GUIDANCE NOTES
GD48-2023

INTERNATIONAL SHIP CLASSIFICATION

GUIDELINES FOR YIELDING STRENGTH ASSESSMENT OF TYPE C INDEPENDENT TANKS BASED ON LOAD-RESISTANCE FACTOR(LRFD) DESIGN CRITERIA

2024

Effective from 1 January 2024

CONTENTS

CHAPTER 1 GENERAL

1.1 General provisions

1.1.1 With regard to the finite element yielding strength assessment (where applicable) of type C independent tanks requested in the International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (hereinafter referred to as the IGC Code)/ISC Rules for Construction and Equipment of Ships Carrying Liquefied Gases in Bulk, the Guidelines provide guidance on assessment based on load-resistance factor (LRFD) design criteria.

1.1.2 The Guidelines may be considered as alternative to FE yielding strength assessment of type C independent tanks specified by the Code/Rules in 1.1.1. Type C independent tanks complying with the requirements of the Guidelines may be assigned the LRFD notation.

1.1.3 Chapter 2 of the Guidelines specifies the limit state design of the cargo containment system using Load-Resistance Factor Design (LRFD). The work procedures and relevant design parameters are to comply with the Limit State Standard (LSD) required by Chapter 2 of the Guidelines.

1.1.4 Three dimensional finite element analysis is to be carried out as required by 2.3, Chapter 2 of the Guidelines and the relevant applicable requirements in Chapter 3 of the Guidelines are to be referred to in implementation.

1.1.5 Yielding strength assessment of type C independent tanks by using methods other than LRFD in the Guidelines may be conducted, subject to ISC agreement.

1.2 Terms and abbreviations

1.2.1 **Limit state:** a condition beyond which the structure, or part of a structure, no longer satisfies the design criteria defined for the state.

1.2.2 **Limit state design**: a systematic approach where each structural element is evaluated with respect to possible failure modes related to the design conditions identified in 4.3.4, Chapter 4 of the IGC Code. A limit state condition can be defined as a load combination beyond which the structure, or part of a structure, will break/crack or have significant deformation and can no longer bear the load or satisfy the requirements.

1.2.3 **Characteristic value:** the load/resistance value not exceeding the specified probability. In the Guidelines, the characteristic value may be taken as the rule load/strength value.

1.2.4 **Load effect:** load effect acting on the structure, which is the most unfavourable combined load effect derived from the design loads (e.g. stresses, strains, displacements and vibrations), and may be expressed by:

$$\sigma_d = q(F_{d1}, F_{d2}, \ldots F_{dN})$$

where: q —— the functional relationship between load and load effect determined by structural analyses.

In the Guidelines, the design load effect is to be taken as stresses.

1.2.5 **Resistance:** the capacity of a structure to resist external loads, such as the profile characteristics of the structural member against the action of the load, the details of the structure, and the strength value of the material. In the Guidelines, the resistance may be taken as tensile/yielding strength value.

1.2.6 **Design value:** the corrected load/resistance characteristic value. In the Guidelines, the design value can be taken as the value obtained by multiplying the characteristic load/resistance/characteristic strength (rule load/strength value) by a load/resistance factor, where:

(1) design load $\boldsymbol{F_{dk}}$——obtained by multiplying the characteristic load by a load factor relevant for the given load category:

$$F_{dk} = \gamma_f F_k$$

where: γ_f—— load factor;

F_k—— the characteristic load as specified in part B and part C of chapter 4 of the IGC Code (note: i.e. the rule load value).

(2) Design resistance $\boldsymbol{R_d}$——determined as follows:

$$R_d = \frac{R_k}{\gamma_R \cdot \gamma_C}$$

where: R_k——the characteristic resistance. In case of materials covered by chapter 6 of the IGC Code, it may be, but not limited to, specified minimum yield stress, specified minimum tensile strength, plastic resistance of cross sections, and ultimate strength;

γ_R——the resistance factor, defined as $\gamma_R = \gamma_m \gamma_S$;

γ_m——the partial resistance factor to take account of the probabilistic distribution of the material properties (material factor);

γ_S——the partial resistance factor to take account of the uncertainties on the capacity of the structure, such as the quality of the construction, method considered for determination of the capacity including accuracy of analysis;

γ_C——the consequence class factor, which accounts for the potential results of failure with regard to release of cargo and possible human injury.

1.2.7 **Ultimate Limit State (ULS):** corresponding to the maximum load-carrying capacity or, in some cases, to the maximum applicable strain or deformation; under intact (undamaged) conditions.

1.2.8 **Accident Limit State (ALS):** concerning the capacity of the structure to resist accident situations.

1.2.9 **IGC Code:** The International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk.

1.2.10 **LRFD:** Load and Resistant Factor Design.

1.2.11 **LSD:** Limit State Design.

CHAPTER 2 LRFD FOR THE USE OF LIMIT STATE METHODOLOGIES IN THE DESIGN OF CARGO CONTAINMENT SYSTEMS

2.1 General requirements

2.1.1 This Chapter provides procedures and relevant design parameters for limit state design of cargo containment systems.

2.1.2 For each yielding failure mode, one or more limit states may be relevant. Considering all relevant limit states, the limit load of structural element is defined as the minimum limit load in all relevant limit states.

2.1.3 According to 1.1.1 of Chapter 1, only limit states in the yielding failure mode are relevant in the Guidelines, which can be categorized into: Ultimate Limit State and Accident Limit States**.**

2.2 Design format

2.2.1 The design format in this Chapter is based on a Load and Resistance Factor Design format. The fundamental principle of the Load and Resistance Factor Design format is to verify that design load effects, σ , do not exceed design resistances , for any of the considered failure modes in any scenario:

$$\sigma_d \le R_d$$

2.2.2 Cargo containment design is to take into account potential failure consequences. Consequence classes are defined in Table 2.2.2, to specify the consequences of failure when the mode of failure is related to the Ultimate Limit State or the Accident Limit State.

Consequence classes **Table 2.2.2**

Consequence class	Definition
Low	Failure implies minor release of the cargo.
Medium	Failure implies release of the cargo and potential for human injury.
High	Failure implies significant release of the cargo and high potential for human injury/fatality.
Note: according to paragraph 3, Preamble of the IGC Code, “release” refers specifically to “Severe collisions or strandings could lead to cargo tank damage and result in uncontrolled release of the product. Such a release could result in evaporation and dispersion of the product and, in some cases, could cause brittle fracture of the ship’s hull.”	

2.3 Required analyses

2.3.1 Three dimensional finite element analyses are to be carried out as an integrated model of the tank and the ship hull, including supports and keying system as applicable. All the failure modes are to be identified to avoid unexpected failures. Hydrodynamic analyses are to be carried out to determine the particular ship accelerations and motions in irregular waves, and the response of the ship and its cargo containment systems (including liquefied cargoes) to these forces and motions.

2.4 Ultimate Limit State (ULS)

2.4.1 Structural resistance may be established by testing or by complete analysis taking account of both elastic and plastic material properties. Safety margins for ultimate strength are to be introduced by partial factors of safety taking account of the contribution of stochastic nature of loads and resistance (dynamic loads, pressure loads, gravity loads, material strength etc.).

2.4.2 Appropriate combinations of permanent loads, functional loads and environmental loads including sloshing loads are to be considered in the analysis. At least two load combinations with partial load factors as given in Table 2.4.2 are to be used for the assessment of the ultimate limit states.

Partial load factors **Table 2.4.2**

Load combination	Permanent loads	Functional loads	Environmental loads
‘*a*’	1.1	1.1	0.7
‘*b*’	1.0	1.0	1.3

Notes: (1) For permanent loads, see 4.12 of the IGC Code; for functional loads, see 4.13 of the IGC Code; for environmental loads, see 4.14 of the IGC Code.

(2) For detailed partial load and condition combination, see 3.2.3, Chapter 3 of the Guidelines.

The load factors for permanent load (see 4.12 of the IGC Code) and functional load (see 4.13 of the IGC Code) in load combination ‘*a*’ are relevant for the normally well-controlled and/or specified loads applicable to cargo containment systems such as vapour pressure, cargo weight, system self-weight, etc. Higher load factors may be relevant for permanent and functional loads where the inherent variability and/or uncertainties in the prediction models are higher.

2.4.3 For sloshing loads, the load factor may be taken as 1.0. Depending on the reliability of the estimation method, a larger load factor may be required by the Administration or ISC.

2.4.4 In cases where structural failure of the cargo containment system are considered to imply high potential for human injury and significant release of cargo, the consequence class factor is to be taken as $\gamma_C = 1.2$. This value may be reduced if it is justified through risk analysis and subject to the approval by the Administration or ISC. In case consequence classes in Table 2.2.2 are obtained, is to be taken as 1.05, 1.1 and 1.2 respectively. The risk analysis is to take account of factors including, but not limited to, provision of full or partial secondary barrier to protect hull structure from the leakage and less hazards associated with intended cargo. Conversely, higher values may be fixed by the Administration or ISC, for example, for ships carrying more hazardous or higher pressure cargo.

The consequence class factor is in any case not to be less than 1.0.

2.4.5 The load factors and the resistance factors used are to be such that the level of safety is equivalent to that of the cargo containment systems as described in sections 4.21 to 4.26 of the IGC Code. This may be carried out by calibrating the factors against known successful designs.

2.4.6 The material factor γ_m is in general to reflect the statistical distribution of the mechanical properties of the material, and needs to be interpreted in combination with the specified characteristic mechanical properties. For the materials defined in Chapter 6 of the IGC Code, the material factor γ_m may be taken as:

- 1.1, when the characteristic mechanical properties specified by the recognized organization typically represent the lower 2.5% quantile in the statistical distribution of the mechanical properties; or

- 1.0, when the characteristic mechanical properties specified by the recognized organization represent a sufficiently small quantile such that the probability of lower mechanical properties than specified is extremely low and can be neglected.

2.4.7 The partial resistance factors γ_{si} should in general be established based on the uncertainties in the capacity of the structure considering construction tolerances, quality of construction, the accuracy of the analysis method applied, etc.

2.4.7.1 For design against excessive plastic deformation using the limit state criteria given in paragraph 2.4.8 of this Chapter, the partial resistance factors γ_s should be taken as follows:

$$\gamma_S = 0.76\frac{B}{\kappa}$$

$$\kappa = Min\left(\frac{R_m}{R_e}\cdot\frac{B}{A}, 1.0\right)$$

Factors A, B, C and D are defined in section 4.22.3.1 of the IGC Code. R_m and R_e are defined in section 4.18.1.3 of the IGC Code.

2.4.8 Design against excessive plastic deformation

2.4.8.1 See 3.2.4, Chapter 3 for the reliable stress criteria of finite element direct calculation applicable to elastic stress analysis.

2.5 Accident Limit States (ALS)

2.5.1 Accident design condition as described in section 4.18.3 of the IGC Code is to be complied with as applicable, depending on the cargo containment system concept.

2.5.2 Load and resistance factors may be relaxed compared to the ultimate limit state considering that damages and deformations can be accepted as long as this does not escalate the accident scenario.

2.5.3 The load factors for ALS are to be taken as 1.0 for permanent loads, functional loads and environmental loads.

2.5.4 Loads mentioned in section 4.13.9 (Static heel loads) and section 4.15 (Collision and Loads due to flooding on ship) of the IGC Code need not be combined with each other or with environmental loads, as defined in section 4.14 of the IGC Code.

2.5.5 Resistance factor γ_R is in general to be taken as 1.0.

2.5.6 Consequence class factors γ_C are in general to be taken as defined in paragraph 2.4.4 of this Chapter, but may be relaxed considering the nature of the accident scenario.

2.5.7 The characteristic resistance R_k is in general to be taken as for the ultimate limit state, but may be relaxed considering the nature of the accident scenario.

2.5.8 Additional relevant accident scenarios should be determined based on a risk analysis.

2.6 Testing

2.6.1 Cargo containment systems designed according to the Guidelines are to be tested to the same extent as described in section 4.20.3 of the IGC Code, as applicable depending on the cargo containment system concept.

