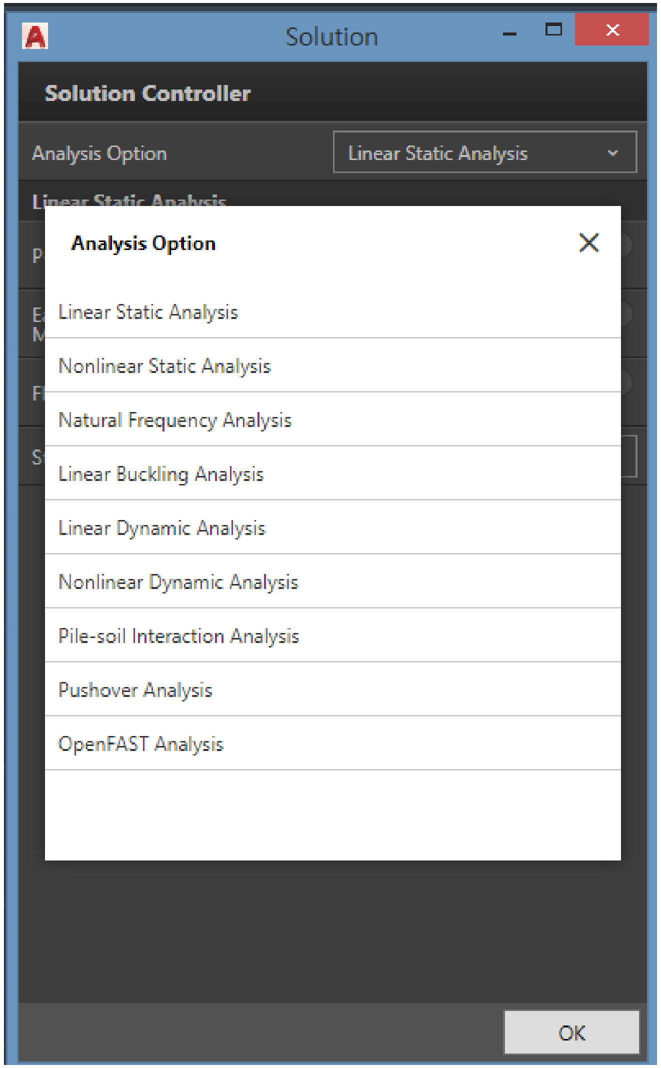
Template for creating jacket, tri/tetrapod, and monopole

The AutoCAD X-SEA contains a template that allows the user to easily create the model of monopile, tri/tetrapod, and jacket structures with line elements, as shown in Figure. The window of the template contains options for generating meshes of line elements and render 3D shapes. This option enables users to model geometries easily and rapidly as compared with CAD drawings.

TEMPLATE OF MONOPILE, JACKET AND TRIPOD MODEL IN X-SEA AUTOCAD

Introduction of X-SEA: Autocad pre&postprocessor

Analysis Option



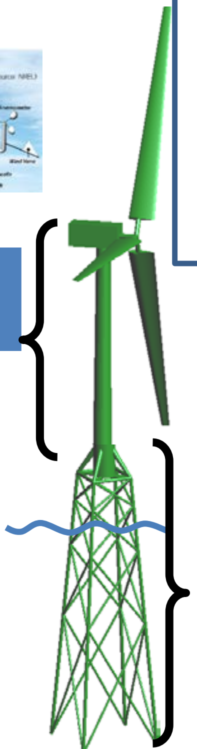
Solution detail

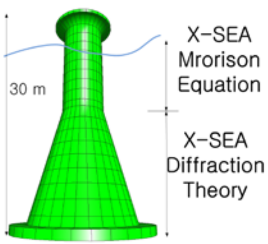
Inplace Analysis
Nonlinear analysis
Eigenvalue Analysis
Linear Dynamics Analysis (Time Integration & Mode Superpostion, Frequency Domain)
Nonlinear Dynamic Time History Analysis
Large deformation elastoplastic analysis of frame, shell and solid elements
Earthquake: Response spectrum analysis, Pushover analysis
Environmental Load(wave,currents,Marine growth,self-weight) and General loads
Regular (5 Kinds) and Irregular wave (PM, JONSWAP, Random Wave)
3D Morison & 3D Linear Diffraction wave pressure (Shell & Solid element)
Prestressing analysis of tendon in PS concrete
Joint modeling: Rigid offset, Local ioint flexibility element(in progress)
Automatic calculation of SCF factor
Fatigue Analysis in Frequency and Time Domain
Mooring Analysis of Floating Structure
Pile Foundation Analysis(p-y,t-z,Q-z) and Pile Super element
Steel Code Check & Design
Ship Collison to Steel and Concrete offshore structure
AutoCAD addin of OpenFAST Graphic Preprocerssor with Multiple load case
Coupled Dynamic Analysis of OpenFAST turbine and X-SEA substructure
Postprocessing the Fatigue analysis using GH-Bladed and OpenFAST output

X-SEA Offshore Load: Steel & Concrete Structure

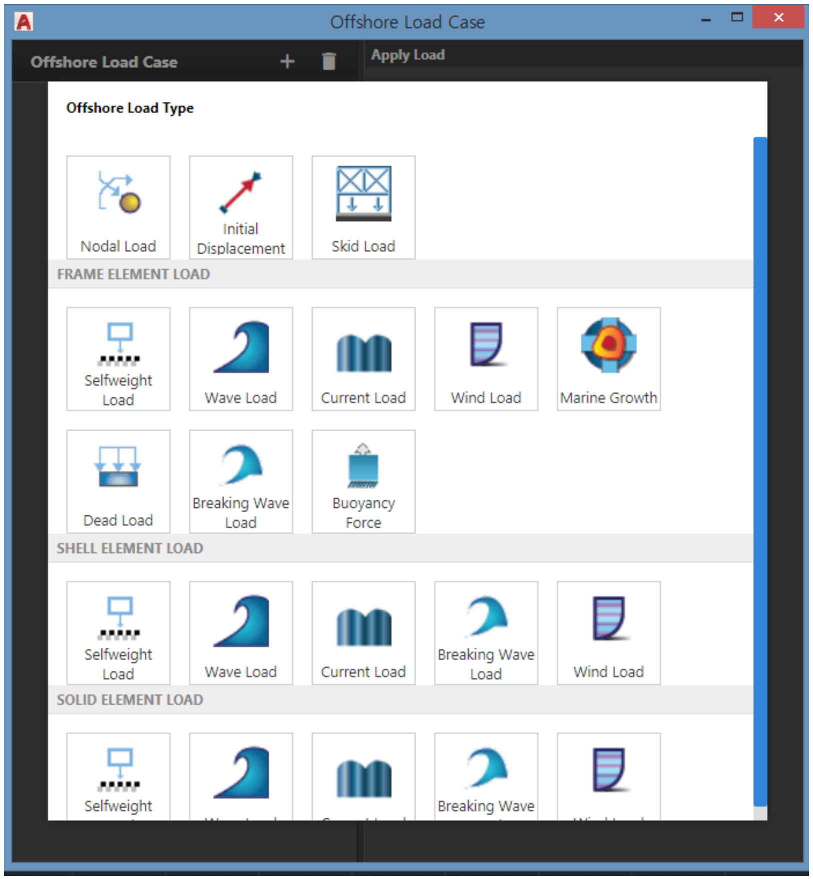
X-SEA offshore load is waves, currents, wind,an earthquake any other naturally occurring phenomenon, or any combination of those phenomena.
Morison equation is used for the calculation of wave load in offshore steel framed structure.
The wave pressure (Sarpakaya)for large concrete offshore structures using the linear wave diffraction theory by MacCamy& Fuchs is available for the very big horizontal diameter to wave length of incident waves (D/L>0.2).

OpenFAST Turbine and Tower Load



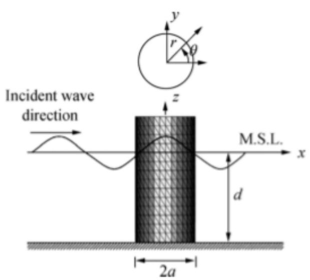


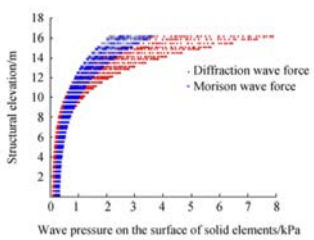
X-SEA Environmental Load



Verification Example of Diffraction wave

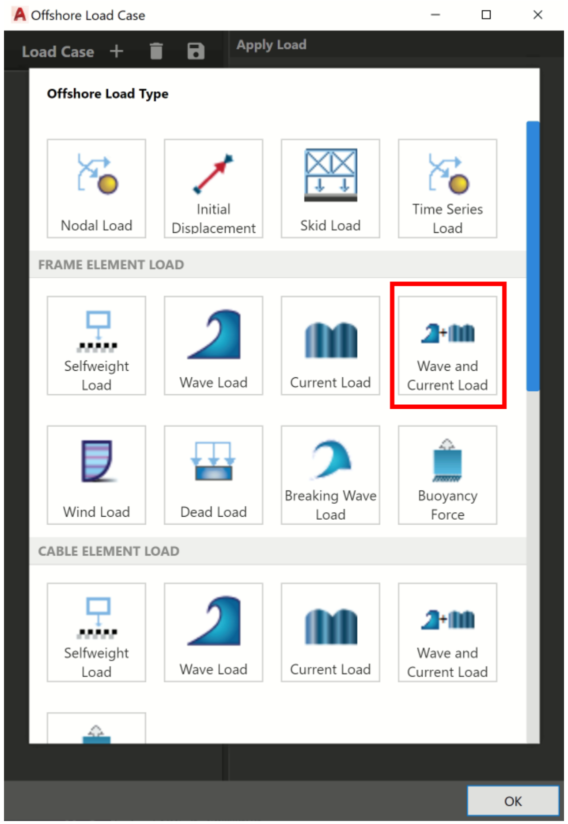
Sarpkaya T, Michael I (1981) Mechanics of wave forces on offshore structures. Van Nostrand Reinhold Company USA



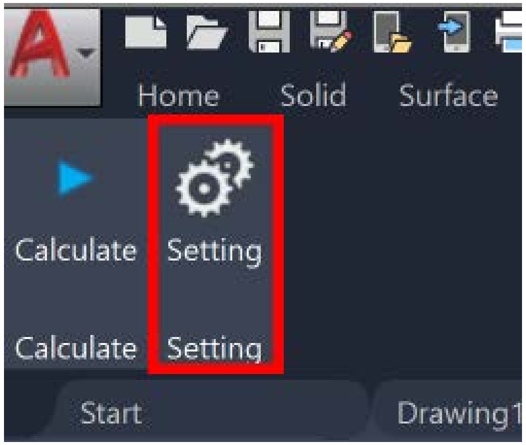


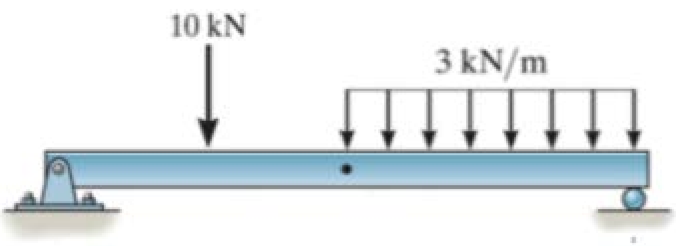
X-SEA Wave and Current interaction

The wave and current interaction is provided in offshore load based on DNV and API.



X-SEA Setting of calculation

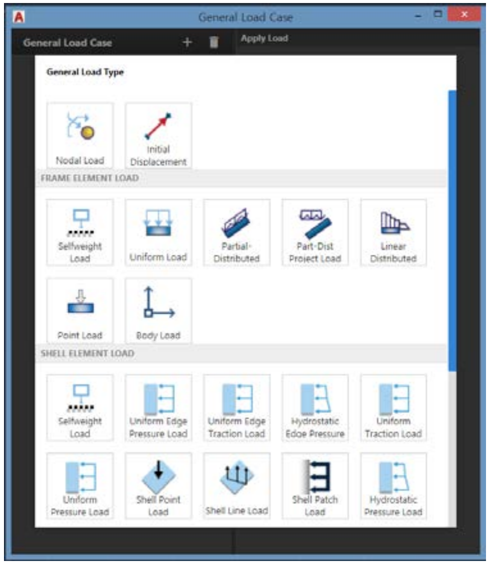


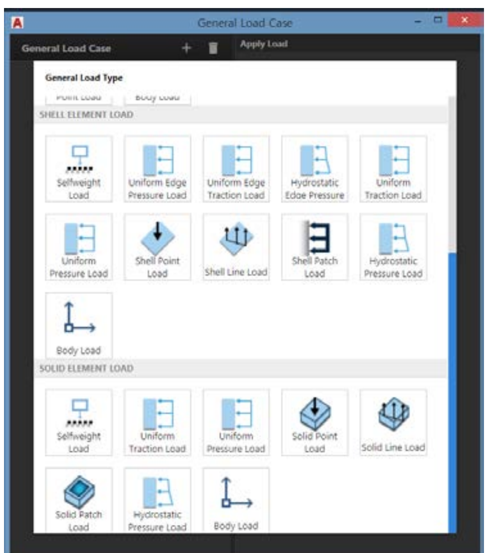


In many different type of load, the setting of calculation can be used in one time analysis without using load combination.