CHAPTER 3 FINITE ELEMENT YIELDING STRENGTH ASSESSMENT OF TYPE C INDEPENDENT TANK BASED ON LRFD

3.1 Scope of application

3.1.1 This Chapter specifies the finite element yielding strength assessment procedure for Type C independent tank (hereinafter referred to as Type C tank) defined in the IGC Code based on LRFD method.

3.1.2 The requirements in 3.2.4 of this Chapter correspond to the LRFD assessment methodology in Chapter 2 of the Guidelines.

3.1.3 Corrosion allowance is not included in this Chapter. If special consideration is needed, it is to be determined according to the actual situation.

3.2 Yielding strength assessment

3.2.1 General

3.2.1.1 For cases where the rule prescriptive formulae for type C tank are not applicable to some structural members and attachments in the Code/Rules, and/or there are some high stress/stress concentration locations, e.g. structural discontinuities at tank supports and Y-joints, tank attachments (stiffening rings, bulkheads and girders and stiffeners, etc.), as well as novel design or configuration, finite element analysis in this Chapter is to be carried out to yielding strength of a Type C tank.

3.2.2 Modelling

3.2.2.1 The extent of the finite element modelling:

(1) whole Type C tank shell, including both ends, and dome (if required);

(2) doubler plate fitted on external surface of the tank shell in way of supports;

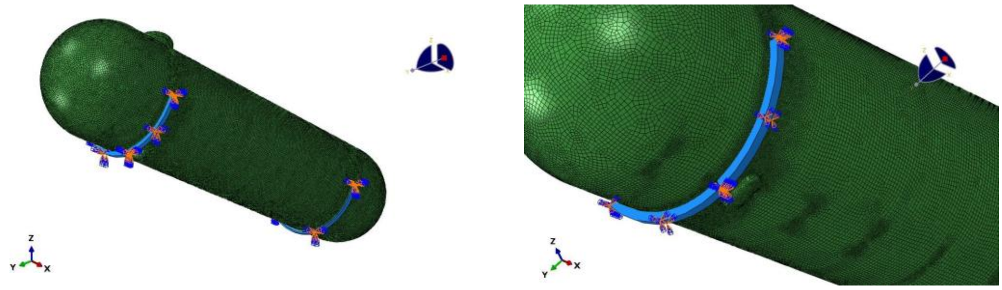
(3) attachment in the tank, including stiffening rings in way of supports, vacuum rings (if fitted), internal bulkhead as well as girders and stiffeners thereof (if fitted);

(4) all keying systems limiting possible relatively large rigid movement of tanks, such as surfaces of the press-wood as well as anti-floatation/anti-roll/anti-movement parts (including chocks limiting their movement);

(5) For saddle supporting structures of tanks, either of the followings may be adopted according to the working task scope specified in the design contract for type C tanks:

① saddle supporting structures not covered in the model, see Figure 3.2.2.1(1);

② saddle supporting structures covered in the model, see Figure 3.2.2.1(2);



saddle supporting structures not covered in the model

saddle supporting structures not covered in the model (partial)

Figure 3.2.2.1(1) Finite Element Model of Type C Tanks
(The tank saddle supporting structure is not covered in the model)

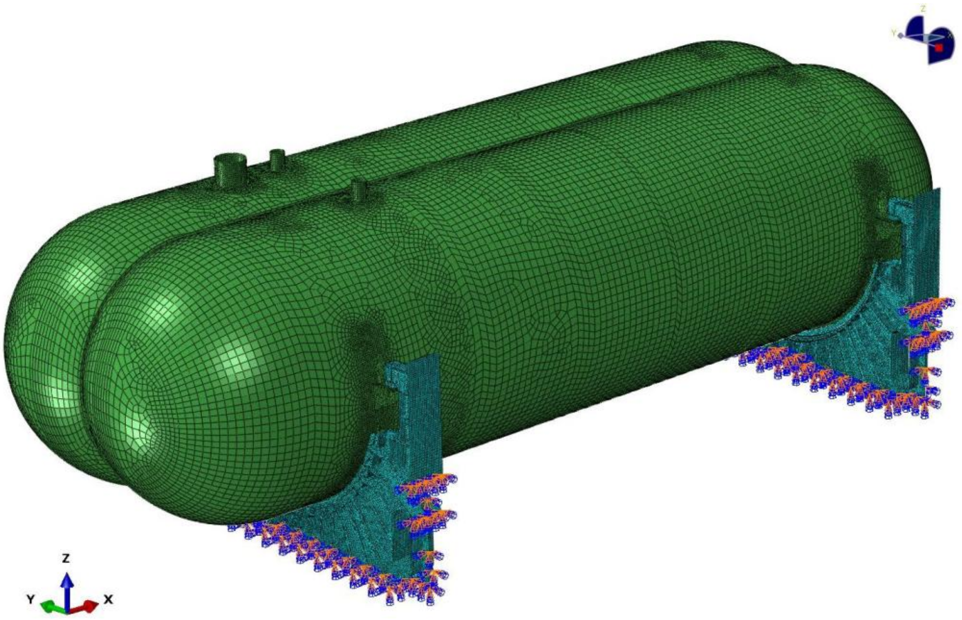
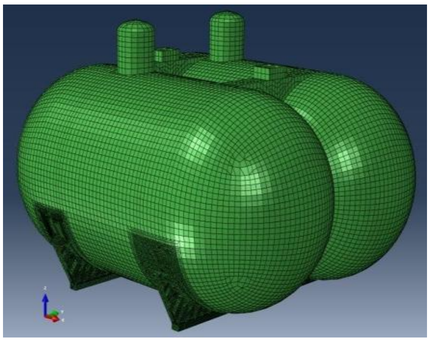


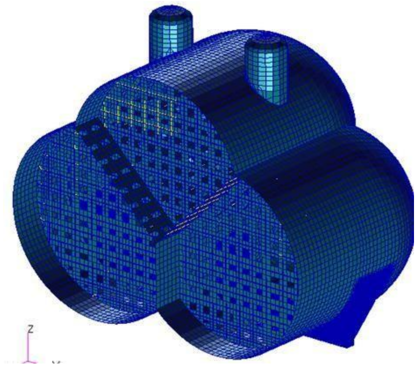
Figure 3.2.2.1(2) Finite Element Model of Type C Tanks
(The tank saddle supporting structure is covered in the model)

For configuration of tanks directly connecting saddle structures, a model specified in ② is to be used, see Figure 3.2.2.1(3).



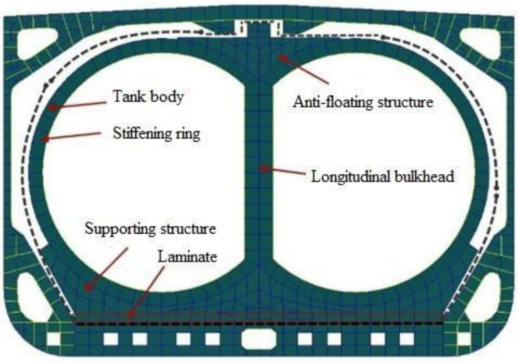
Bi-lobe

(Tanks directly connecting saddle structures)



Tri-lobe

(Tanks directly connecting saddle structures)



Note: for type C tanks of this configuration, the lowest press-wood surface is to be set as the lowest boundary of the model.

Figure 3.2.2.1(3) Finite Element Models of Type C Tanks

(The tank saddle is covered in the model - the saddle directly connecting the tank)

3.2.2.2 Element types and mesh density in models

(1) Tank shell: shell elements and/or solid elements may be used as follow:

① The elements away from areas of structural discontinuities: coarse meshes may be used as appropriate, mesh density: the lesser of R/30 (R being cylindrical radius, in mm) or 200 mm;

② local areas of structural discontinuities (where the influence of secondary stresses are to be considered): fine meshes are to be used, i.e. 8-node shell elements with the mesh size of 1.0*t* up to 50 mm, where *t* is the plate thickness.

In addition, for relatively small local areas of structural discontinuities, e.g. Y-connections of the bi-lobe tank, etc. It is recommended to use iso-parametric 20-node elements with a size of plate thickness *t* (t×t×t/4).

(2) Tank attachment:

① inner bulkheads: bulkhead plates are simulated by shell elements, stiffeners by beam elements, girder webs by shell elements, face plates by beam or plate elements;

② stiffening rings: webs are simulated by shell elements, face plates by beam or plate elements;

③ saddle plates attached to the tank: simulated by shell elements.

The mesh density of the above structure is to be compatible with the mesh density of adjacent shell elements as far as practicable.

(3) Saddle press-wood: solid elements of 50×50×50 mm are used.

(4) Saddle support structures (applicable to 3.2.2.1(5)②): the relevant provisions in the rules for hull structures may be referred to for the element and mesh size of plates and stiffeners, if any.

3.2.2.3 Model meshing and transition

(1) In order to reduce the error of the model, for cylindrical shell, the division of fine mesh is not to be carried out on the basis of coarse mesh, but is to be directly based on the circular arc line of the shell, see Figure 3.2.2.3(1);

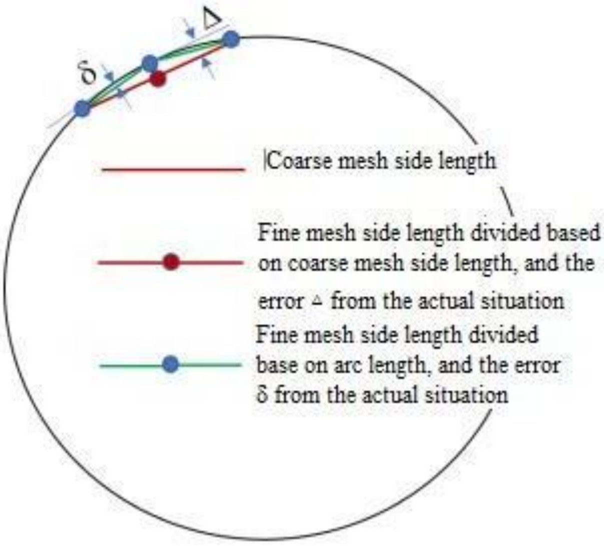


Figure 3.2.2.3(1) Points to be paid attention to for categorization of cylindrical shell fine meshes

(2) Consideration is to be given to the smooth transition to coarse mesh to get appropriate stress distribution. The requirements are as follows:

① The fine mesh size should extend over at least 10 elements in all directions from the structural intersection. For the doubler plate in way of the saddle, the mesh should extend from the external edge of the doubler plate, see Figure 3.2.2.3(1).

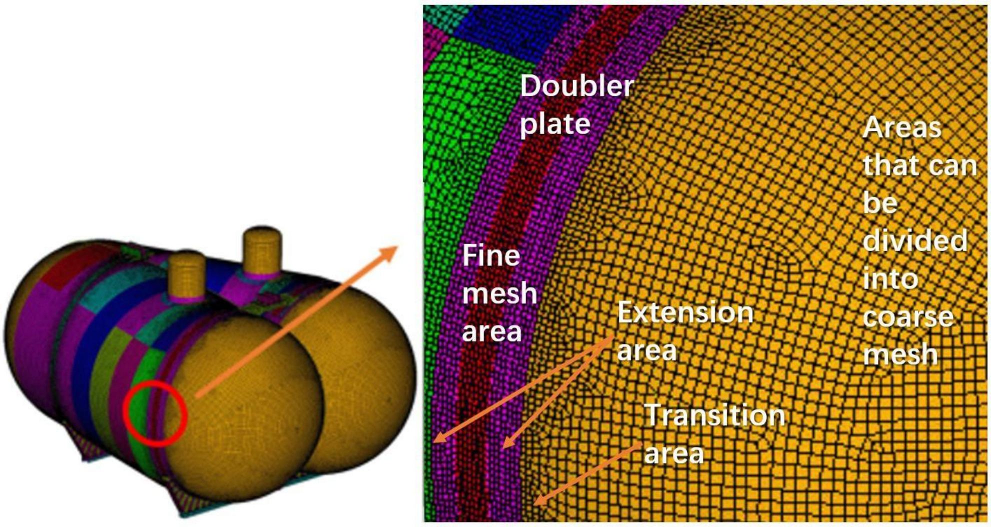
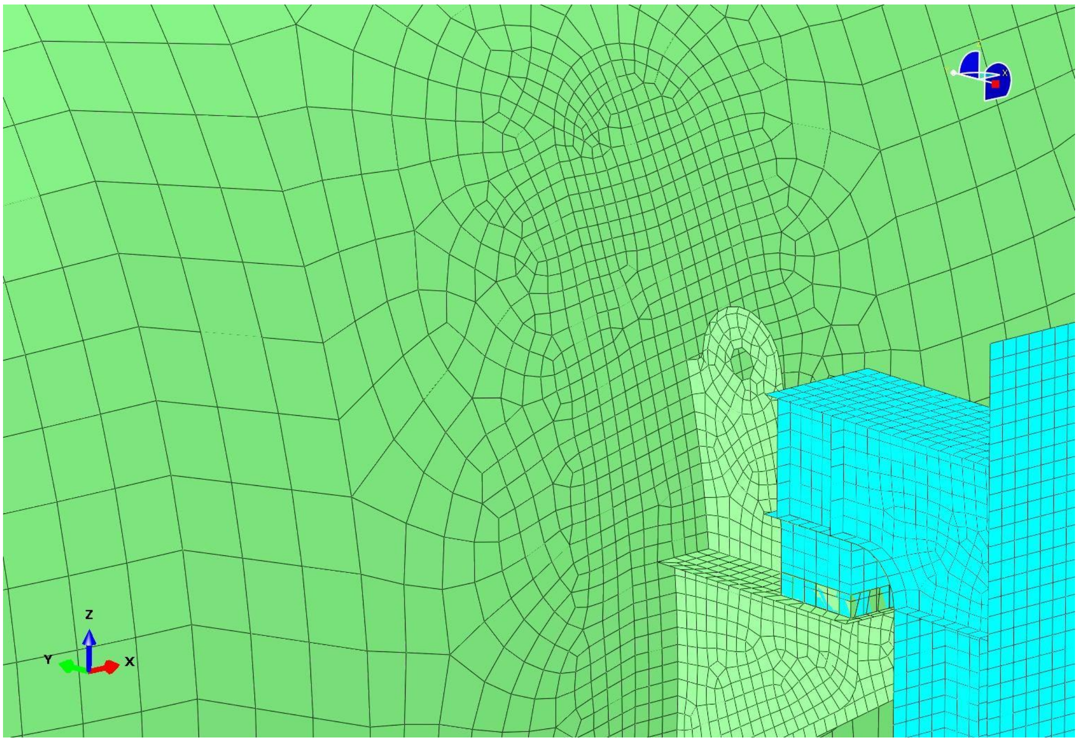
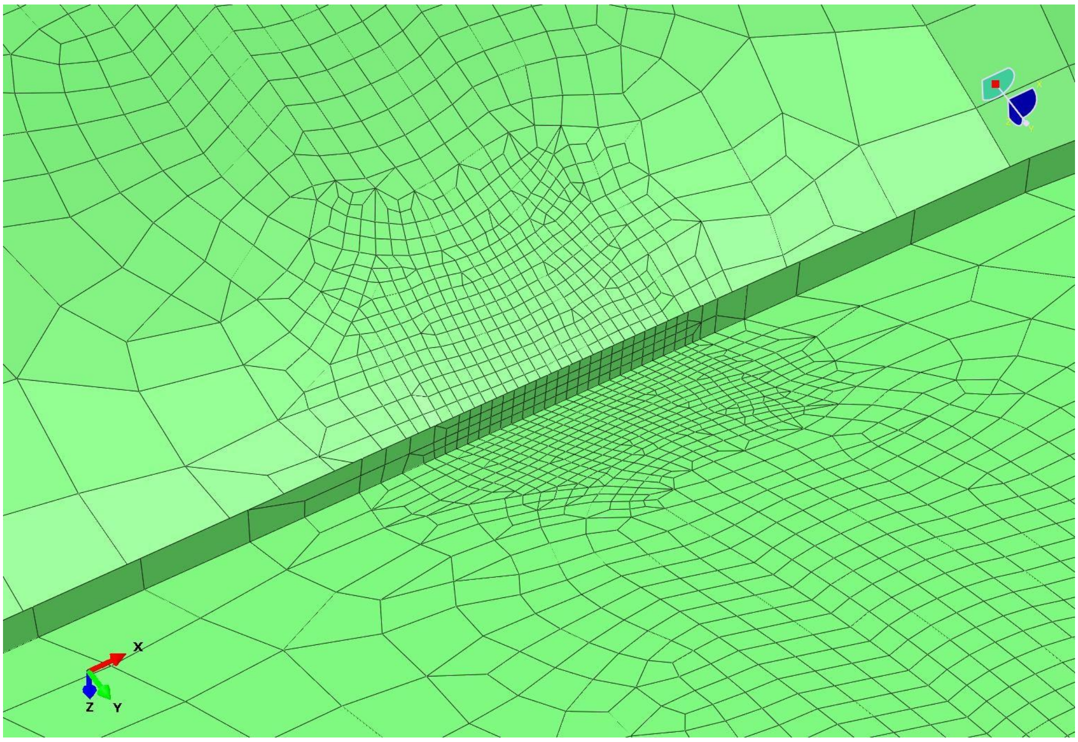


Figure 3.2.2.3(1) Meshes at areas of structural discontinuity and scope of transition—at doubler plate

② for doing fine meshing in way of details and transition area, especially for meshing in way of larger curvature, the principle of 3.2.2.2(1) should be followed. However, if solid elements are not used, the automatic mesh division function of the software is to be used as far as practicable (note: the quality of the meshes should be guaranteed without report errors), see Figure 3.2.2.3(2), so as to reduce the inappropriate stress results due to poor quality of mesh shape by manual outline.


Z
Y
X


X
Z
Y

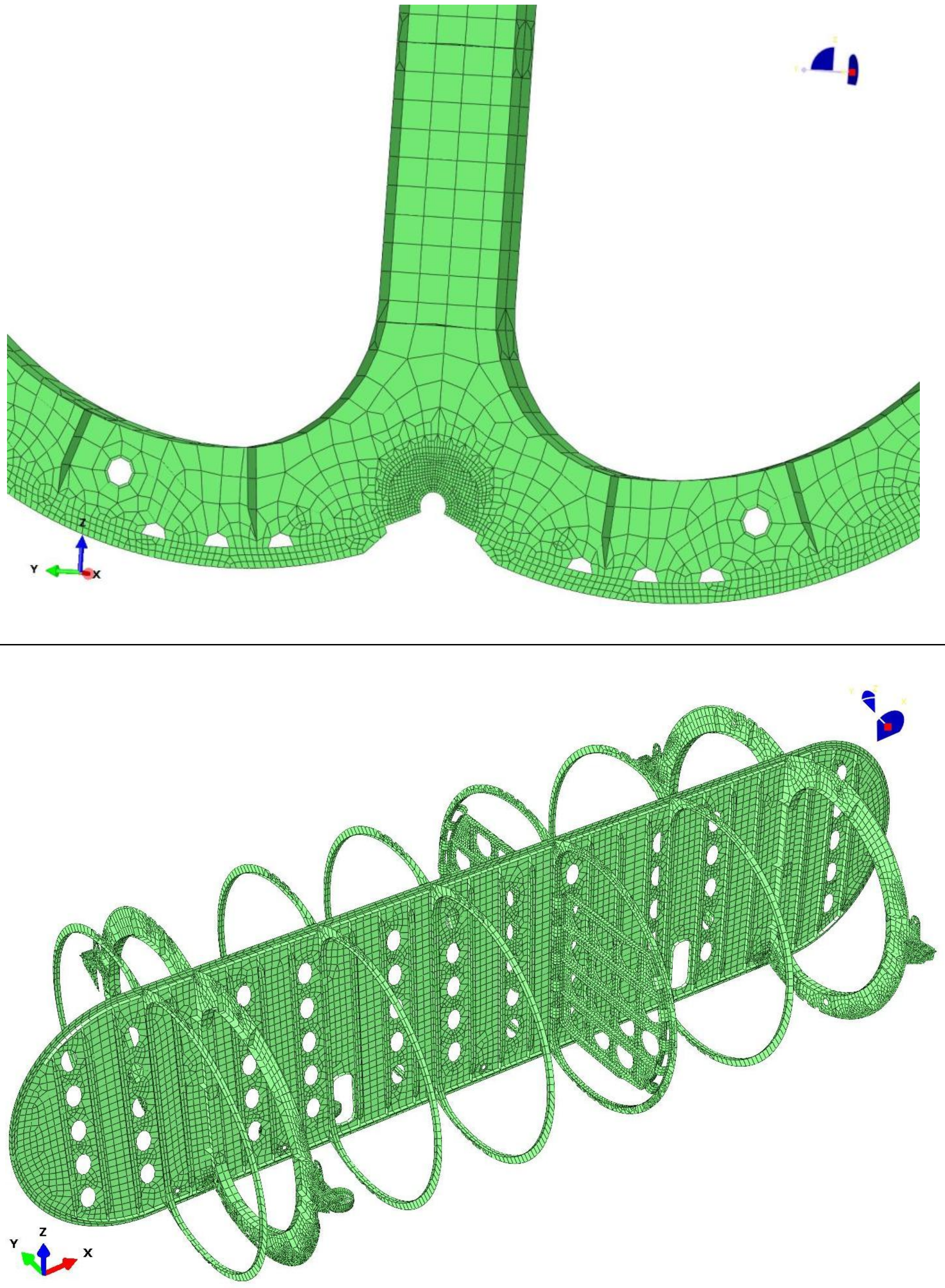


Figure 3.2.2.3(2) Meshes at areas of structural discontinuity and scope of transition

③ If the applied software, e.g. ABAQUS, is equipped with automatic matching function for meshes of different sizes between the “sub-structure” and main structure, the transition area may be reduced as appropriate, but the mesh shape should be as regular as possible, see Figure 3.2.2.3(3).