X-SEA General Load & Load Combinations

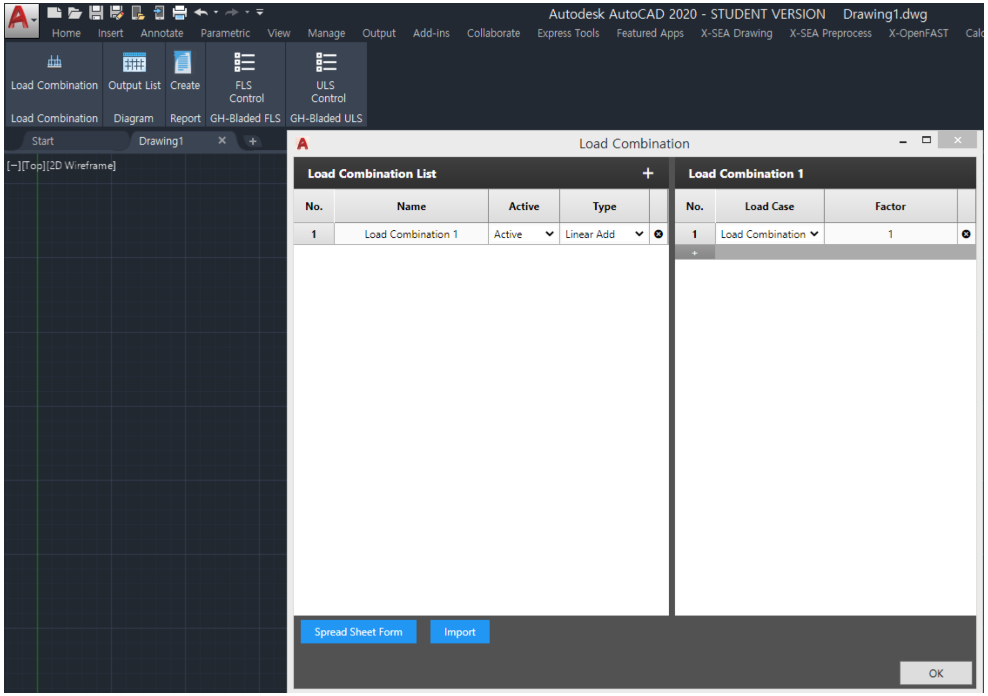
General loads





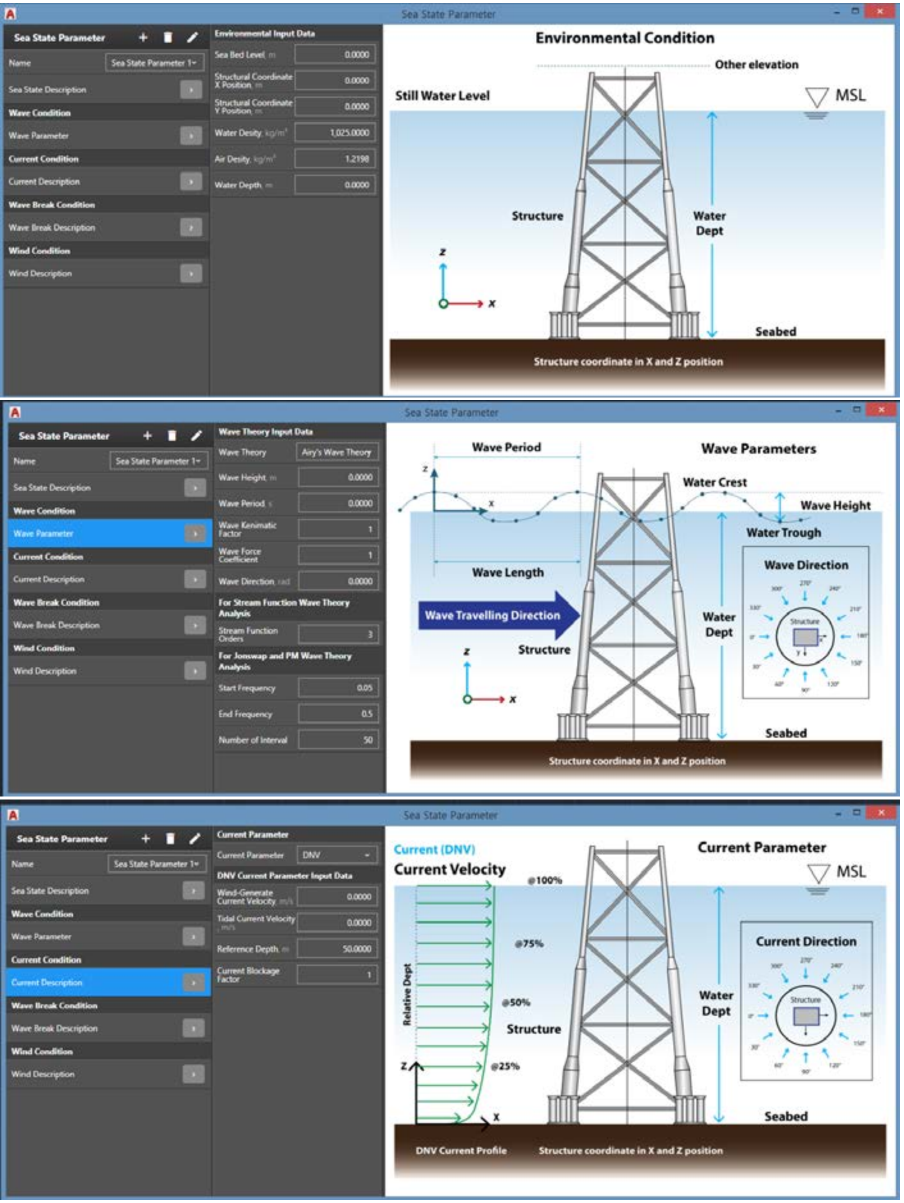
Load Combinations Postprocess: table format

Click the load combination cases to combine the results of static wind, current, wave, buoyancy, response spectrum and others for offshore analysis.

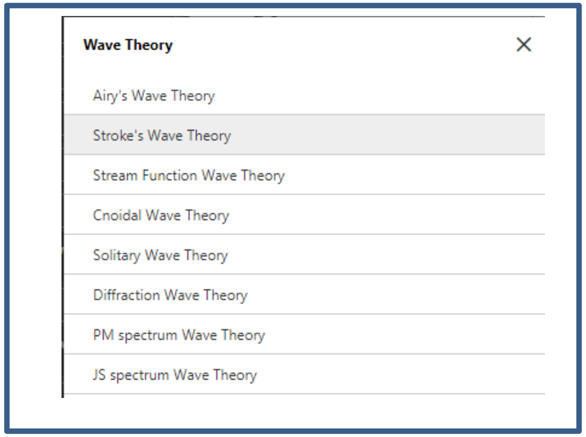


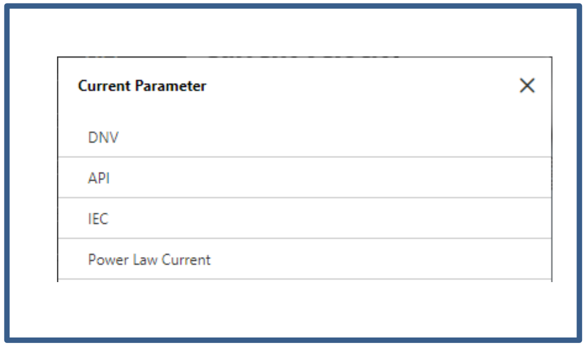
Prof. Ki-Du Kim Konkuk University, Seoul, Korea

Sea State Parameter: Easy User-friendly AUTOCAD Input

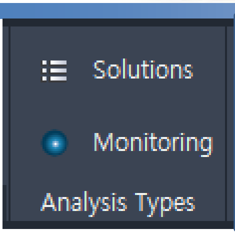


A sea state is characterized by statistics, including the wave height, period, and power spectrum with respect to wind, waves and swell. The sea state varies with time, as the wind conditions or swell conditions change.

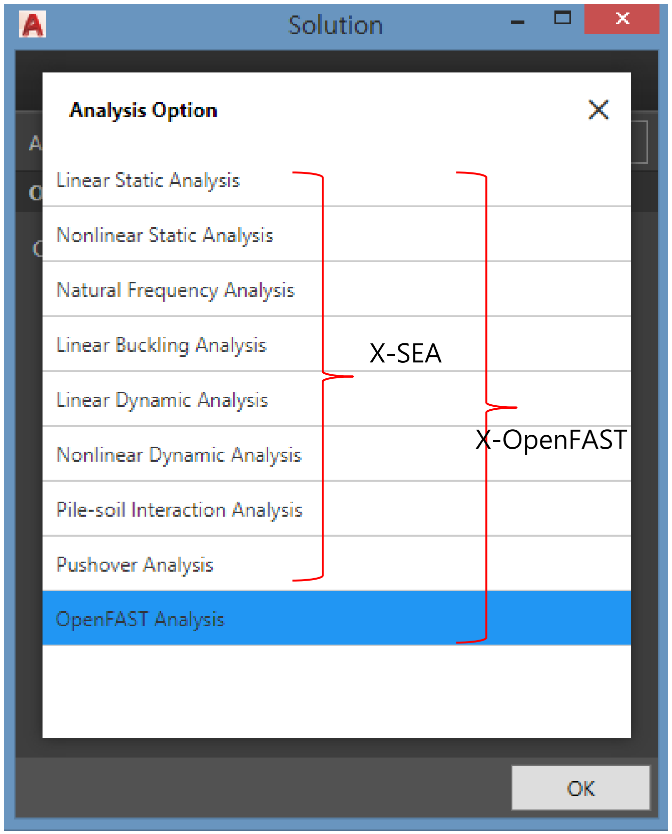




X-OpenFAST: GUI of Wind Turbine Analysis software



The OpenFAST analysis is executed independently in "**Solution**".

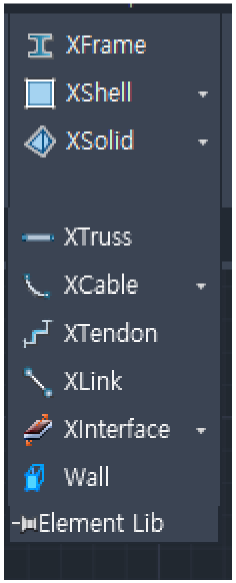


Brief Introduction of X-OpenFAST

- The OpenFAST by NREL, USA is an integrated software package for wind turbine performance and loading calculation in onshore and fixed/floating offshore wind turbine.
- OpenFAST is one of the most popular softwares in research and design of floating offshore wind turbine.
- X-OpenFAST, Pre & Post Processor of OpenFAST is developed using X-SEA AutoCAD interface and includes the offshore structural dynamics.
- Without changing main algorithm, only input and output of OpenFAST is modified to develop the pre/post processor.
- X-OpenFAST is easy and user-friendly AutoCAD graphic user interface.
- Fully coupled analysis of OpenFAST is available on X-SEA substructure and independently working on AutoCAD.
- The sequentially coupled dynamic analysis of substructure can be carried out using OpenFAST and X-SEA substructures.
- The load cases of OpenFAST is automatically created and combined with X-SEA.
- The X-Y graphs of OpenFAST results are available.
- Geometry of offshore wind turbine support structures in X-OpenFAST is created by AutoCAD drawing tools or template.
- AutoCAD GUI of NEMOH(Diffraction/radiation, France) will be available as separate solution.

X-SEA Nonlinear Element Library

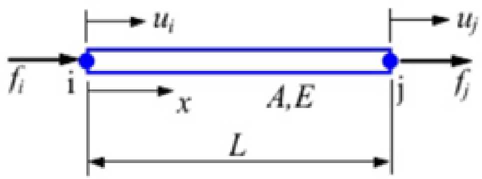
X-SEA structural elements have the geometrical and Material Nonlinear properties.



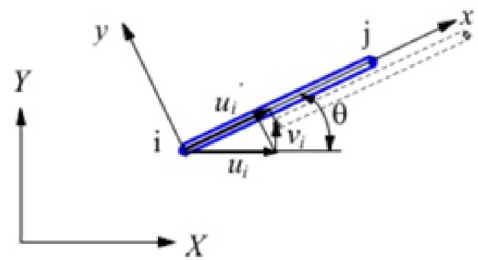
X-SEA Linear & Nonlinear Element library		X-SEA Nonlinear Material
Frame element	XFRAME :2-node frame element with warping (7 dof, Shear deformation, tapered)	Elastoplastic: Von Mises, CONCRETE CREEP,
Shell element	XSHELL3-QSI : 3 node quasi-conforming XSHELL4-ANS : 4 node Assume Natural Strain	Elastoplastic: Von Mises with strain hardeing, Ivanov-Yulishin, Concrete Elsto-plastic & Elasto-plastic Fracture, laminate composite, Concrete creep
Solid element	XSOLID4T & XSOLID10T: 4 & 10 node, Tetrahedral XSOLID8-EAS: Enhanced Assumed Strain 8 node	Elasto-plastic: Von-Mises, Mohr-Coulomb, Drucker-Prager, Tresca
Truss element	XTRUSS: 2-node three dimensional element	Elastoplastic :Von Mises
Cable element	XCABLE–Parbolic XCABLE–Catenary XCABLE-Mooring	5-point nonlinear model
Spring element	XSPRING : 3-D Spring	
Link Element	Gap, Hook, Gap-Hook	
Interface element	1-D, 2-D,3-D (Bond-slip element)	
Tendon element	3-D prestressing tendon	

X-SEA Truss (Bar) Element

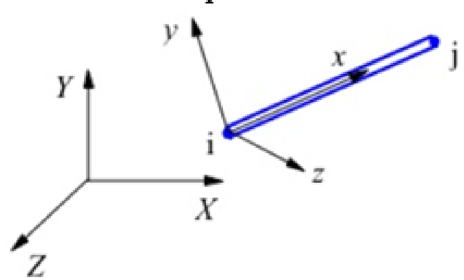
Truss element in 1 D space



Truss element in 2 D space



Truss element in 3 D space



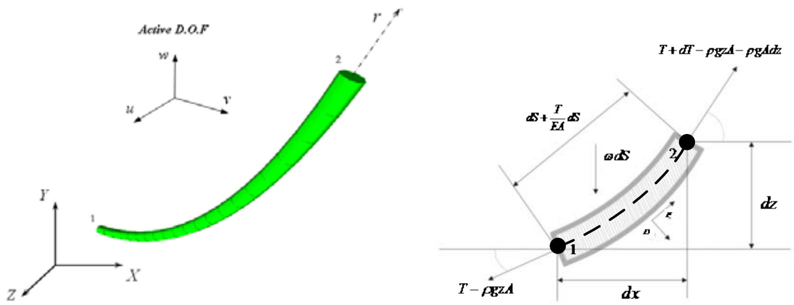
Truss Element stiffness matrix is calculated in the local coordinate system and transformed into the global coordinate system automatically.

A truss element is structural member capable of transmitting stress only in the direction normal to the cross section. The normal stress is assumed to be constant over the cross-section area. The two-dimensional and three dimensional truss elements are shown in the X-SEA element library. The linear and geometrically nonlinear element modules are available.

Truss Element

Configurations	Straight 2-node element
Nodal coordinates	Global Cartesian coordinates X,Y,Z
Degrees of freedom	Displacements u, v, w in the X, Y and Z direction
Shape functions	Isoparametric, the shape linear functions are used for the coordinate and displacement
Stress & Strain components	σ_x , ε_x
Material prop.	E - young's modulus υ - Poisson's ratio σ_{y0} - yield stress in simple tension H - strain hardening parameter (E_p/(1-Ep/E)) ρ^m - mass density
Geometric prop.	Number of node: 2 A area
Formulations :	Small displ., elastic material Small displ., nonlinear material Updated Largrangian
Material laws :	Linear-Elastic Elasto-Plastic
Load types	Nodal load Body load Thermal load
Mass modeling	Consistently lumped & Consistent mass
Stress output	With respect to the global coordinate system X, Y, Z. The axial stresses are printed for each element.