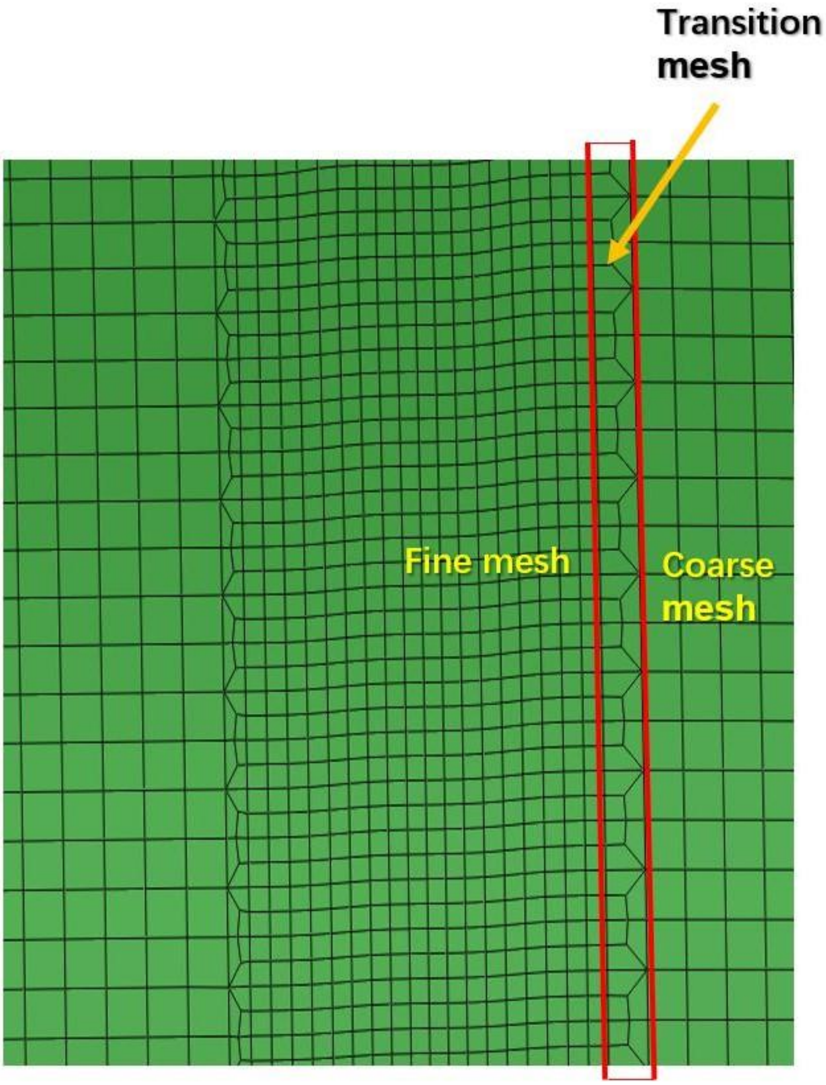


Figure 3.2.2.3(3) Transition area with "sub-structure" embedded in the main structure

④ If the transition area between solid elements and shell elements are integrated, care should be taken to ensure that the structural response can be correctly transmitted between the two types of elements (such as setting up a rigid element at the interface junction, etc.). The transition area between two types of elements should be kept away from the areas with high stresses, as shown in Figure 3.2.2.3(4). For transition areas, it is recommended to use meshes of regular shape so as to facilitate local analysis using solid elements. Stress analysis of solid elements may be carried out using local "sub-structure" or "embedment" model methods.

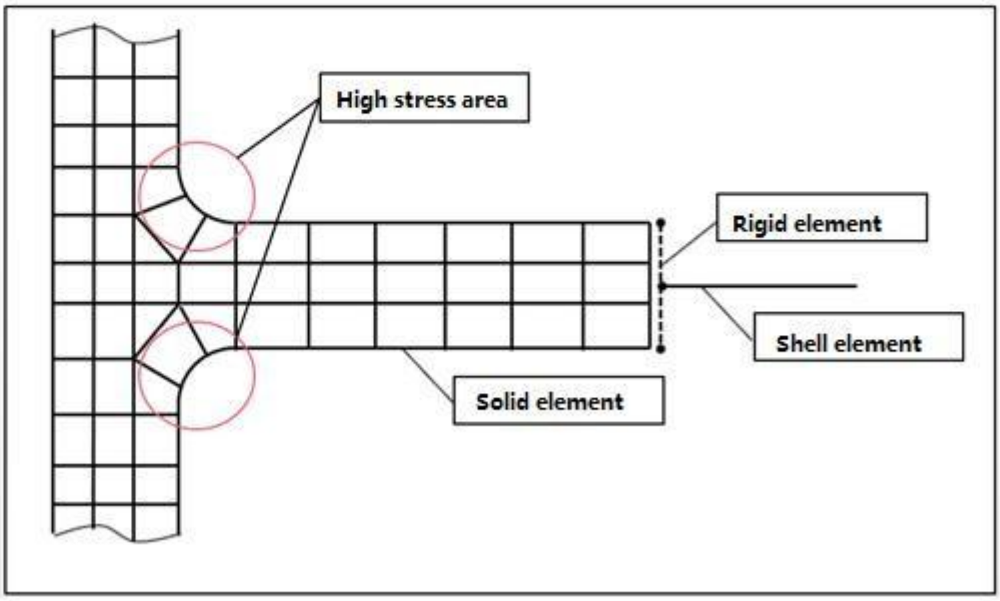


Figure 3.2.2.3(4) Transition area between solid and shell elements

⑤ For the doubler plate fitted at supports of the tank, as shown in Figure 3.2.2.3(5), it is recommended that welding and contact condition between the doubler plate and the tank be modeled by solid elements, as shown in Figure 3.2.2.3(6). If more precise results are required, it is recommended that the doubler plate and weld seam be simulated by solid elements with the high order, see Figure 3.2.2.3(7). (Note: if the hotspot stress fatigue assessment of weld location of the doubler plate is not involved, the doubler plate may be modeled as shell element).

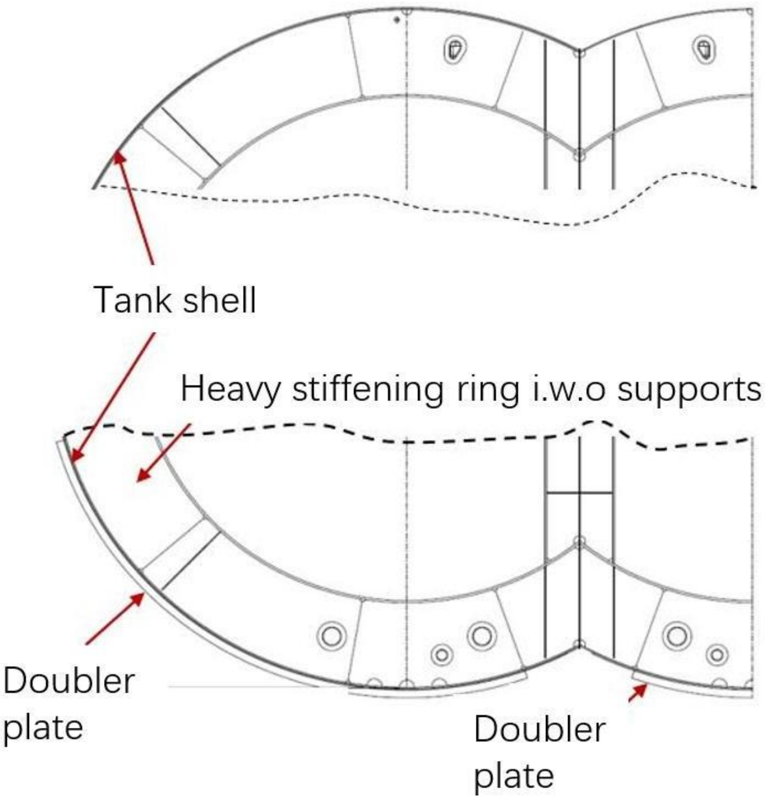


Figure 3.2.2.3(5) **Doubler plate fitted i.w.o. supports of the tank**

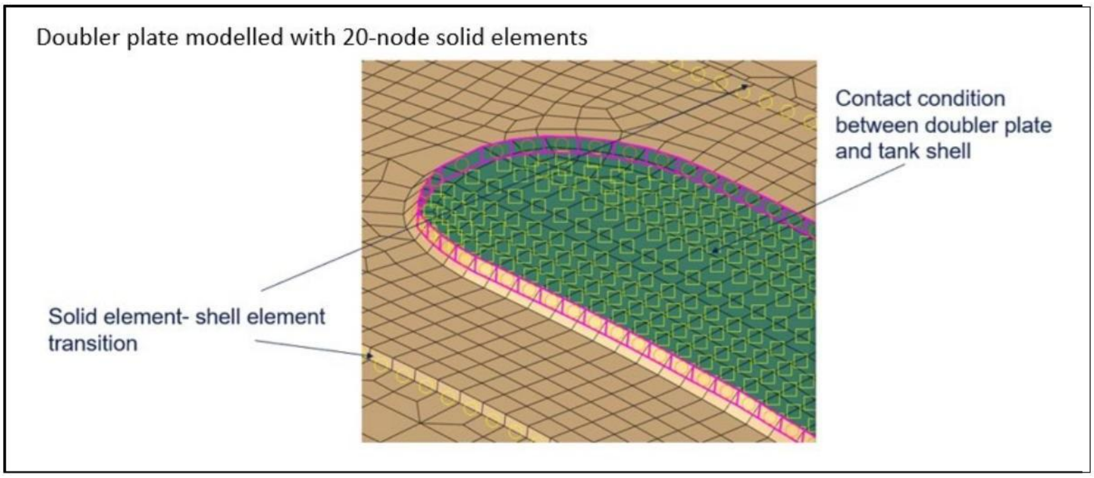


Figure 3.2.2.3(6) **Recommended modelling for the doubler plate and the weld in way of tank support**

⑥ For solid elements used in Figure 3.2.2.3(7), it is recommended to use solid elements with the same high order.

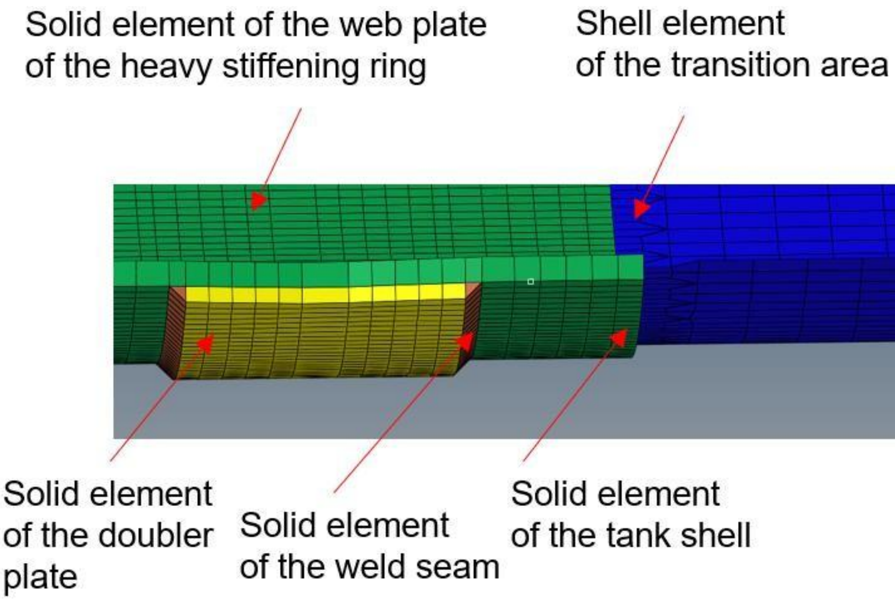


Figure 3.2.2.3(7) Solid elements with the same high order

3.2.2.4 Boundary conditions

(1) “Contact” boundary conditions are to be set for all contact restraint relationship for tanks, such as tank at the fixed end and sliding end of the saddle with the press-wood surface, press-wood laminated surface, if any, and chock surfaces limiting rigid movement of the anti-floatation/anti-roll/anti-movement parts, of which: contact conditions of press-wood/chocks: contact condition is to be set between press-wood and tanks as well as supporting structures, and the contact type is surface-to-surface contact. The contact tangential is set as “no friction” and the contact normal is set as “no penetration”. Considering the convergence of nonlinear calculation when running software, the contact tangential may be set as friction coefficient of 0.001. Contact conditions (if any) are also to be provided between the grooves of the press-wood and the supporting structure and between the supporting structure and the press-wood at the top and bottom of the cargo tank.

Deflection plots should be reviewed to ensure that the physics of the tank and supports are appropriately modeled where the tank is allowed to deflect relatively to the saddle shape due to the relative shrinkage between tank and saddle structure, see Figure 3.2.2.4(1);

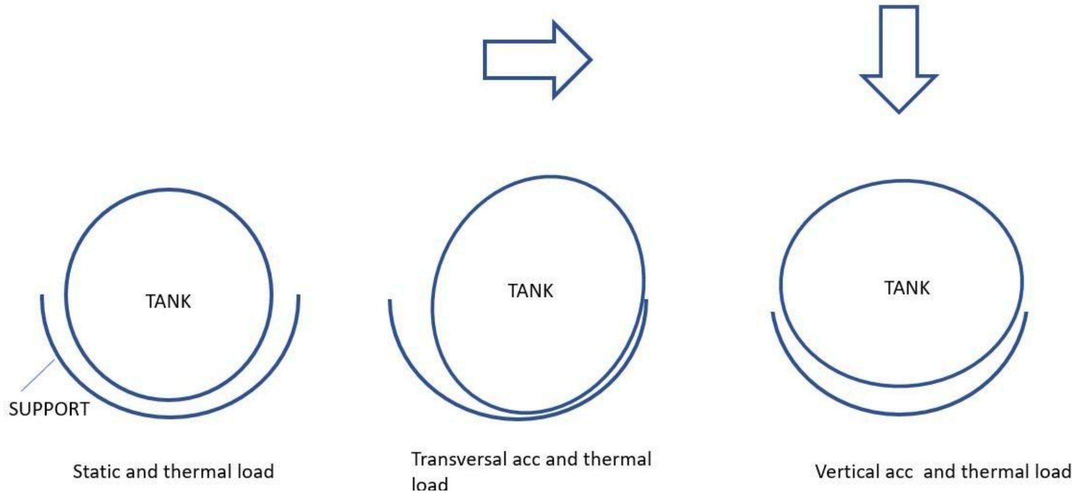


Figure 3.2.2.4(1) Contact conditions between tank and support need to allow for the relative deflection due to thermal contraction and inertial loads

(2) Rigid restraint condition is set when anti-floatation/anti-roll/anti-movement arrangements are connected to the hull or one other of other fixtures.

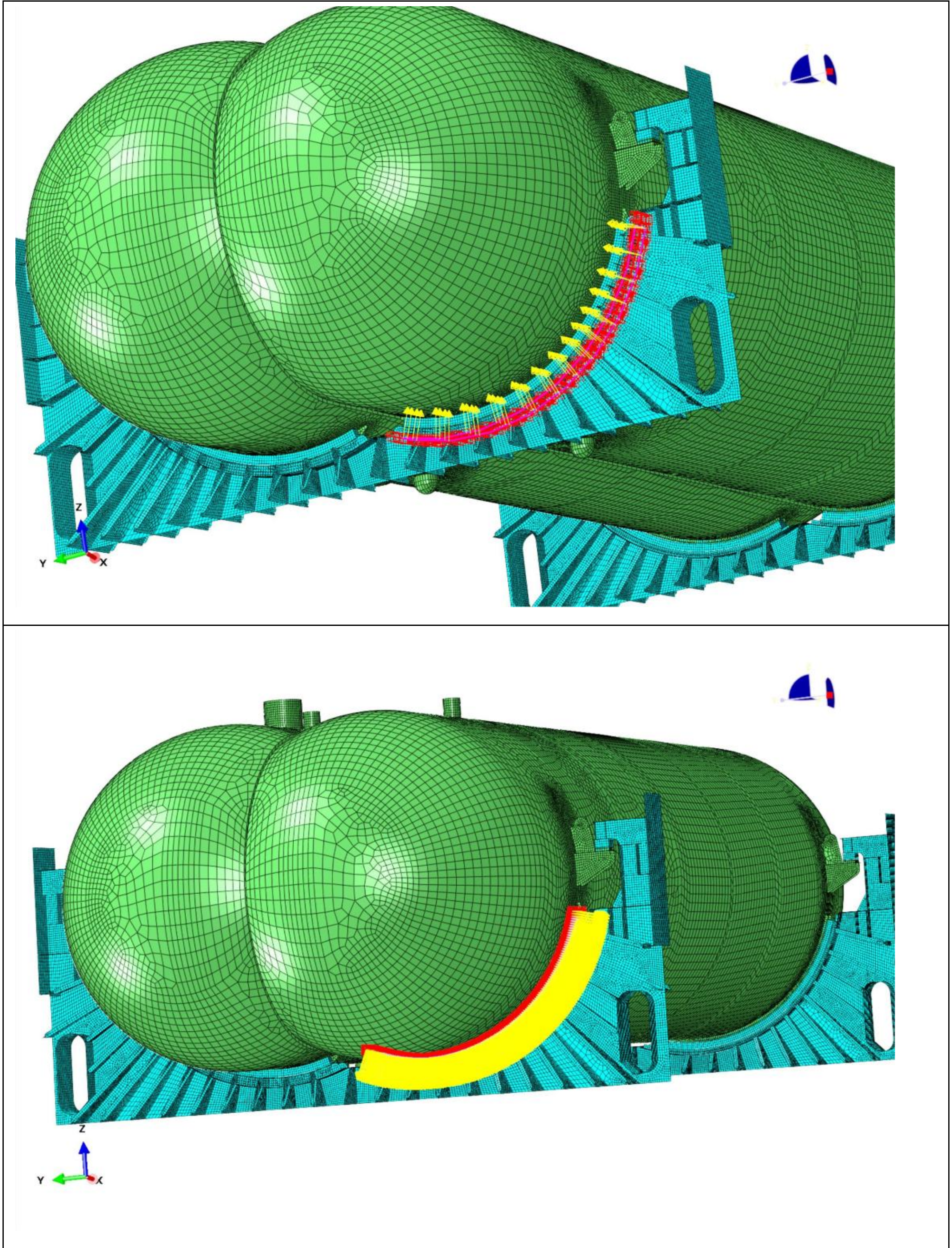
(3) For models not containing saddle supporting structures, rigid restraint condition is set at the lowest edge of the saddle press-wood, see Figure 3.2.2.1(1).

(4) For models containing saddle supporting structures, rigid restraint condition is set at the connection between the outermost edge of the saddle supporting structures and the hull, see Figures 3.2.2.1(2) and 3.2.2.1(3).

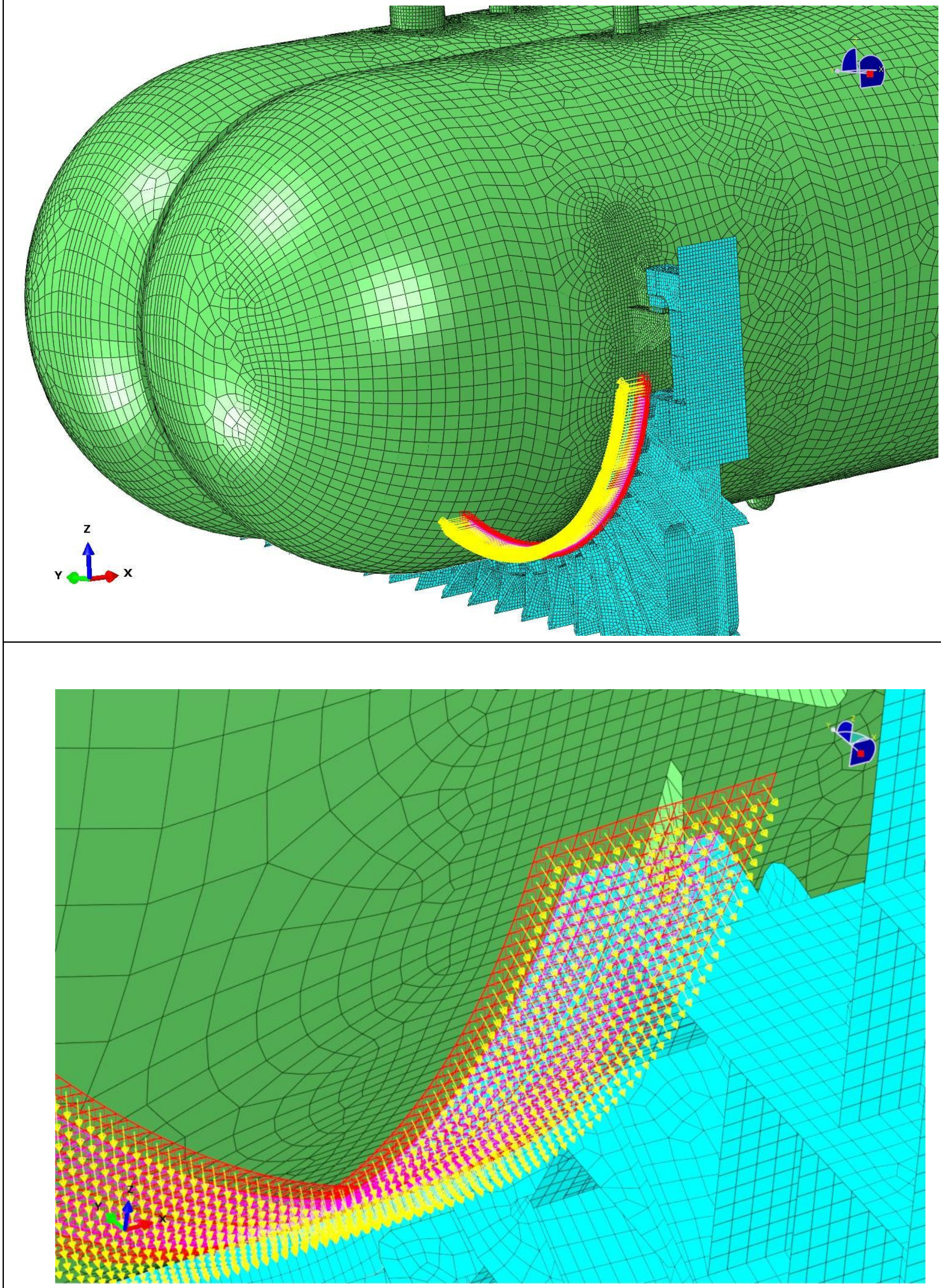
(5) For the type in Figure 3.2.2.1(3), the lowest surface of the saddle press-wood is to be considered as the lowest boundary of the model and rigid restraint condition is to be set.

(6) The welding and contact condition between the doubler plate and the tank are given in 3.2.2.3(2)⑤. The welding contact condition between the edge point of the doubler plate and the shell is bonding restraint, e.g. setting “Tie” or common joint connection in ABAQUS, contact relationship between the part within the edge point of the doubler plate and the shell, the contact surfaces between the doubler plate and the press-wood are all set as contact conditions.

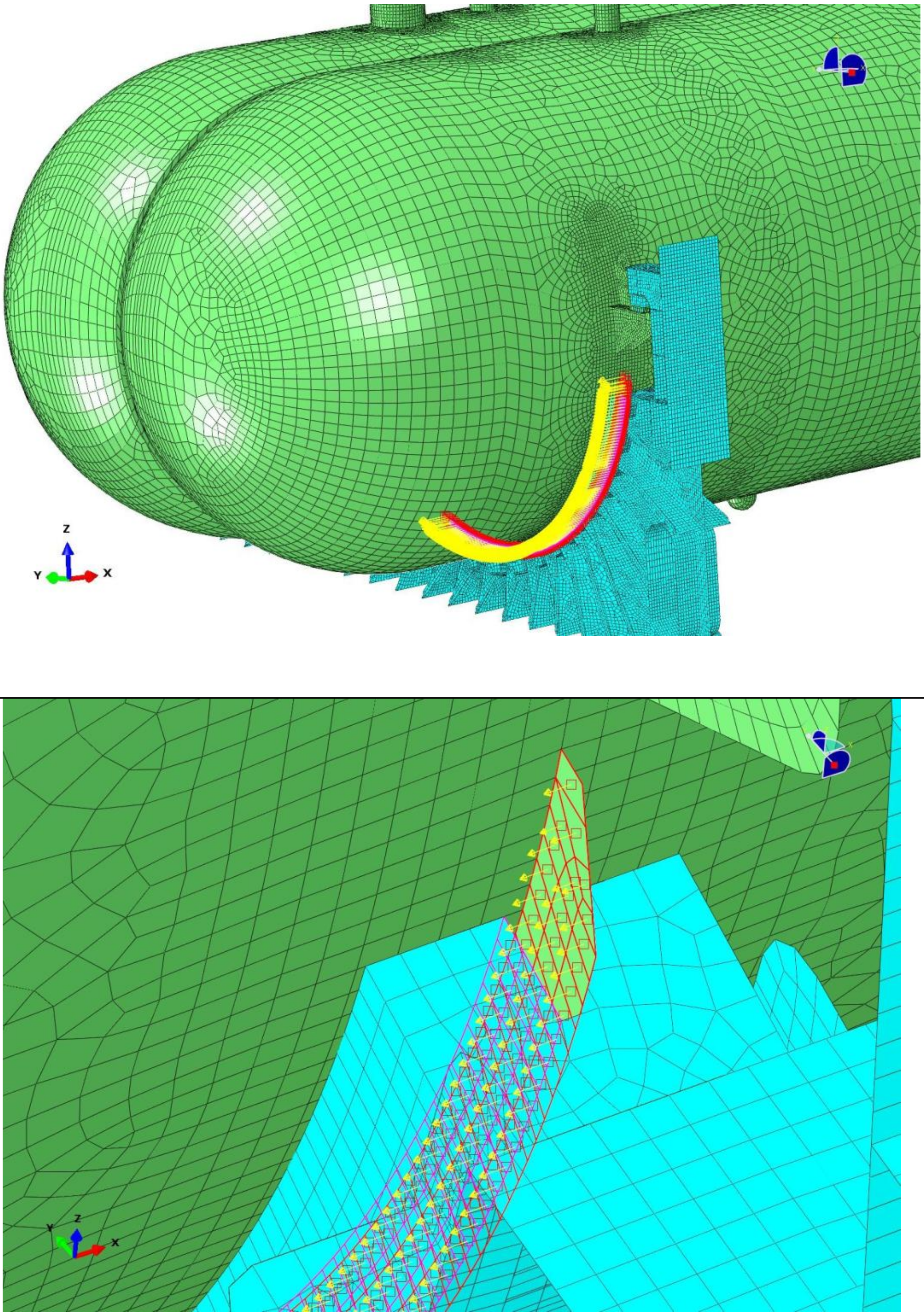
(7) Some examples of contact arrangement of the saddle (only the starboard side) are given in Figure 3.2.2.4(2); some examples of contact arrangement of the anti-floatation chocks are given in Figure 3.2.2.4(3).