X-SEA Cable Element



X-Catenary Cable Element

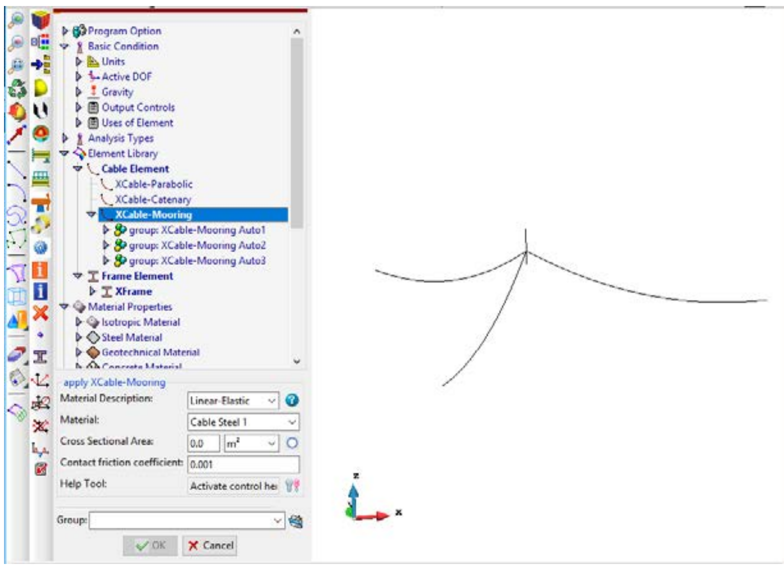
The nonlinear cable element has 2 nodes and total 6 DOF. Its can resist only tensile load i.e. it has no strength and stiffness in the compressive direction.

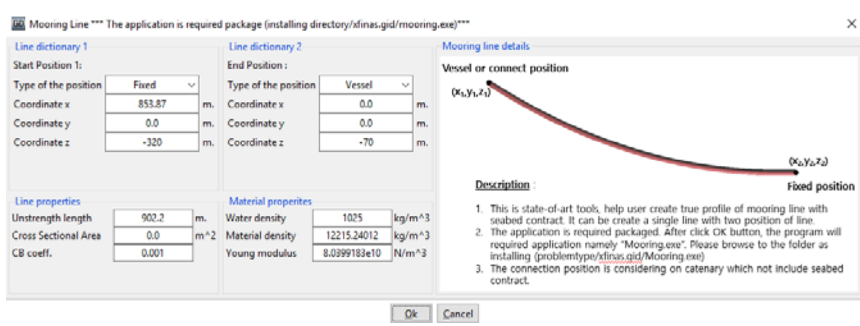
The stiffness of the catenary cable element is dependent on its weight, length and the tension force itself. The nonlinear force-displacement relationship was included to take into account the sag effect that is importance in the practical cable structures.

The multi-linear material behavior was also included into the element formulation, thus the element can be used in geometric and material nonlinear analysis of the cable structures such as suspension bridges.

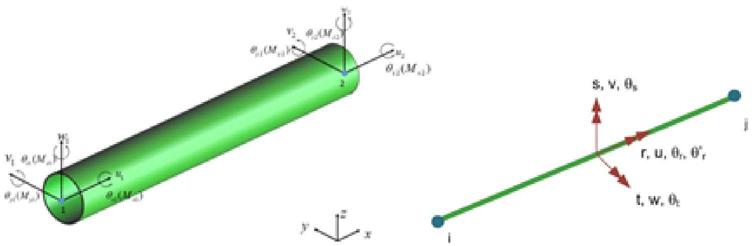
T is the line tension, *A* is the cross-section area of the line, *E* represents the elasticity modulus, *F* and *D* correspond to the drag or mean hydrodynamic forces both normal and tangential direction, respectively,

The Xcable-Mooring is provided for helping users to generate true profile of the mooring line with seabed contract. This line will give begin and end position of seabed contract.

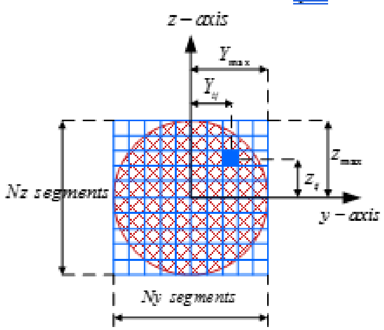




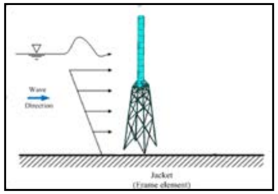
X-SEA Frame Element: 7 D.O.F



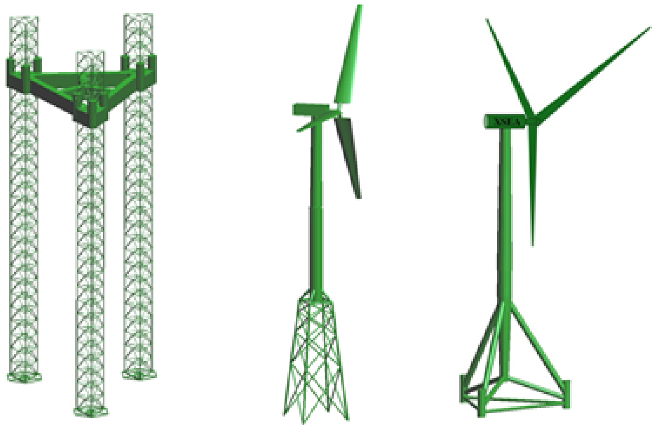
XFRAME ELEMNET (7 DOF)



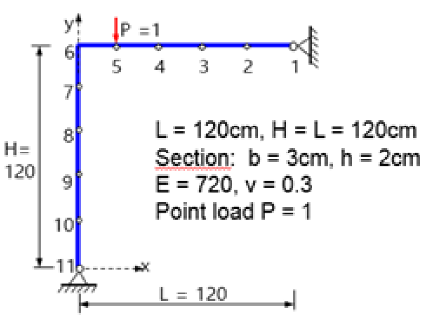
Fiber Cross Section of XFRAME ELEMNET

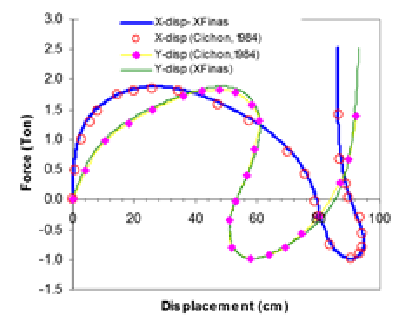


Offshore Model using XFrame_Element



Large displacement elastic and elasto-plastic Analyses of Lee's frame to validate the nonlinear performance

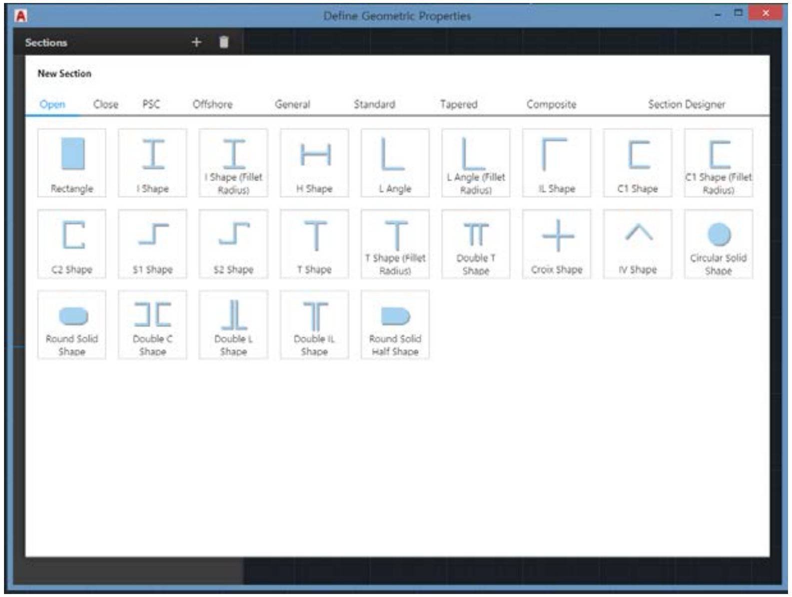


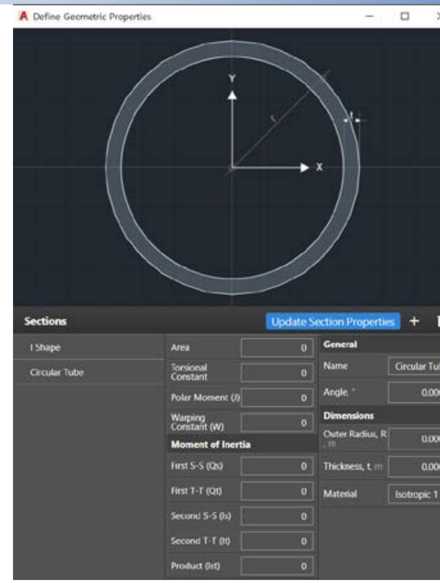


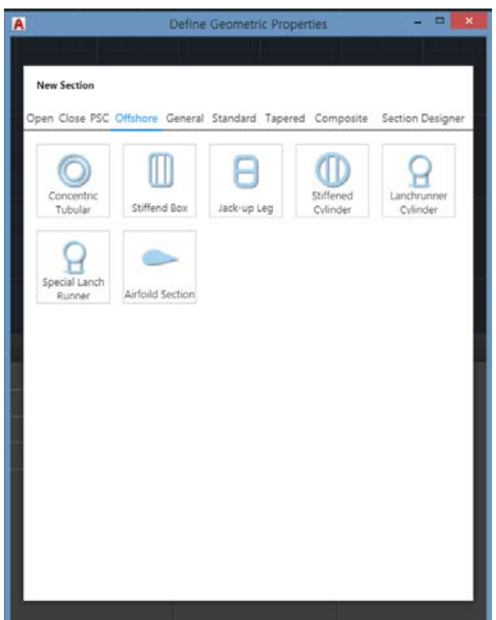
A three dimensional 2-node frame element can be used for the linear and nonlinear dynamic analysis of 3-D offshore framed structures.

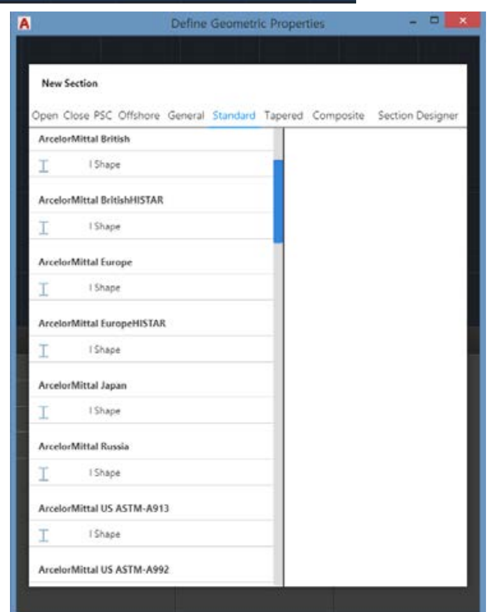
- The XFRAME element has a spring and offset for easy and efficient modeling.
- Fiber cross section analysis using 8-node element
- Geometrical and Material nonlinear frame element
- Tapered frame element
- Warping analysis of steel cross section of frame element.

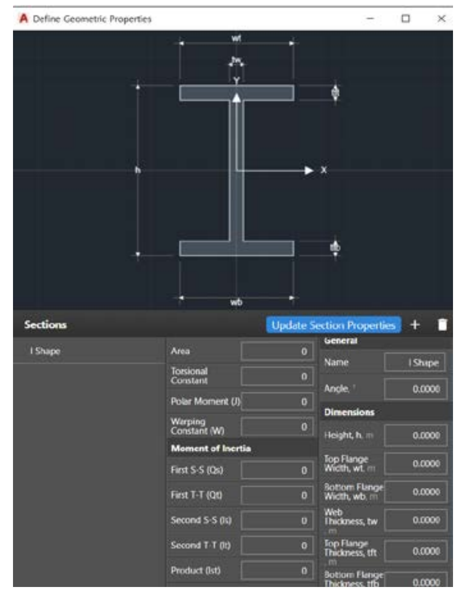
X-SEA Frame Element: Section Properties





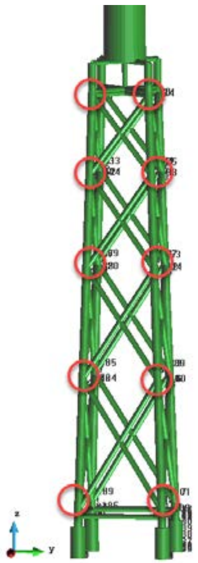




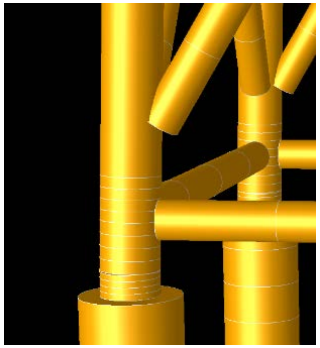


X-SEA Frame Element: Offset of Structural Joint

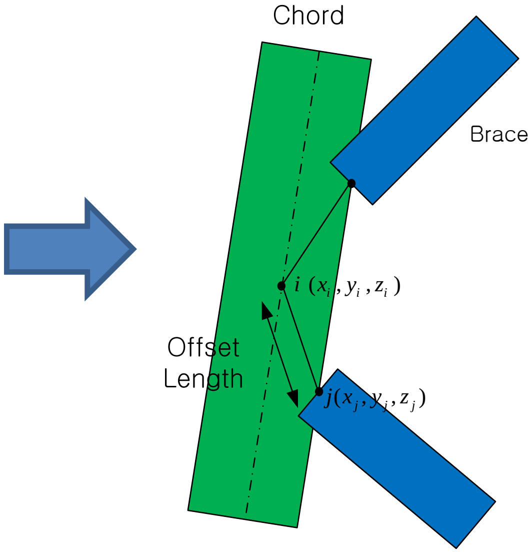
- When chord and brace members are connected with the same joint, there is some overlap of the cross section. To solve, "member offset" function was applied.
- Offset member will be divided into a flexible zone and rigid offset zone. The rigid offset zone will be calculated by transformation and will not affect on axial and torsional deformation. The rest zone is assumed to be deformable frame element.