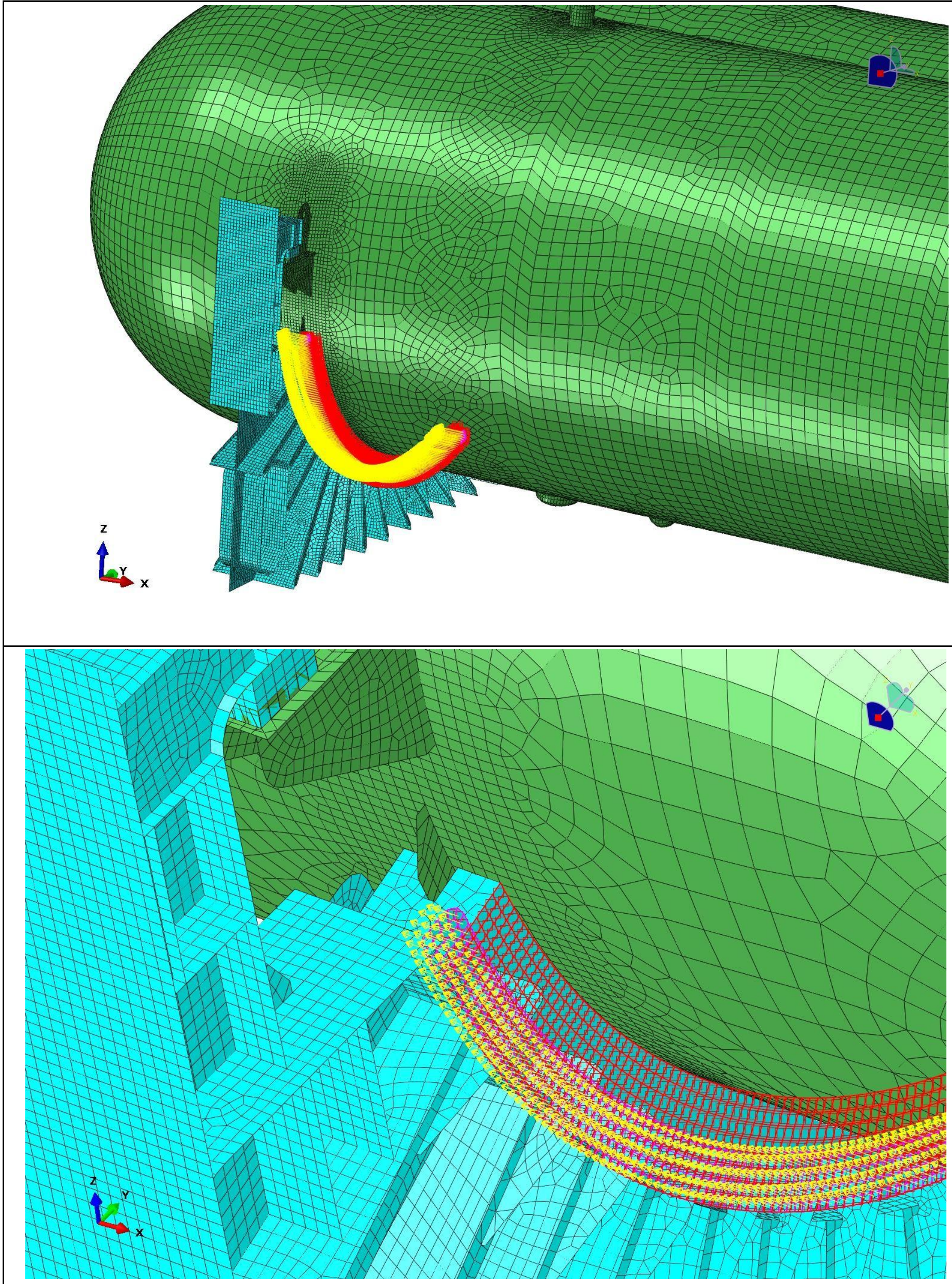
（a）Contact arrangement of saddle and press-wood (fixed end)



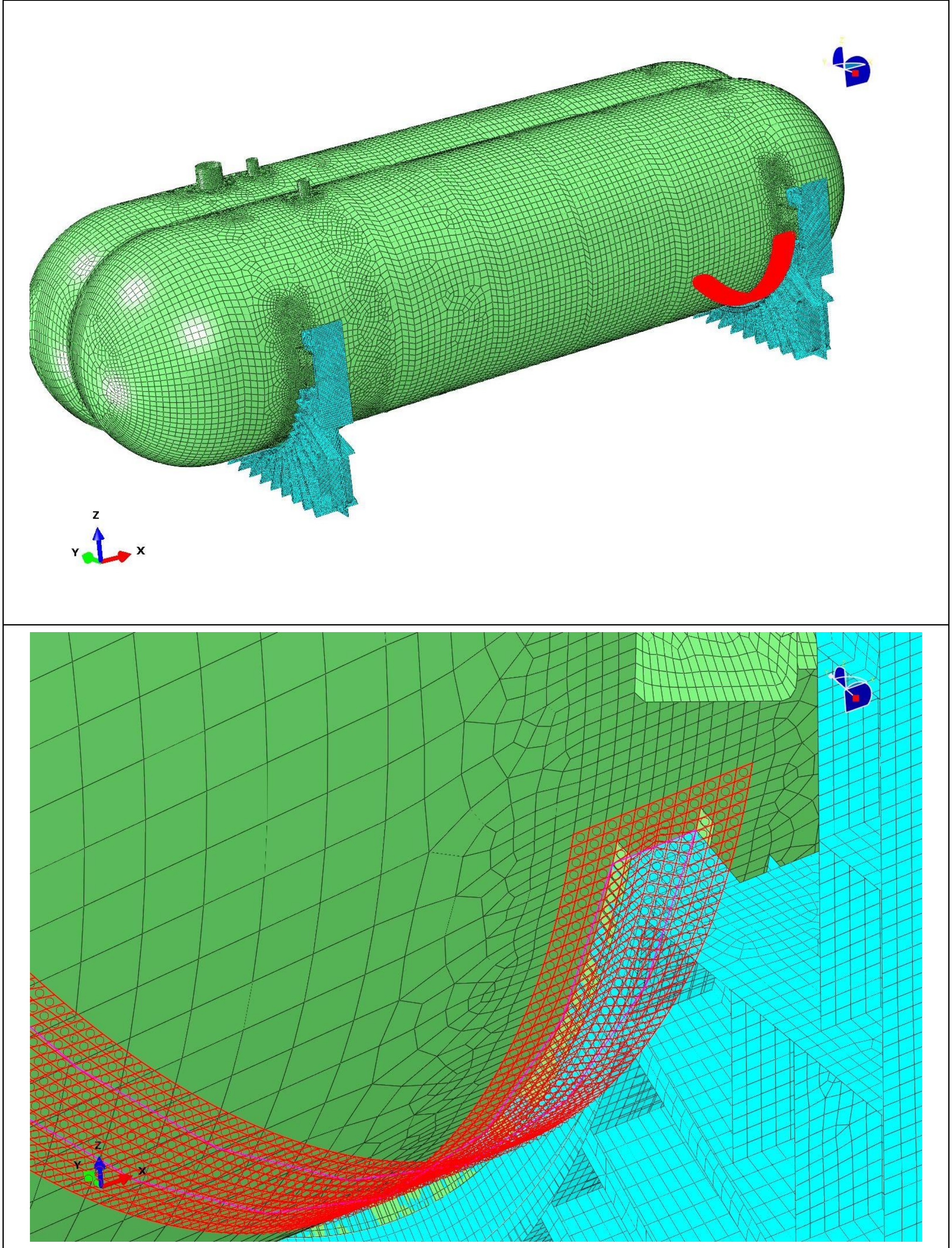
（b）Contact arrangement of shell and press-wood (fixed end)



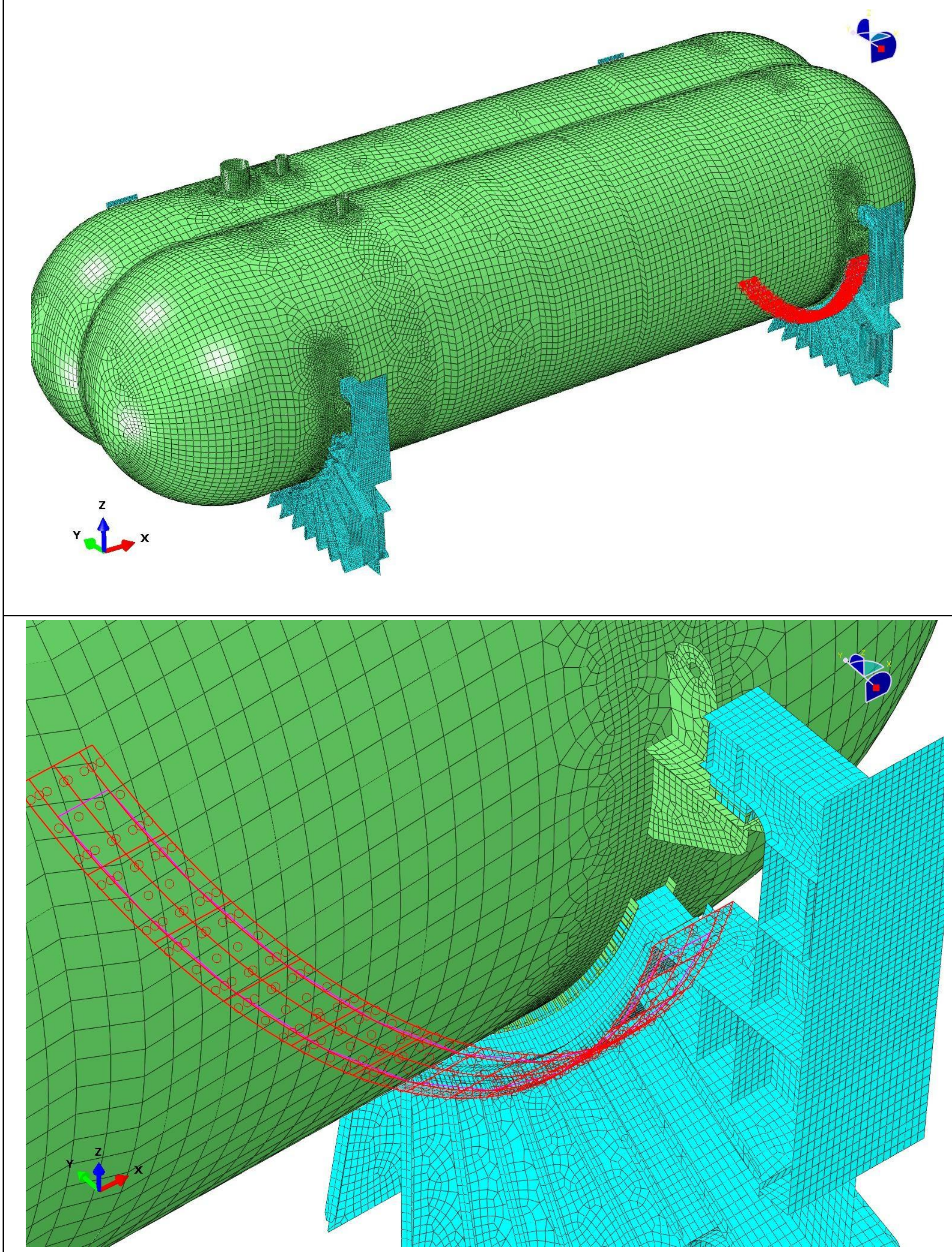
（c）Contact arrangement of stop flat and chock (fixed end)