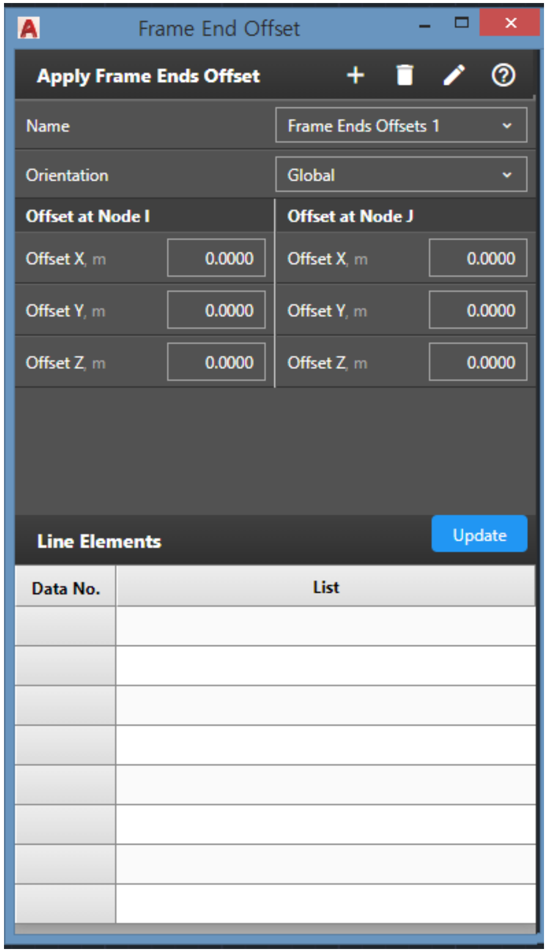
Jacket model with offset



Offset member (rendered)

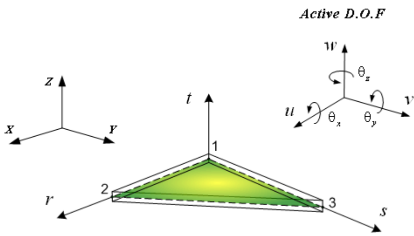


Offset Modelling

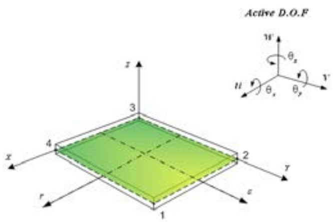


X-SEA interface of automatic and direct input of offset length

X-SEA Shell Element: 6 D.O.F



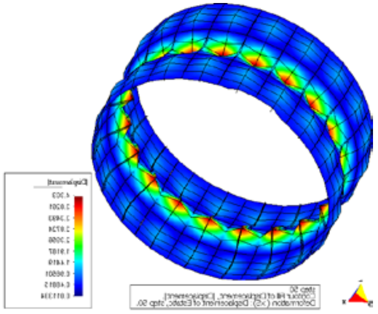
3-node Shell element

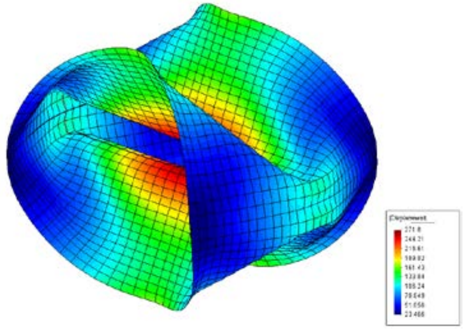


4-node Shell element

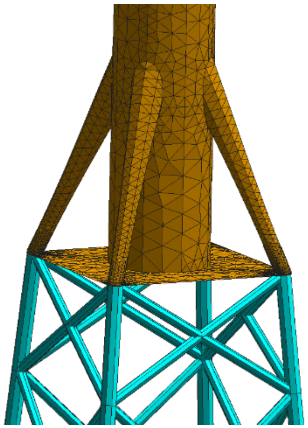
- The formulation of the shell elements use Mindlin-Reissner theory
- Assumed Strain Method and Quasi-Conforming method to remove the shear locking
- Co-rotational formulation in nonlinear analysis
- The thin shell structures.
- Rotation free X-Shell 3 node element is very efficient in memory and CPU time.

Verification of large displacement elstoplastic analysis of shell structures

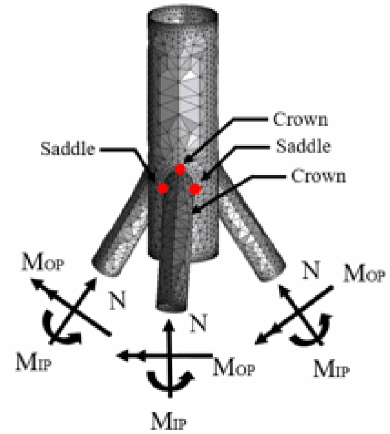




Application of offshore wind turbine

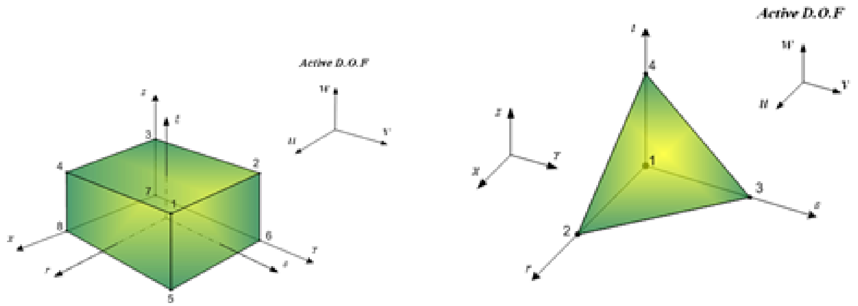


Transition Pieces of Jacket structures is discretized with many shell elements

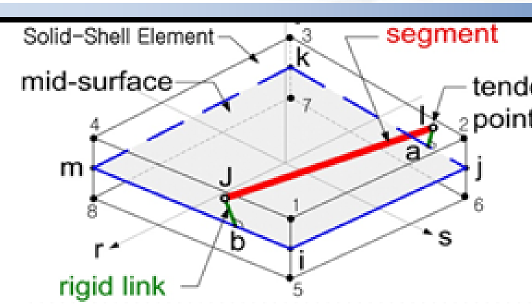


Connection Joint of Jacket structures is discretized with many shell elements

X-SEA 3D Solid Element: 3 D.O.F



3D Solid Element (3 D.O.F)



3D Solid-Shell Element (3 D.O.F)

Three types of solid elements are available.

XSolid-4T – 4 node tetrahedron,

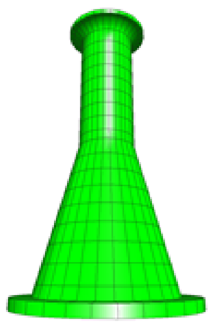
XSolid-10T – 10 node tetrahedron

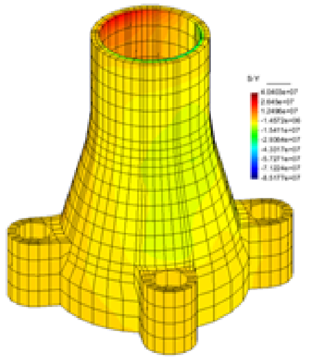
XSolid-8-EAS – 8 node hexahedron with enhanced assumed strains.

XSoilid-shell-8- 8 node assumed strain and enhanced assumed strains.

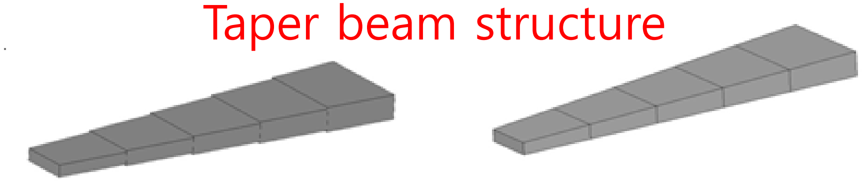
Advantages

- The solid-shell element is analytically integrated through the thickness.
- Computationally efficient element for large concrete structures (more than 50 % CPU time saving)
- Section force, moment & stress at node
- The same DOF as shell element but easier and smoother than shell element model in the tapered beam structures
- The calculation of the membrane force, moments and stresses at node by stress smoothing



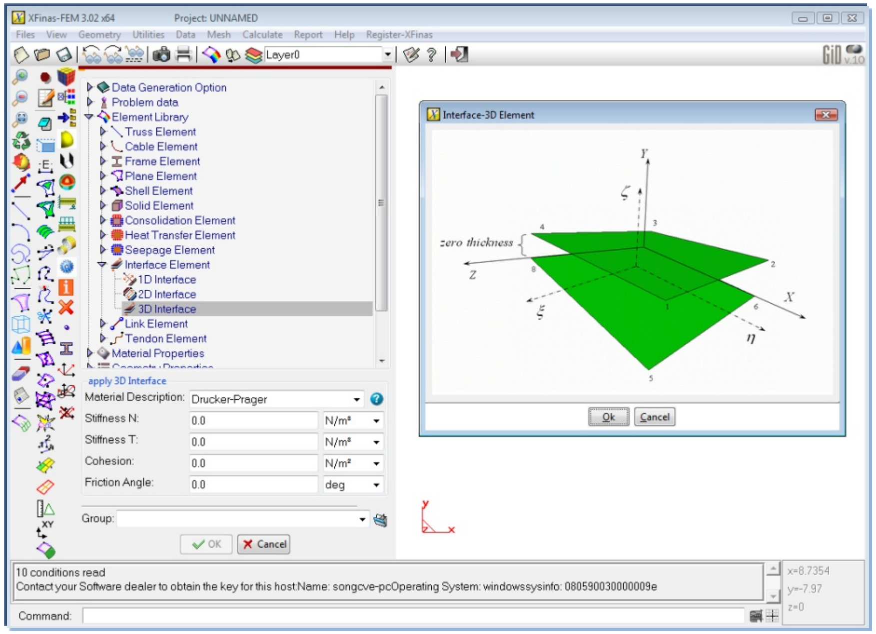


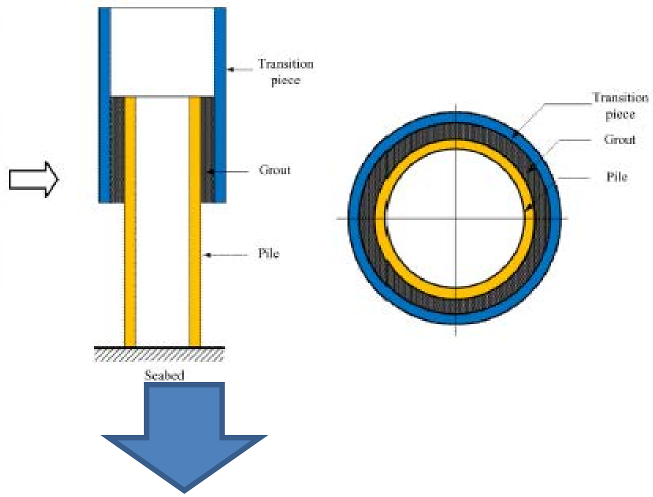
Taper beam structure



Shell Element modeling Solid-shell element modeling

X-SEA Interface Element: Bond-slip behavior





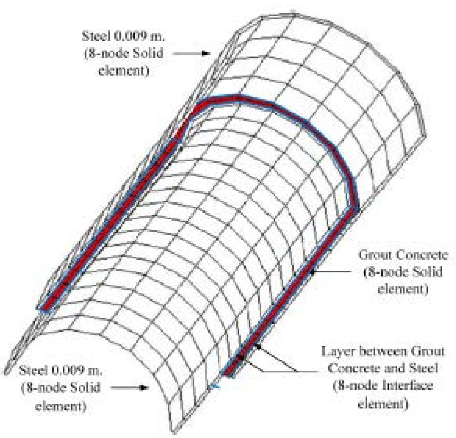
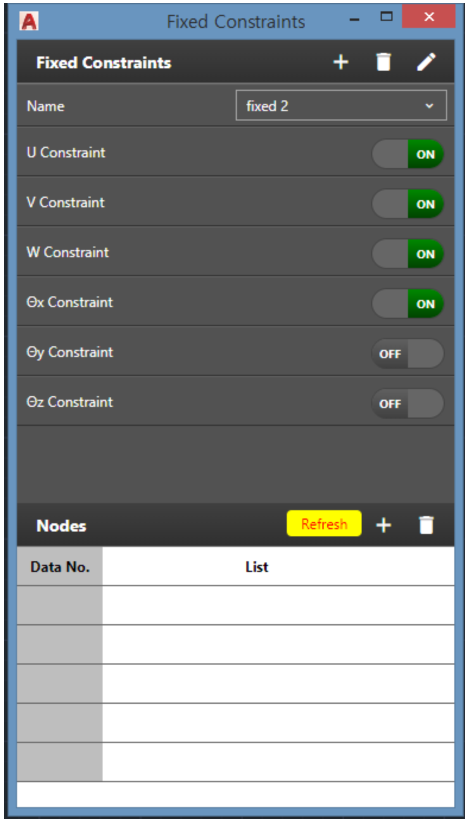


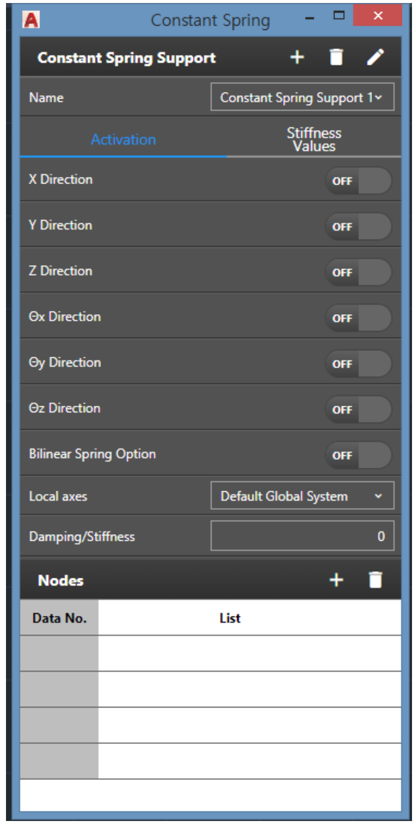
Figure 3. Element mesh at grouted connection.

For the Bond-slip behavior of Grouted Connection, the Interface Element is used for the interface between transition piece and monopile Wind Turbine Offshore Structure.