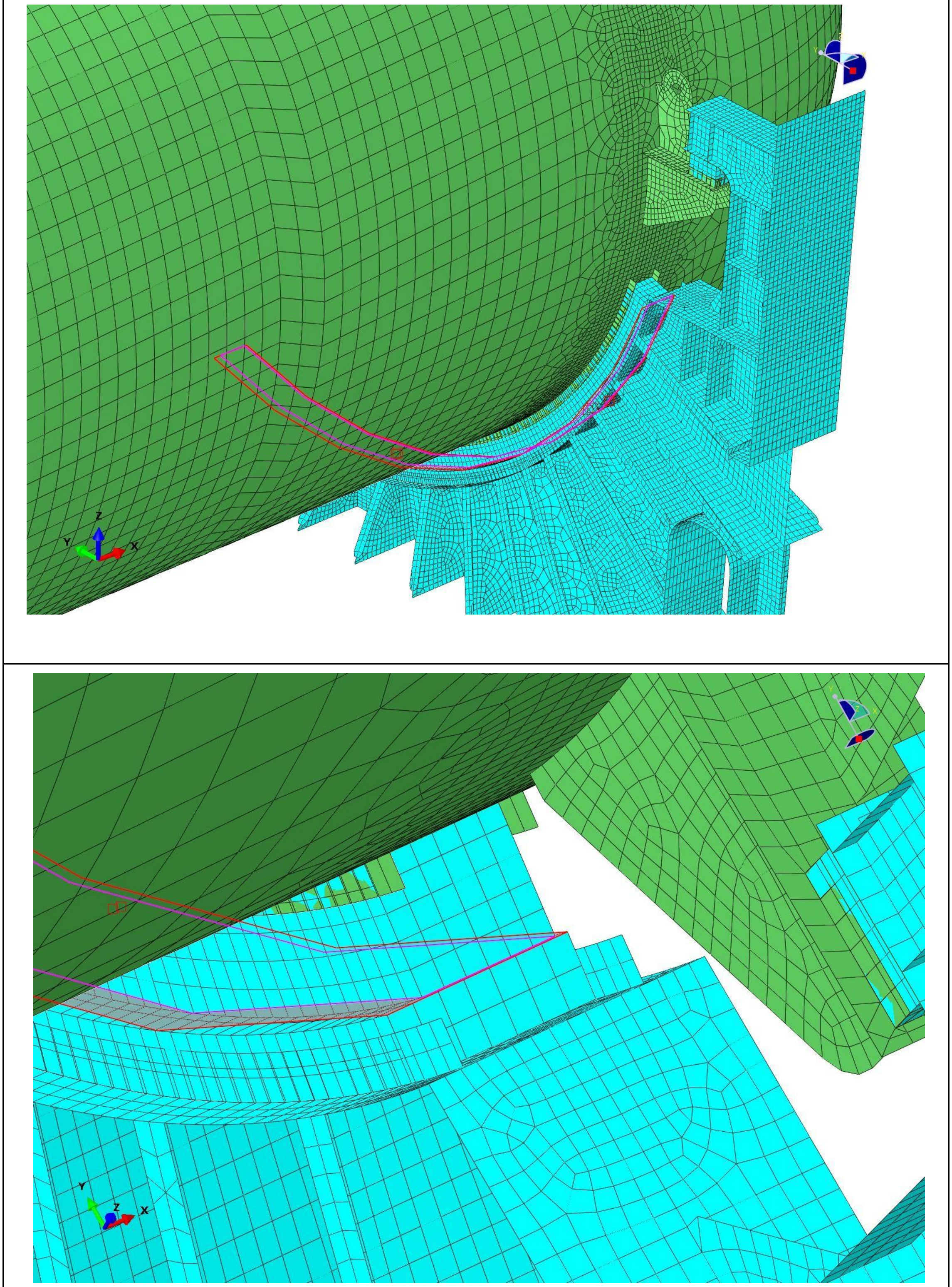
（d）Contact arrangement of saddle baffle and chock side (fixed end)



（e）Restraint arrangement of shell and press-wood (sliding end)

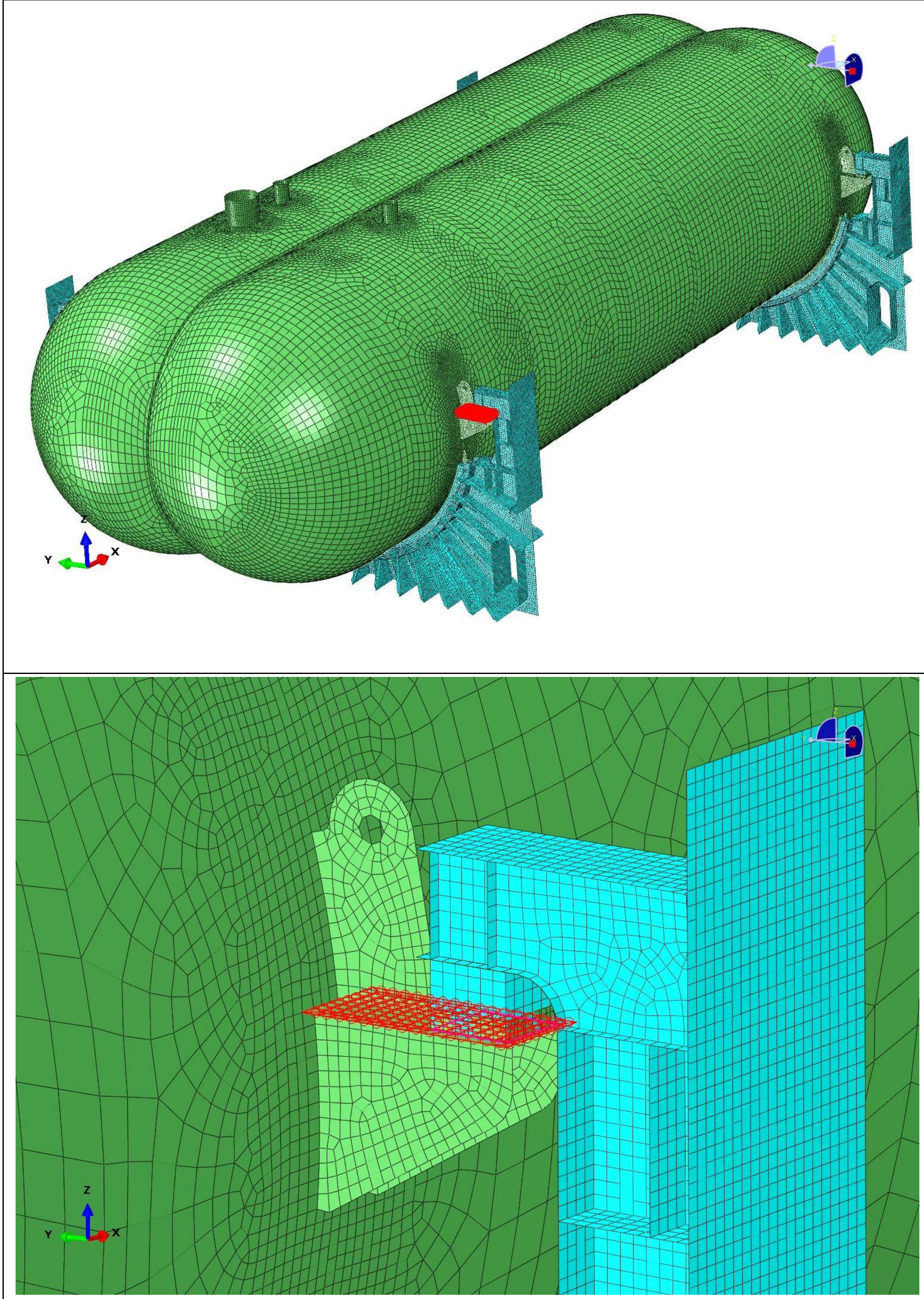


（f）Restraint arrangement of saddle and press-wood (sliding end)

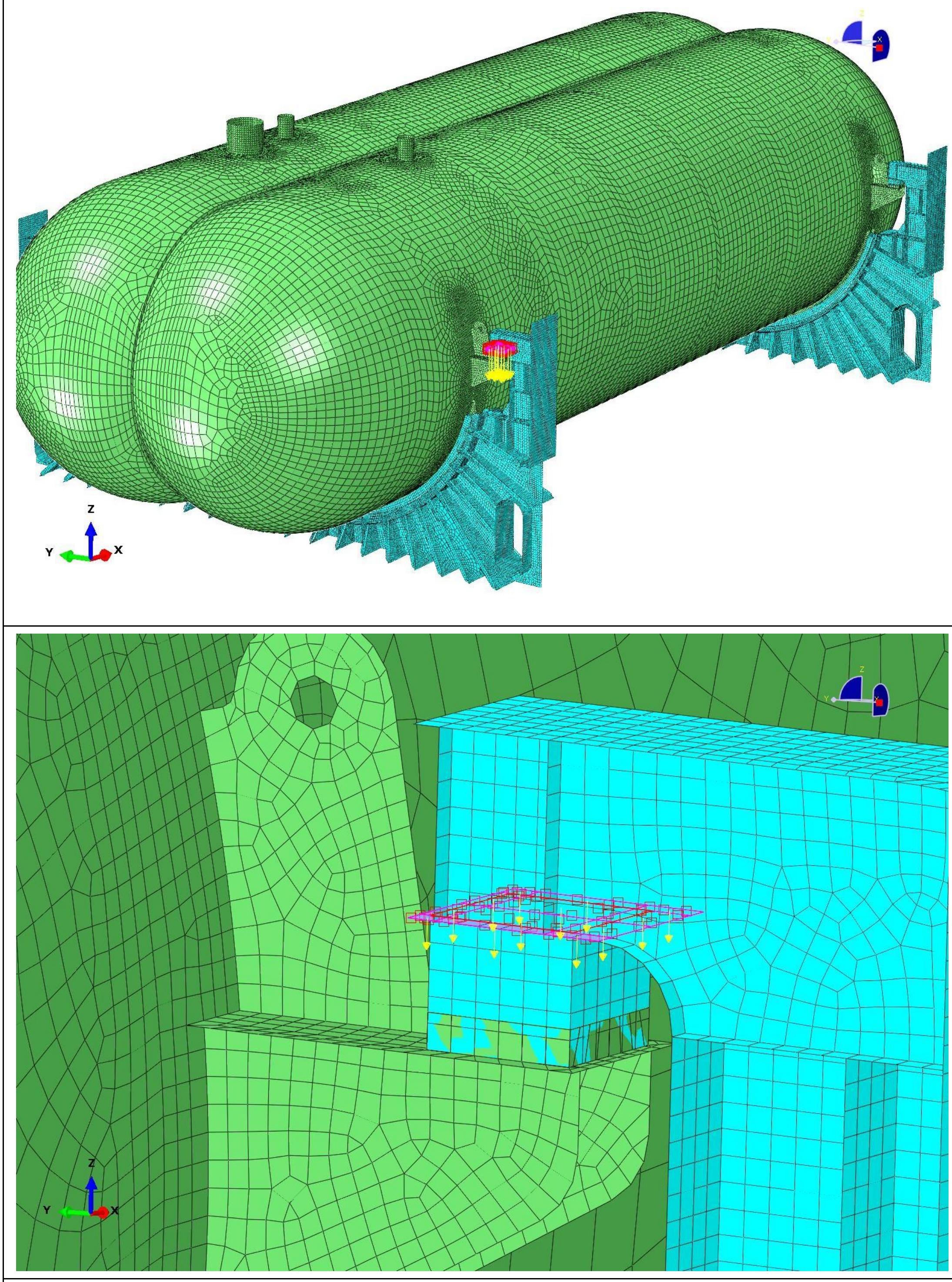


（g）Contact arrangement of upper and lower layers of press-wood (sliding end)