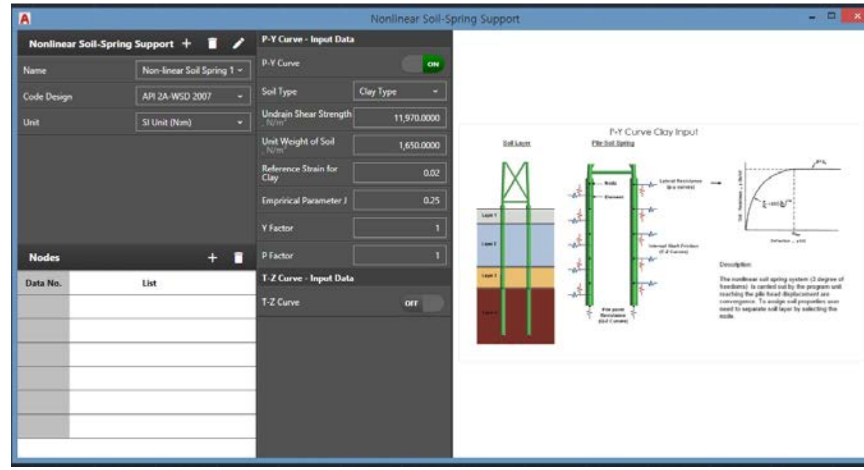
Boundary Condition: Structure & Pile-Soil Foundation



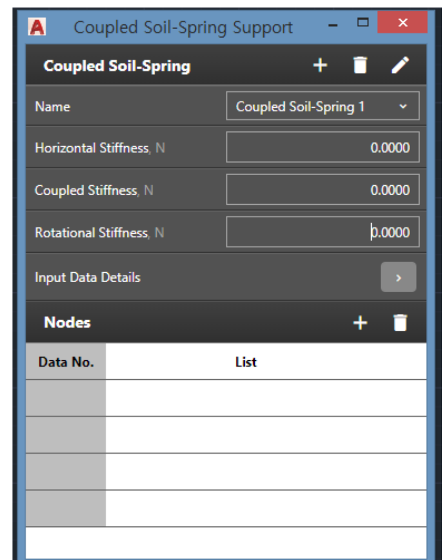
Global or Local Fixed Supports



6 DOF Constant Spring Stiffness

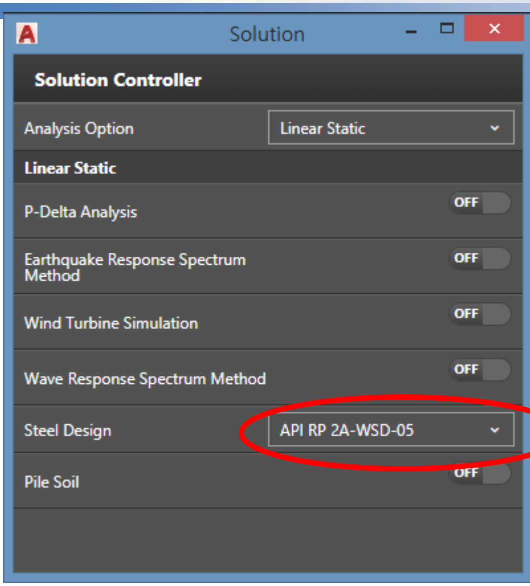


3 DOF Soil Spring : PSI analysis

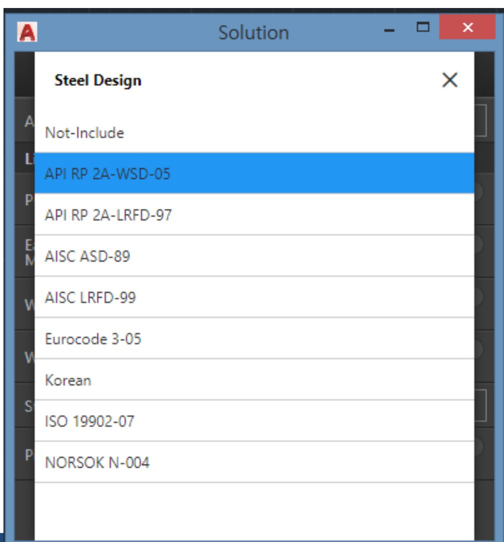


4 DOF Coupled Soil Spring

Steel Structural Analysis & Design (Code Checking)

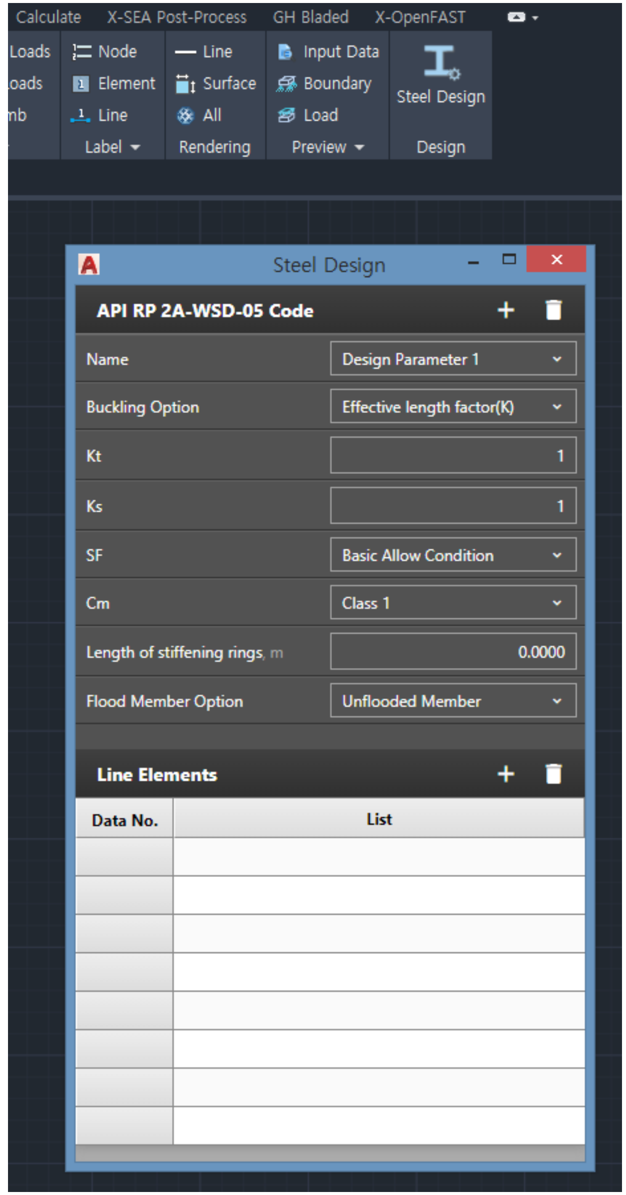


X-SEA software is supporting Major rules and standards as following design code.

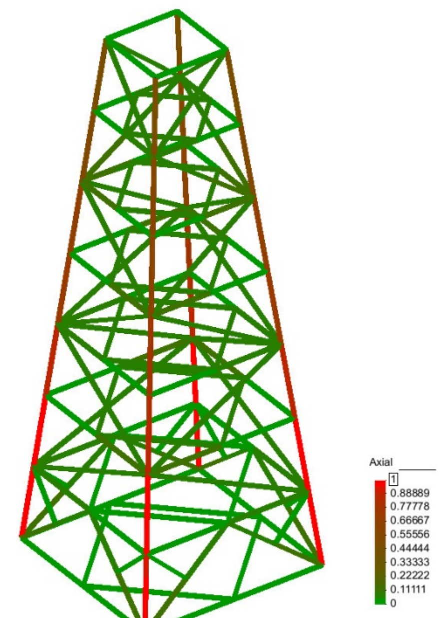


Click

Steel Design



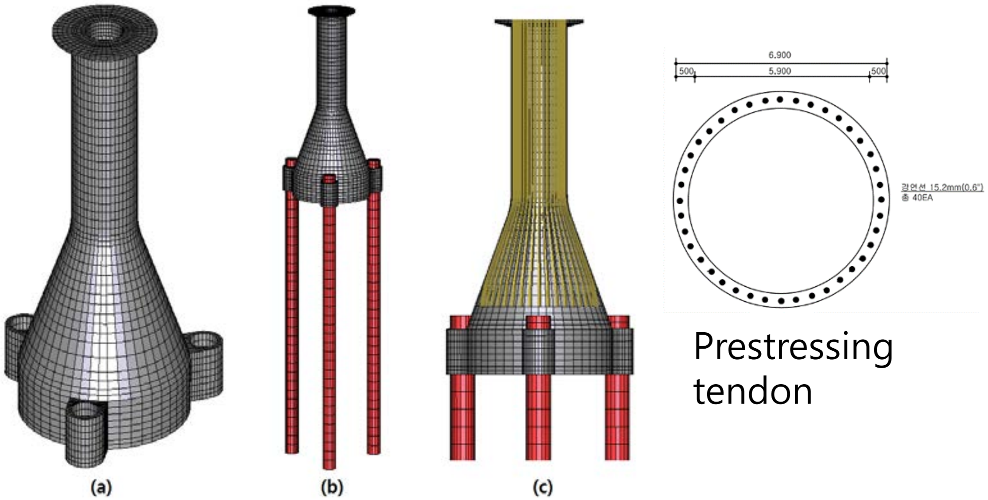
After in-place analysis, the member force and moments can be checked from the various design code and printed by the colorful unit value.



Stress ratio of Jacket Structure

- To design of reinforced concrete(RC) structure, the shell element can be used to obtain the membrane forces and moments.
- To design of prestressed concrete(PC) structure, the solid element can be used to obtain the stresses.

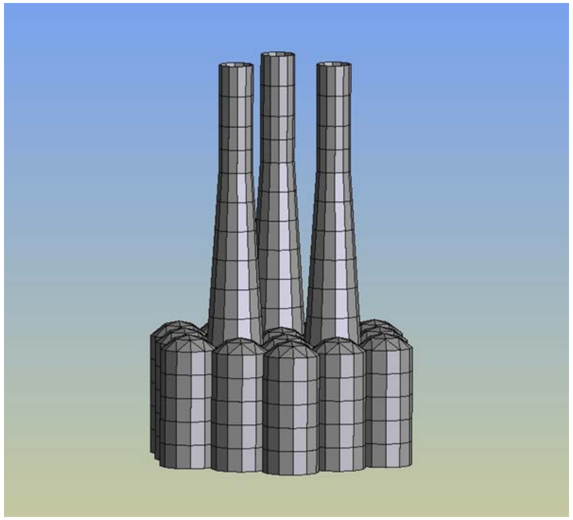
Solid-Shell Element



Pile-support Wind Turbine Concrete structure with prestressed tendon

Advantages for RC & PC

- Prestressing analysis of tendon using short and long term loss (time dependent loss of creep & shrinkage)
- Easy input of tendon
- The calculation of the member force, moments and stresses at node



Concrete Gravity Oil Platform

Linear & Nonlinear Dynamic Analysis in Time domain

- Dynamic Time-history analysis
  - Explicit method: Central difference
  - Implicit method: Newmark-beta, Wilson-theta and HHT
  - Nonlinear dynamic analys: HHT
- Mode superposition method for linear dynamic analysis with damped and undamped system
  - Eigenvector
  - LD Ritz vector

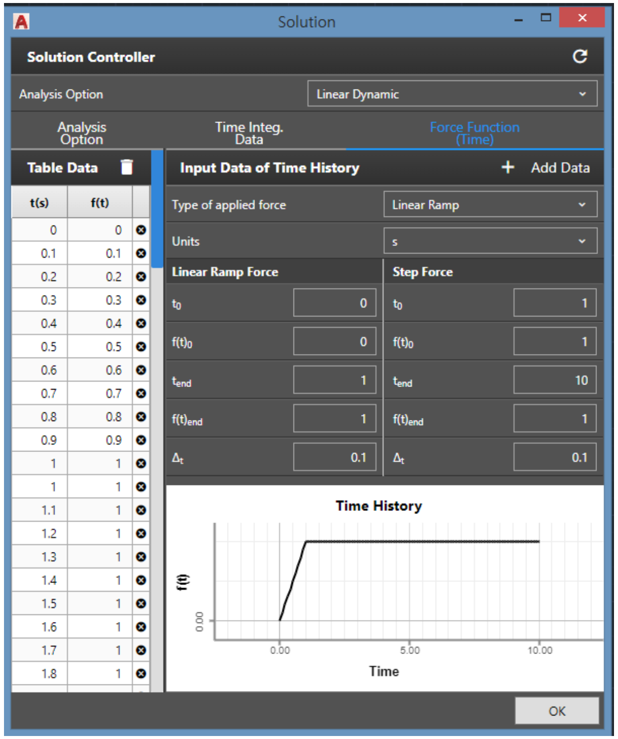
- Hydrodynamic analysis
  - Morison equation for the offshore steel framed structures
  - Diffraction theory for the large offshore structures such as the concrete gravity structures.

- Time history earthquake analysis with seismic code spectrum

- Impact dynamic analysis
  - Impact dynamic analysis of large deformation elasto-plastic analysis can be carried out.

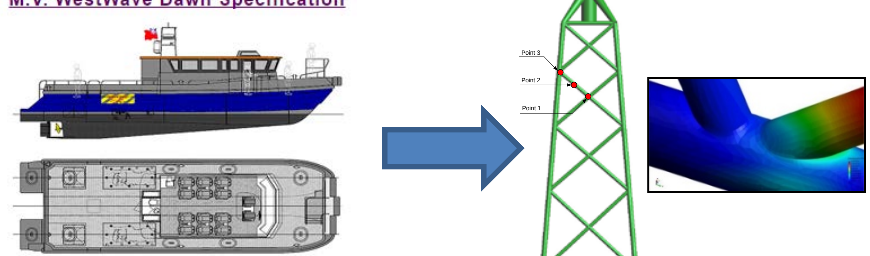
Automatic Generation of Force function

[Linear ramp force]



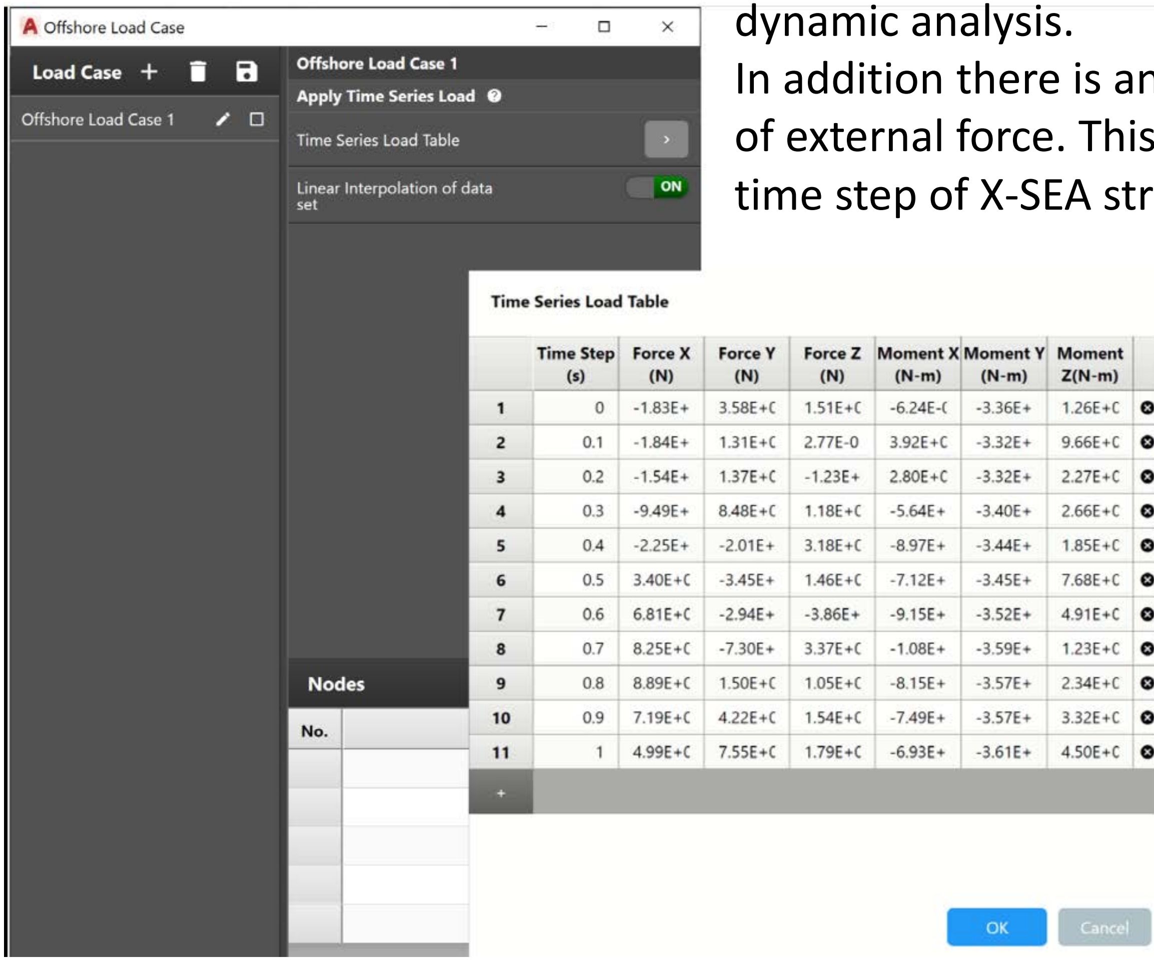
Ship Impact Analysis

M.V. WestWave Dawn Specification



Import of the external dynamic force in X-SEA

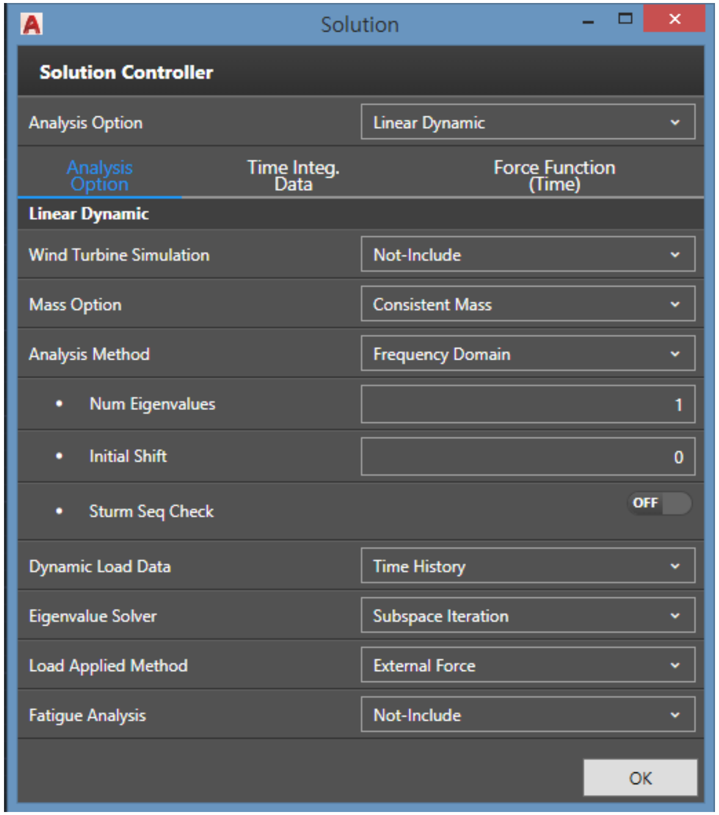
The external force from the wind turbine dynamic load of OpenFAST can be imported into X-SEA offshore structural dynamic analysis.
In addition there is an option of linear interpolation of external force. This option is used in case of not same time step of X-SEA structural dynamic analysis.

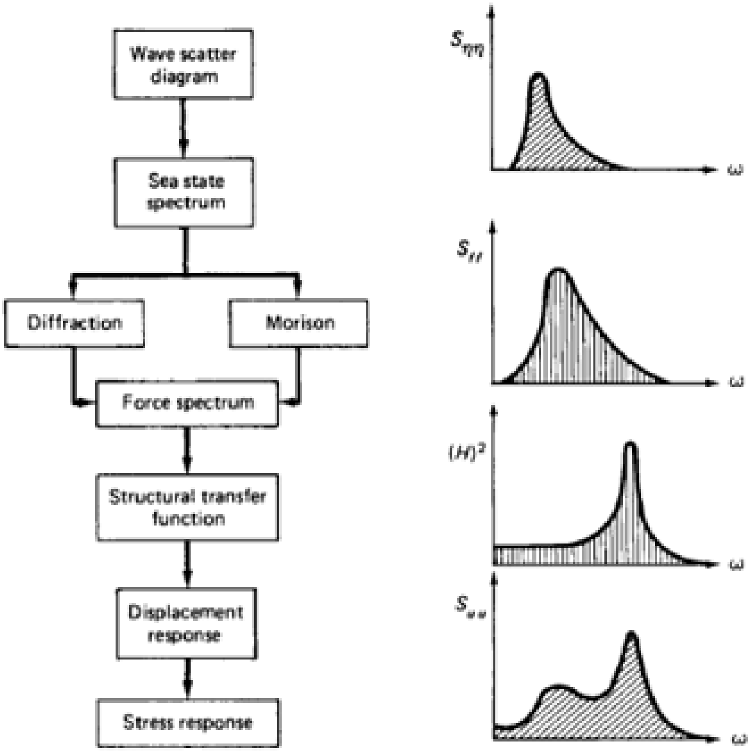


	Time Step (s)	Force X (N)	Force Y (N)	Force Z (N)	Moment X (N-m)	Moment Y (N-m)	Moment Z(N-m)
1	0	-1.83E+	3.58E+C	1.51E+C	-6.24E-(	-3.36E+	1.26E+C
2	0.1	-1.84E+	1.31E+C	2.77E-0	3.92E+C	-3.32E+	9.66E+C
3	0.2	-1.54E+	1.37E+C	-1.23E+	2.80E+C	-3.32E+	2.27E+C
4	0.3	-9.49E+	8.48E+C	1.18E+C	-5.64E+	-3.40E+	2.66E+C
5	0.4	-2.25E+	-2.01E+	3.18E+C	-8.97E+	-3.44E+	1.85E+C
6	0.5	3.40E+C	-3.45E+	1.46E+C	-7.12E+	-3.45E+	7.68E+C
7	0.6	6.81E+C	-2.94E+	-3.86E+	-9.15E+	-3.52E+	4.91E+C
8	0.7	8.25E+C	-7.30E+	3.37E+C	-1.08E+	-3.59E+	1.23E+C
9	0.8	8.89E+C	1.50E+C	1.05E+C	-8.15E+	-3.57E+	2.34E+C
10	0.9	7.19E+C	4.22E+C	1.54E+C	-7.49E+	-3.57E+	3.32E+C
11	1	4.99E+C	7.55E+C	1.79E+C	-6.93E+	-3.61E+	4.50E+C

Linear Dynamic Analysis in Frequency domain

Frequency domain analysis for the simplified solution is useful for the dynamic response of long term prediction . It is simple to interpret the process of analysis and use for the preliminary design stage. Moreover, it can estimate responses due to a random wave input through spectral formulations.



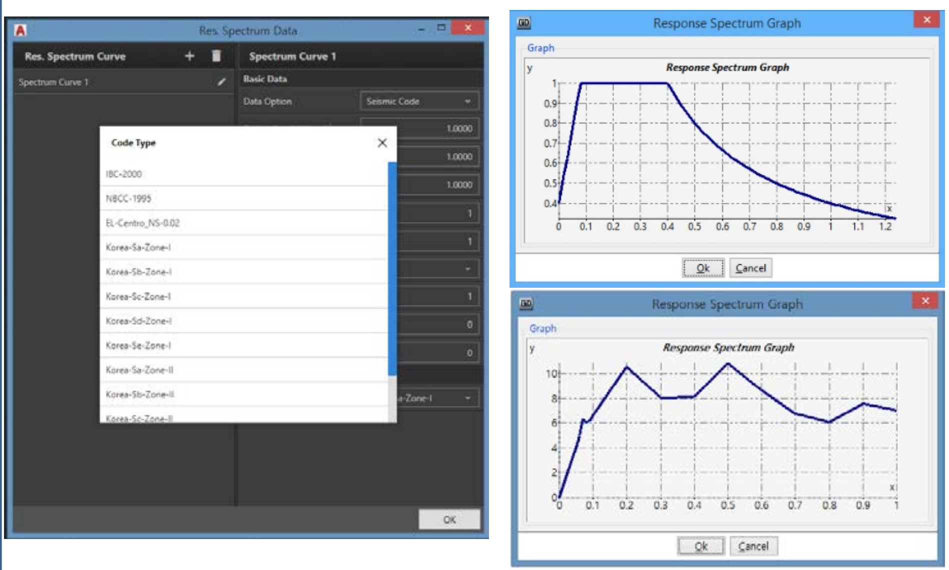


Earthquake Analysis: Response Spectrum & Linear Dynamic analysis

Response Spectrum Analysis

Response Spectrum Analysis calculates modal responses using the natural frequency analysis from the Eigenvalue analysis.
The maximum response is calculated from a scale factor*mode shape. This maximum response is combined with responses from other loads to give a total response of the structure.

X-SEA Seismic Code Spectrum

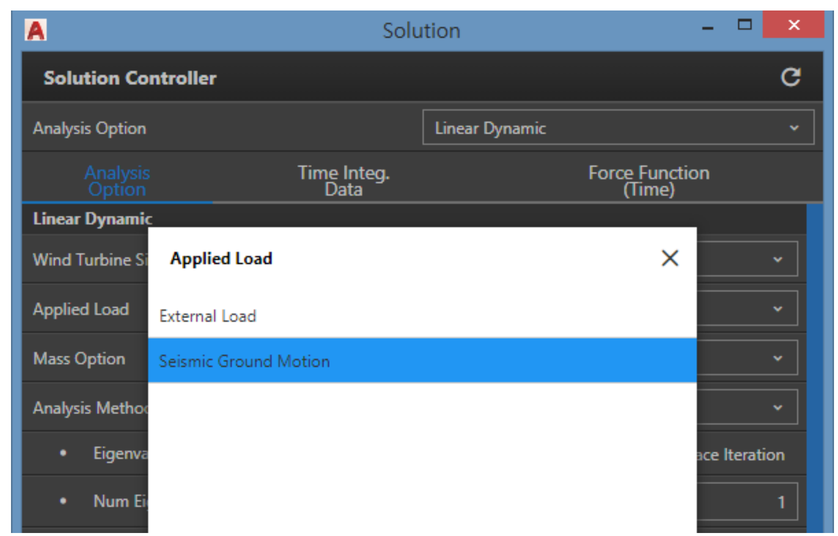


Linear Dynamic Analysis

In the linear dynamic procedure, the offshore structure is modelled as a multi-degree-of-freedom (MDOF) system with a linear elastic stiffness matrix, an equivalent viscous damping matrix and mass matrix. The following methods are used.

- Direct Time Integration methods
- Mode Superposition methods

In ideal cases, the ground accelerations are represented by some time history function, such as the harmonic trigonometric function of time, linear or pulse functions. The internal forces and displacements at each time step are determined from linear dynamic analysis.



Coupled Load Analysis of Fixed Offshore Wind Turbine

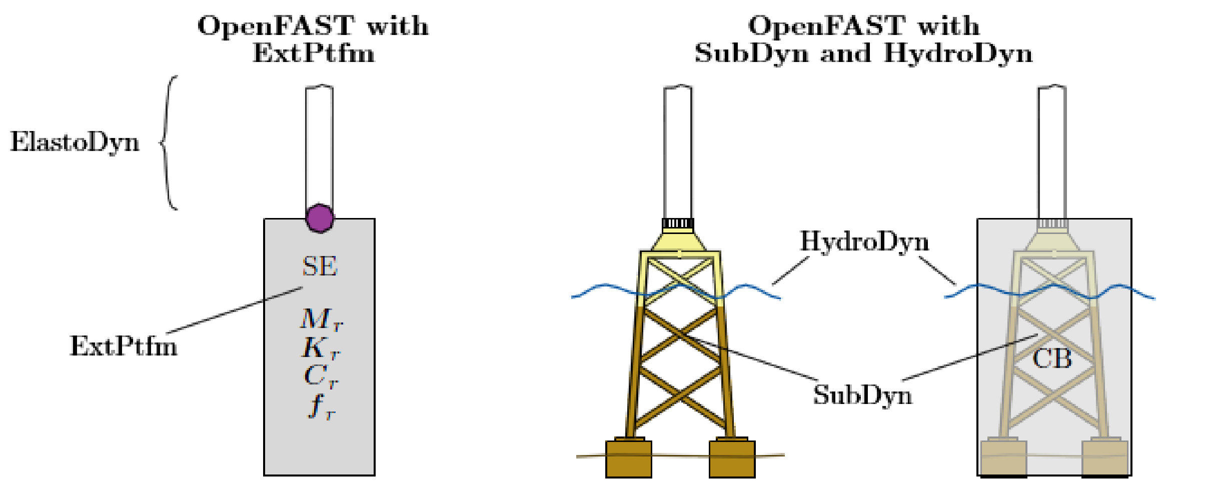


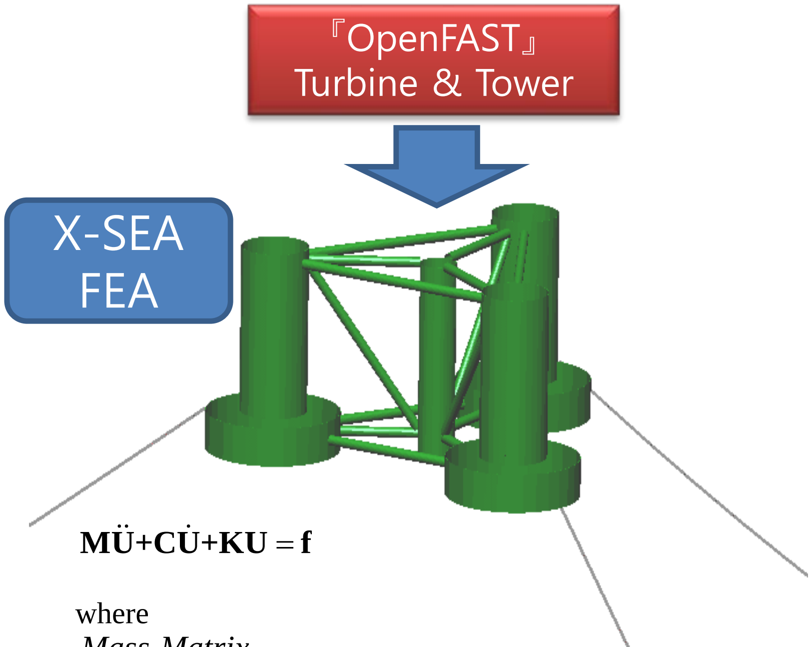
Figure 2: Sketch of the three different options to model a wind turbine with a substructure in *OpenFAST*

- In the analysis and design of **offshore wind turbine support structure**, engineers need a loads from the coupled analysis of **wind turbine**.
- In X-OpenFAST, fully coupled analysis(Figure 2) of offshore wind turbine fixed structure can be carried out using a high performance graphical input of OpenFAST 3.0.
- By the full modelling of structures, all the output of displacement and member forces are available in X-OpenFAST and used in the postprocess, design code checking, FLS and ULS.

E. Branlard, M. Shields, B. Anderson, R. Damiani, F. Wendt, J. Jonkman, W. Musial, National Renewable Energy Laboratory,Superelement reduction of substructures for sequential load calculations in OpenFAST, NAWEA WindTech 2019 Journal of Physics: Conference Series **1452** (2020) 012033 IOP Publishing

Structural Dynamic Analysis of Floating Offshore

Coupling OpenFAST with X-SEA



$$\mathbf{M}\ddot{\mathbf{U}}+\mathbf{C}\dot{\mathbf{U}}+\mathbf{K}\mathbf{U}=\mathbf{f}$$

where

Mass Matrix

$$\mathbf{M}=\mathbf{M}_{structure}+\mathbf{M}_{moor}+\mathbf{M}_{added\ mass}$$

Damping Matrix

$$\mathbf{C}=\mathbf{C}_{structure}+\mathbf{C}_{moor}$$

Stiffness Matrix

$$\mathbf{K}=\mathbf{K}_{structure}+\mathbf{K}_{moor}+\mathbf{K}_{restore}$$

Force Vector

$$\mathbf{f}=\mathbf{f}_{\underset{\substack{(Morrison\ or\\ Differaction)}}{wave}}+\mathbf{f}_{current}+\mathbf{f}_{wind}+\mathbf{f}_{moor}+\mathbf{f}_{buoy}+\mathbf{f}_{\underset{(tower+turbine)}{FAST8}}$$

Morison equation

The hydrodynamic analysis of substructures includes linear hydrostatic restoring, wave force from Morison's equation, added mass and damping and incident wave excitations.

Diffraction/radiation pressure

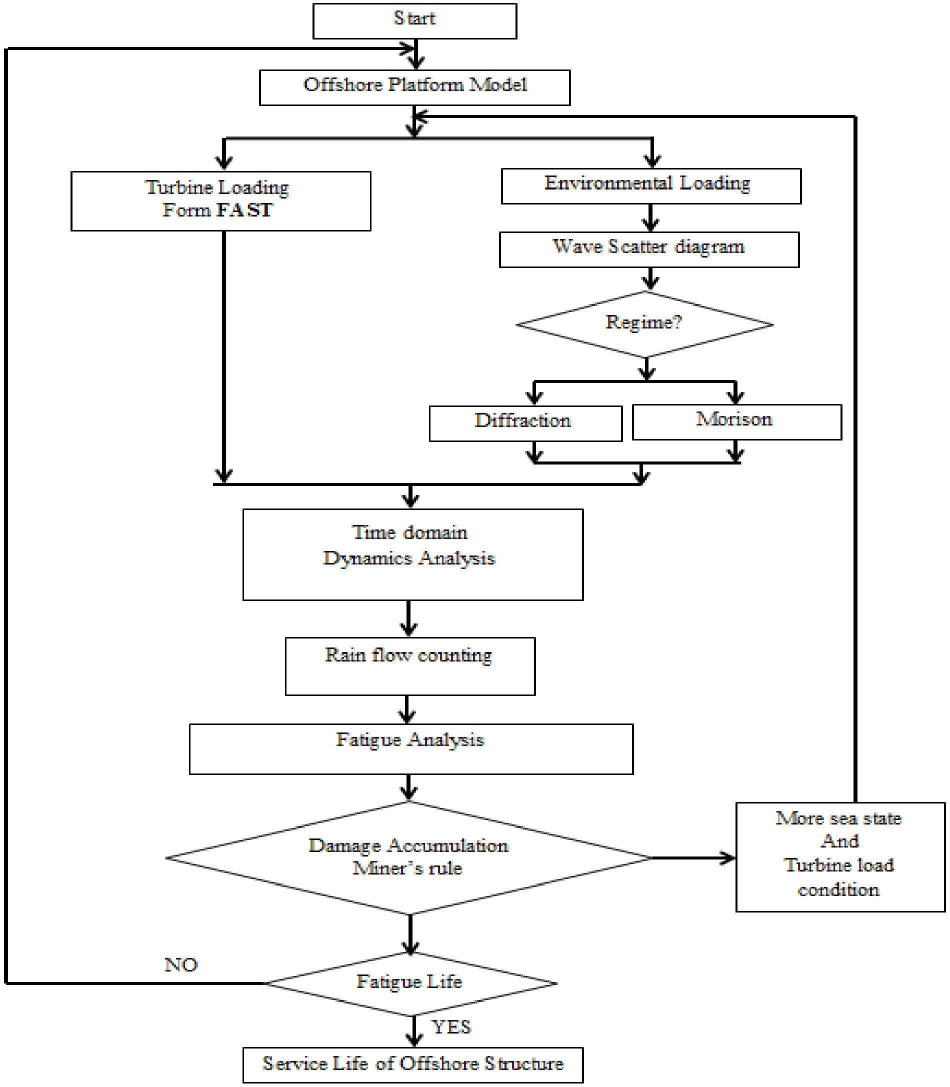
Waves can be analyzed using first-order or first-plus second-order diffraction wave theories based on potential flow theory. The wave-induced load is computed based on the diffraction/radiation problem in the open-source BEM code, NEMOH (France), which can be used in X-SEA AutoCAD. To perform simplified calculations of a complex geometric structure, GUI in the AutoCAD platform can be used.

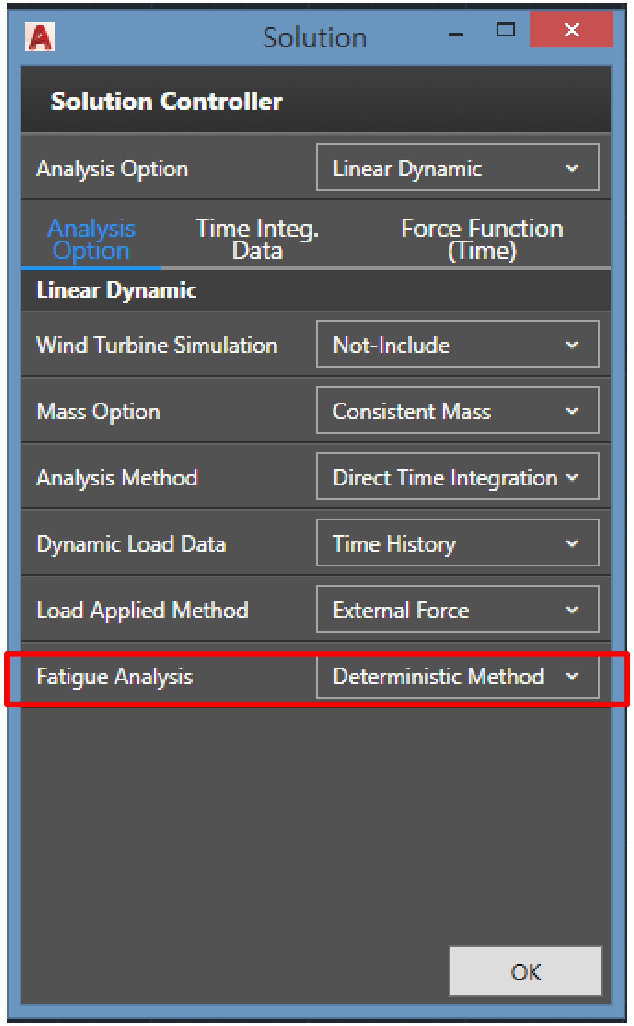
A quasi-static mooring analysis

X-SEA mooring analysis module accounts for the self weight of the mooring line in sea water, the elastic tension of the mooring line, and the seabed friction contact of each line.

For steady flow below the surface, Morison's formula is appropriate for computation of forces on a submerged mooring cable.

Fatigue Analysis in Time Domain

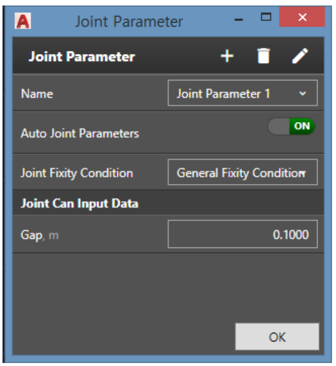


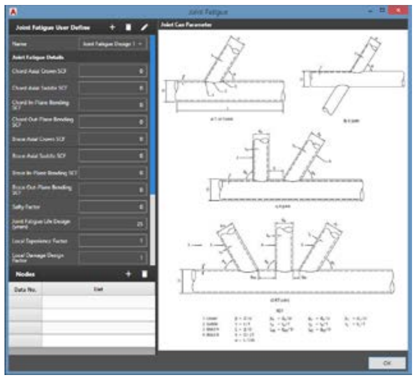


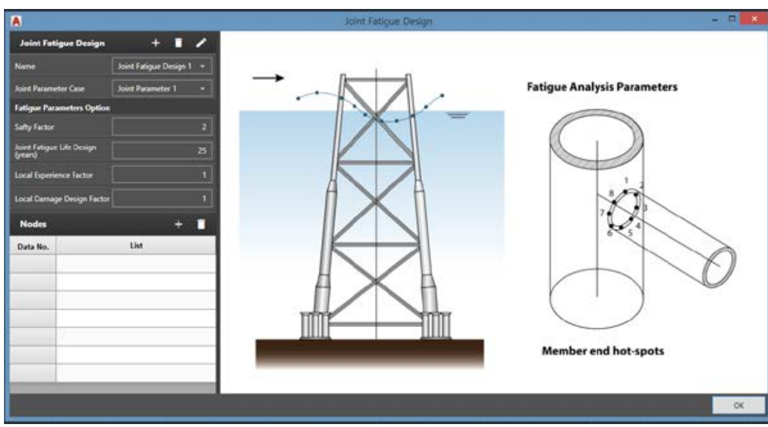
Time Domain

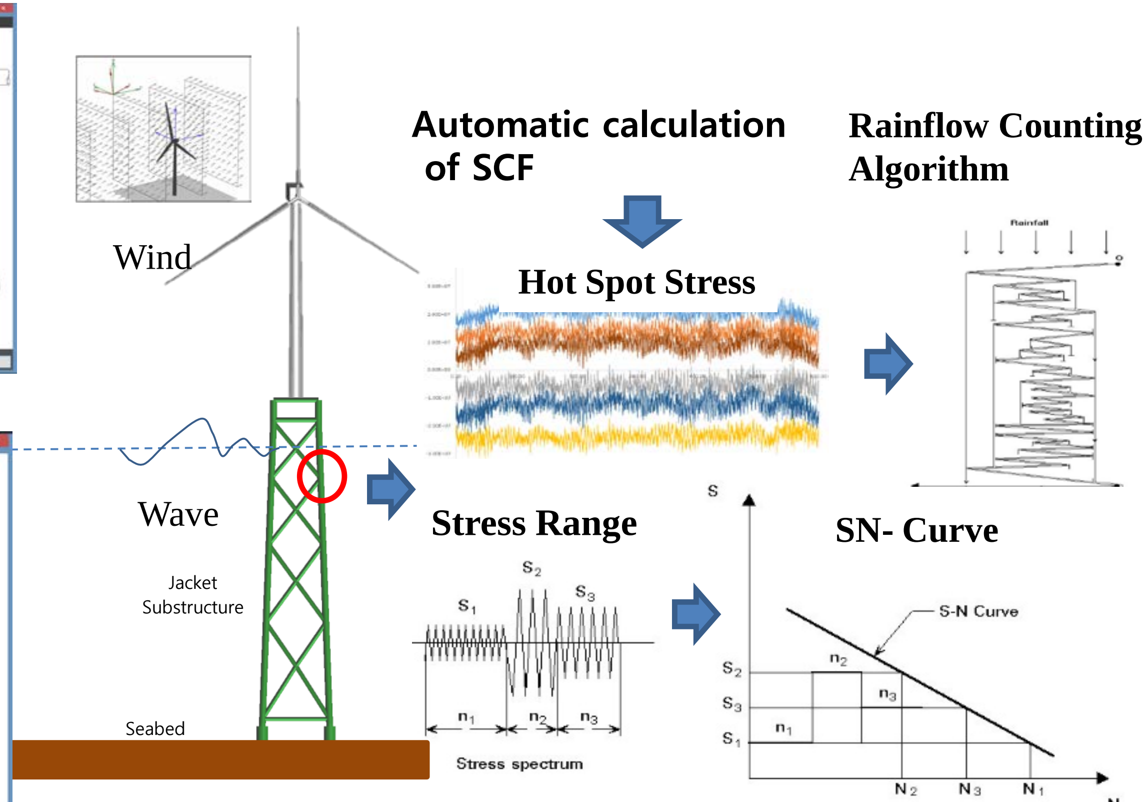
Fatigue Analysis in Time Domain

The wind turbine and foundation are subject to fatigue damage from environmental loading (wind, waves) as well as turbine loading. The wind turbine design code recommends time domain simulations with completely coupled turbine dynamics and control and simultaneous wind and wave loading.









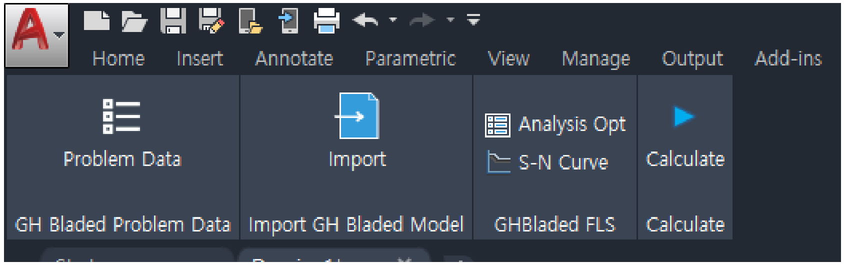
Fatigue Parameter

Dynamic Analysis → **Fatigue Analysis**

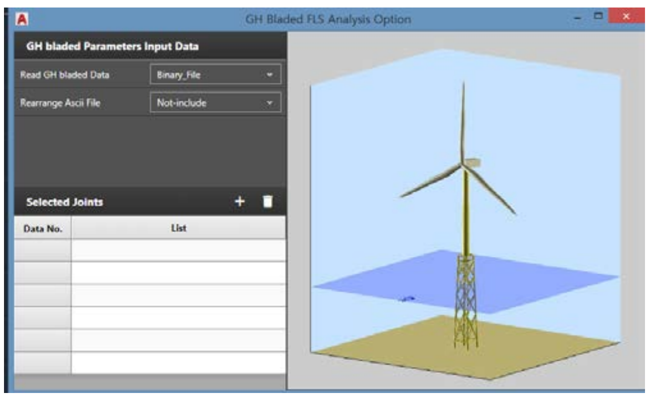
Post-processing of ULS & FLS from GH-Bladed & OpenFAST

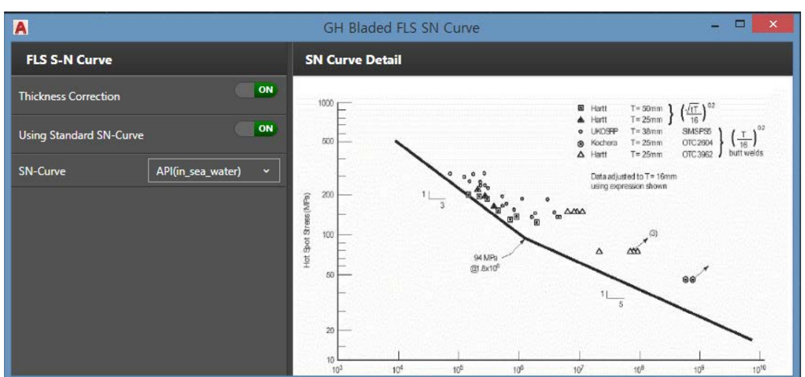
ULS: Ultimate Limit State FLS: Fatigue Limit State

GH-Bladed: FLS & ULS

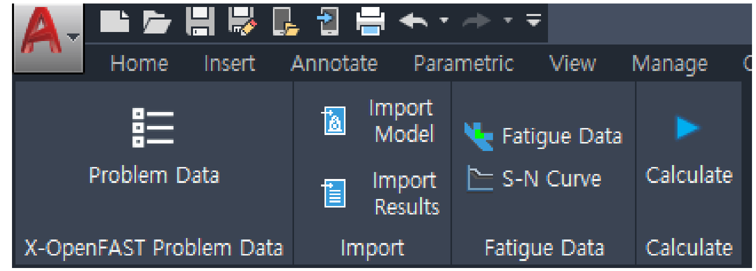


FLS Input

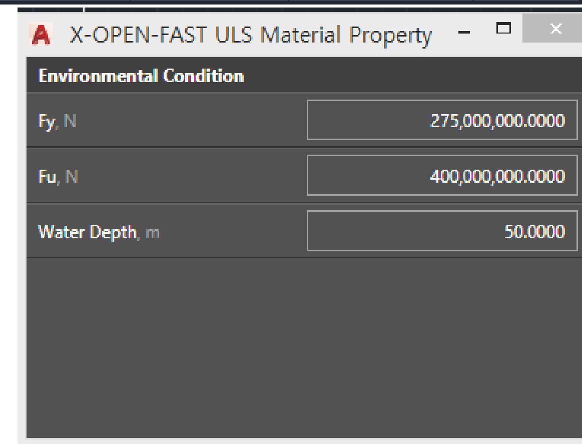




OpenFAST: FLS & ULS



ULS Input

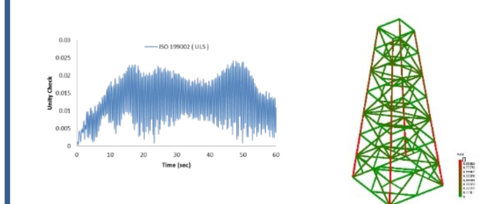


Design Code Checking

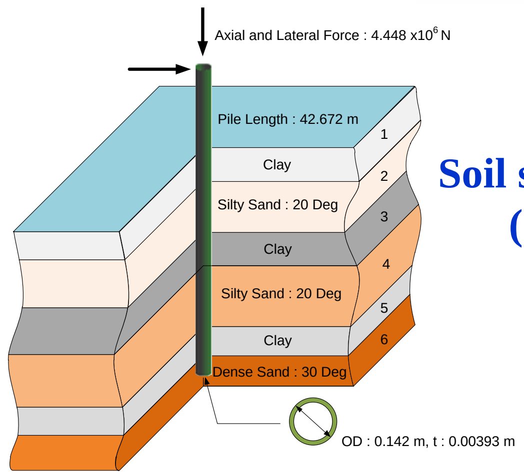
Design Standards

- API RP 2A-WSD
- API RP 2A-LRFD
- AISC ASD-89
- AISC LRFD-99
- Eurocode 3-05 (ULS)
- NORSOK N-004 (ULS)
- ISO 199002 (ULS)
- Korean Code (ULS)

Result of Unity Check

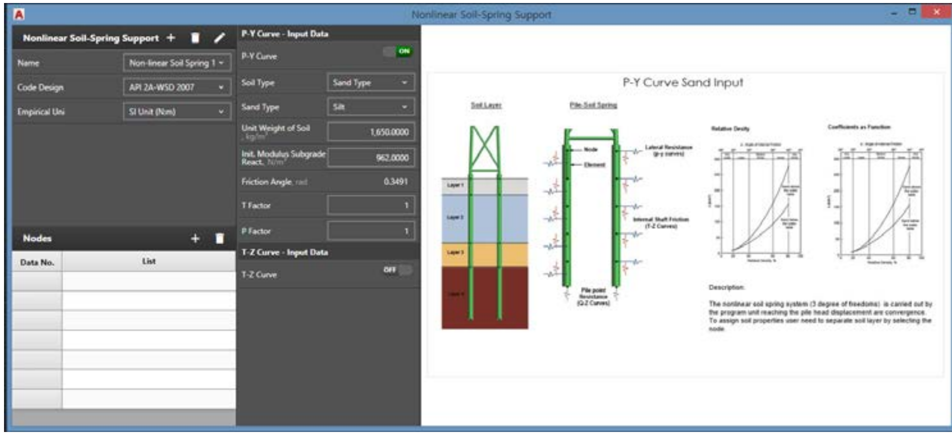


Pile Soil Interaction Analysis (PSI) with nonlinear soil spring



Soil spring of pile (3 D.O.F.)

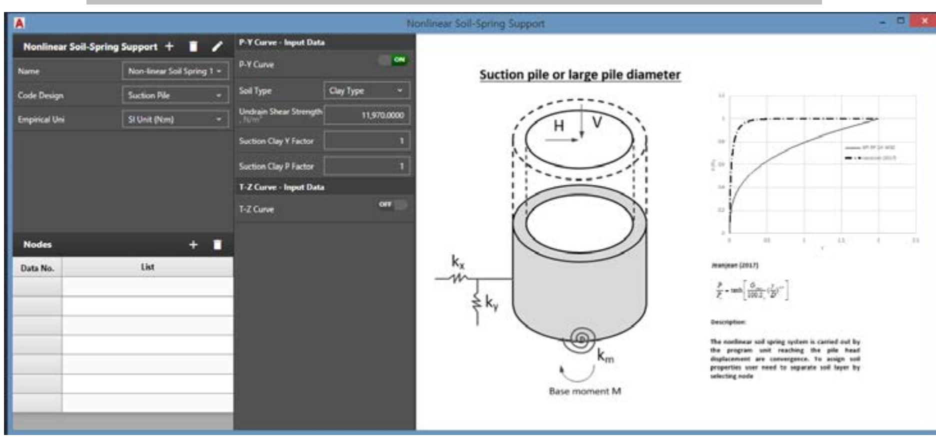
Soil Properties Windows API 2A-WSD 2007



Windows dialog box of P-Y Curve for sand

- The computer simulation of a pile foundation takes into account the pile stiffness and the lateral behavior of the soil.
- The nonlinear behavior for pile soil interaction is considered based on the geotechnical data of P-Y, T-Z, and Q-Z curves for the analysis to obtain a rigorous solution of the pile-soil-structure interaction.
- Iterative analysis is carried out by the PSI program until reaching the pile head displacement convergence. Thereafter, PSI extracts the final pile head loads and analyzes the pile.

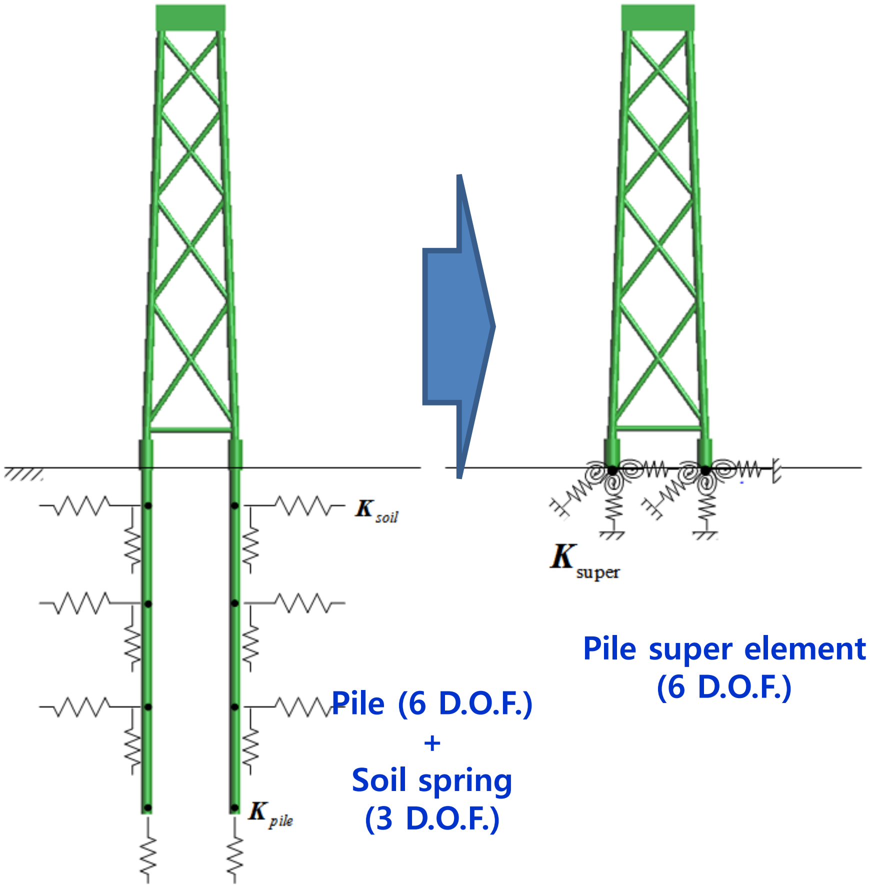
Suction Bucket:
Soil Properties Window Jeanjean (2017)



Windows dialog box of P-Y Curve for clay

X-SEA Pile Super Element

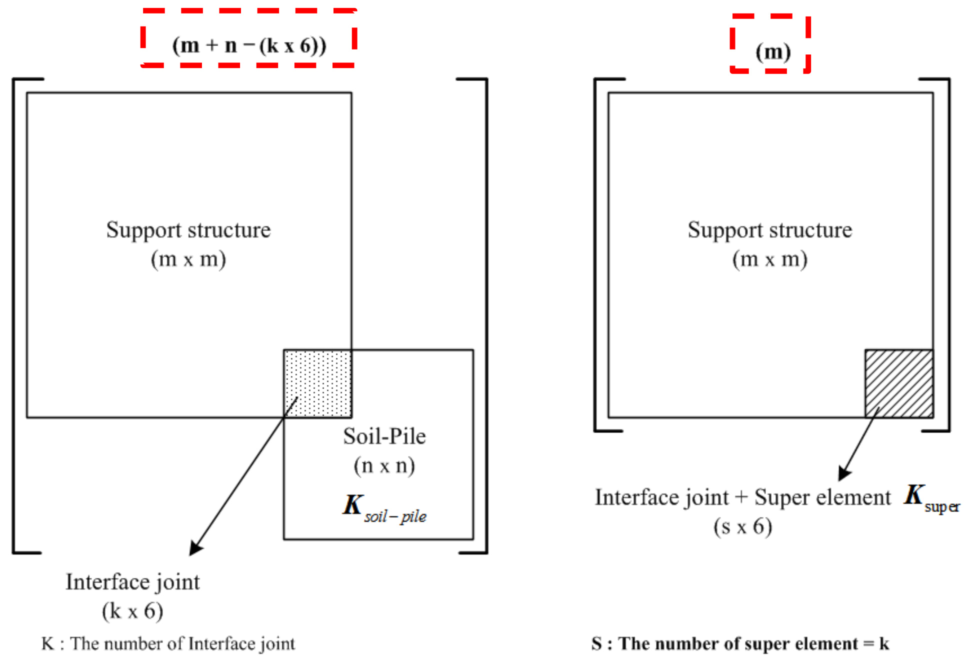
In order to save the computational time, Pile Super Element can be used for the dynamic and fatigue analysis as support boundary condition.



(a) Jacket model with pile

(b) Jacket model with pile super element

『Comparison of Stiffness Matrix』



(a) Total stiffness of structure with soil-pile

(b) Total stiffness of structure with pile super element

- **Stiffness matrix of pile super element**

$$K_{pile} + K_{soil} = K_{super}$$

Verification of X-SEA

Verification of XFINAS

The **XFINAS** which is a general purpose software for construction enables a nonlinear dynamic structural analysis, taking into account of material and geometric nonlinearity. XFINAS includes automatic analysis of bridge moving load, construction stage analysis of prestressed concrete bridge and dynamic analysis of railway bridge-train-track interaction.

CIMNE, SPAIN (International Center for Numerical Methods in Engineering)

Computational Structural Engineering Institute of Korea

Verification of X-SEA

X-SEA is an extended version of XFINAS for offshore structural analysis.

X-SEA is being verified by the comparison with offshore software SACS and other software using following items.

- Wave load by Airy, Stokes, Stream Function wave etc.
- Current load by API, DNV and others.
- Reaction , Displacement, Member force
- SCF factor, Fatigue life
- Coupled analysis of wind turbine structure
- Soil-pile structure interaction
- And other items

NREL (Nnational Renewable Energy Laboratory) USA

MaREI (Universty, College, Cork, Ireland)

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Thank you