Figure 3.2.2.4(2) Contact arrangement of tank saddle



（a）Contact arrangement of press-wood and anti-floatation chock



（b）Contact arrangement of press-wood and side support

Figure 3.2.2.4(3) Contact arrangement of anti-floatation chock

3.2.3 Design load

3.2.3.1 The ultimate and accident design conditions should be assessed as outlined in Table 3.2.3.1. These conditions should be combinations of permanent, functional, environmental and accidental loads as outlined in Tables 3.2.3.2(1) to 3.2.3.2(5) as per the IGC Code. The design conditions shown on Tables 3.2.3.2(1) to 3.2.3.2(5) should be considered for the finite element analysis.

Design conditions and load cases **Table 3.2.3.1**

Design limit state	Description	Load case
ULS	For the maximum load-carrying capacity or, in some cases, to the maximum applicable strain, deformation or instability in structure resulting from buckling and plastic collapse under intact (undamaged) conditions. In the Guidelines, for the yielding capacity under intact (undamaged) conditions.	Longitudinal dynamic
		Transverse dynamic
		Vertical dynamic
		Sloshing
ALS	For the capacity of the structure to resist accidental situations	Static heel 30° (1)
		Collision
		Floatation
(1)	The condition can also be considered to cover an ultimate limit state (ULS) condition with small GM values, which cannot be assessed by the other ULS conditions. This condition may correspond to large roll angles and consequently provides large transverse inertial loads due to the gravity component. Accordingly, (if the calculated value of the roll angle exceeds 28°) the ULS criteria can be considered relevant for this condition subject to the discretion of ISC.	

3.2.3.2 The load combinations defined in Tables 3.2.3.2(1)~3.2.3.2(5) should be considered for each load case.

Load combinations for considering dynamic load cases Table 3.2.3.2(1)

Load case ID	Description	Permanent loads (including the tank and its attachment, liquid cargo and insulation materials, etc.)	Functional loads			Environment loads
			Filling level	Internal pressure	Thermal load	Loads due to ship motion
LD	Longitudinal acceleration	Gravity	Full	P_{eq} (1)	Minimum design cargo temperature (3)	$+a_x$ (2)
TD	Transverse acceleration	Gravity	Full	P_{eq} (1)	See above	$+a_y$ (2)
VD	Vertical acceleration	Gravity	Full	P_{eq} (1)	See above	$-a_z$ (2)

(1) Internal pressure as defined in IGC Code 4.13.2.4. For FE calculation, under LD and TD conditions, according to the pitch angle and roll angle corresponding to $+a_x$ and $+a_y$, acceleration ellipse method taking into account the gravitational acceleration is to be used to obtain the value of $\alpha_{\beta;}$ then calculate P_{gd} according to 4.28.1.2 of the IGC Code (or apply acceleration field function directly in the model), see ISC4.28.1.2.a~ ISC4.28.1.2.d, Chapter 4, PART TWO of ISC Rules for Construction and Equipment of Ships Carrying Liquefied Gases in Bulk.

See 'Environmental loads' column for applicable acceleration component for the calculation of internal pressure.

(2) Maximum dimensionless accelerations in longitudinal, transverse and vertical directions as defined in IGC Code 4.28.2.1. Direct calculation may be considered in accordance with IGC Code 4.14.1.3. For determination of ship acceleration and motion in irregular waves as well as the response of the ship and cargo containment system to the above actions and motions, refer to 4.14.1 of the IGC Code.

(3) Minimum design cargo temperature is given for tank. Applicable temperature gradient for the saddle supports can be obtained by relevant temperature field analysis, see Section 6, Appendix 2, PART TWO of ISC Rules for Construction and Equipment of Ships Carrying Liquefied Gases in Bulk.

Load combinations for static heel load case **Table 3.2.3.2(2)**

Load case ID	Description	Permanent loads (including the tank and its attachment, liquid cargo and insulation materials, etc.)	Functional loads		
			Filling level	Internal pressure	Thermal load
SH1	Static heel	Gravity	Full	• 30° static heel pressure • P_0 (1)	Minimum design cargo temperature (2)

(1) Design vapour pressure as defined in IGC Code 4.1.2.

(2) Minimum design cargo temperature is given for tank. Applicable temperature gradient for the cradle supports can be obtained by relevant temperature field analysis,, see Section 6, Appendix 2, PART TWO of ISC Rules for Construction and Equipment of Ships Carrying Liquefied Gases in Bulk.

Load combinations for collision load cases **Table 3.2.3.2(3)**

Load case ID	Description	Permanent loads (including the tank and its attachment, liquid cargo and insulation materials, etc.)	Functional loads			Accidental loads
			Filling level	Internal pressure	Thermal load	
CL1	Collision forward direction	Gravity	Full	• Collision pressure • P_0 (1)	Minimum design cargo temperature (2)	0.5 g forward acceleration
CL2	Collision aft direction	Gravity	Full	• Collision pressure • P_0 (1)	Minimum design cargo temperature (2)	0.25 g aft acceleration

(1) See note (1) of Table 3.2.3.2(2).

(2) See note (2) of Table 3.2.3.2(2).

Load combinations for floatation load case Table 3.2.3.2(4)

Load case ID	Description	Permanent loads (including the tank and its attachment, liquid cargo and insulation materials, etc.)	Functional loads		Accidental loads
			Filling level	Thermal load	
FL1	Tank floatation	Gravity	Empty	Not applicable	Loads caused by the buoyancy of an empty tank in a hold space flooded to the summer load draught

Load combinations for tank testing load case Table 3.2.3.2(5)

Load case ID	Description	Permanent loads (including the tank and its attachment, liquid cargo and insulation materials, etc.)	Functional loads			
			Filling level	Vapour pressure	Thermal load	Sloshing loads
SL1	Longitudinal sloshing	Gravity	See (2)	P_0 (1)	Minimum design cargo temperature	Longitudinal sloshing load (3)
SL2	Transverse sloshing	Gravity	See (2)	P_0 (1)	See above	Transverse sloshing load (3)

(1) See note (1) of Table 3.2.3.2(2).

(2) See 5.2.3, Appendix 2, PART TWO of ISC Rules for Construction and Equipment of Ships Carrying Liquefied Gases in Bulk for the filling level.

(3) Sloshing loads are calculated according to 5.2.3, Appendix 2, PART TWO of ISC Rules for Construction and Equipment of Ships Carrying Liquefied Gases in Bulk.

3.2.3.3 In case swash bulkheads and longitudinal bulkheads are fitted in the tank, sloshing loads are to be calculated according to 5.2.3, Section 5, Appendix 2, PART TWO of ISC Rules for Construction and Equipment of Ships Carrying Liquefied Gases in Bulk.

3.2.3.4 For ULS, when applying loads, the load combinations and partial load factors in 2.4.2 and Table 2.4.2, Chapter 2 are to be taken account of. Pay attention that for the combination P_{eq} of in Table 3.2.3.2(1) (see 4.13.2.4 of the IGC Code), P_0 is functional load and P_{gd} is environmental load.

3.2.3.5 For ALS, see 2.5 of Chapter 2 for load combinations and partial load factors.

3.2.4 Reliability based stress criteria

3.2.4.1 For areas of structural continuity of Type C tank shell, the FE stress criteria of the shell elements are as follows:

- $\sigma_{e\_membrane} \leq 1.0f$
- $\sigma_{eL\_surface} \leq 1.5f$

where: $\sigma_{e\_membrane}$ ——element equivalent stress (i.e. mid-surface stress) derived from the stress components of the membrane stress at any point, i.e. to be taken as equivalent membrane stress of the element in the FE result at that point;

$\sigma_{eL\_surface}$ ——element equivalent stress derived from the stress components of the top and bottom surfaces for any local area, whichever is greater, i.e. to be taken as element equivalent stress of the top and bottom surfaces at that point, whichever is greater, where the surface stress is to be the sum of the membrane stress and bending stress, see $\sigma_{\mathrm{m+b}}^{\mathrm{top/bottom}}$ in 3.2.4.7.

3.2.4.2 For areas of structural discontinuity of Type C tank shell, the FE stress criteria of the shell elements are as follows:

- $\sigma_{eL\_membrane} \leq 1.5f$
- $\sigma_{eL\_surface} \leq 1.5f$
- $\sigma_{eL\_surface\_g} \leq 3.0f/\gamma_p$ (relatively smaller local areas containing self-limiting stresses, generally being areas with a sudden change in geometry or a restrictive structure, such as Y-connection between saddle support area and inner bulkhead plates of the shell (if fitted) and stiffening rings, connecting areas of shells and torispherical heads, as well as doubler plate connecting the saddle (if fitted)).

where: $\sigma_{eL\_membrane}$ ——element equivalent stress (i.e. mid-surface stress) derived from the stress components of the membrane stress for the local area of structural discontinuities, i.e. to be taken as equivalent membrane stress of the element in the FE result at that point;

$\sigma_{eL\_surface}$ ——element equivalent stress derived from the stress components of the top and bottom surfaces for the local area of structural discontinuities, whichever is greater, i.e. to be taken as element equivalent stress of the top and bottom surfaces at that point, whichever is greater, where the surface stress is to be the sum of the membrane stress and bending stress, see $\sigma_{\mathrm{m+b}}^{\mathrm{top/bottom}}$ in 3.2.4.7. Stress linearization of the membrane stress and bending stress may be carried out for solid elements, using recognized methods or referring to 3.2.4.7;

$\sigma_{eL\_surface\_g}$ ——element equivalent stress derived from the stress components of the top and bottom surfaces for the relatively smaller local area of structural discontinuities containing self-limiting stresses, whichever is greater, i.e. to be taken as element equivalent stress of the top and bottom surfaces at that point, whichever is greater, where the surface stress is to be the sum of the membrane stress and bending stress, see $\sigma_{\mathrm{m+b}}^{\mathrm{top/bottom}}$ in 3.2.4.7. Stress linearization of the membrane stress and bending stress may be carried out for solid elements, using recognized method or referring to 3.2.4.7;

f —— to be calculated as follows:

$$f = \frac{R_e}{\gamma_S \cdot \gamma_m \cdot \gamma_C}$$

where: γ_S, γ_m, γ_C —— see 2.4.7.1, 2.4.6 and 2.4.4 respectively, as well as 2.5.6 (applicable to accidental condition);

γ_p —— safety factor taking into account of different target reliability, to be taken as:

- for target reliability of 3.09① (i.e. failure probability being 10^{-3}): $\gamma_p = 1.0$;
- for target reliability of 3.71② (i.e. failure probability being10^{-4}): $\gamma_p = 1.1$;

Note①: Characterized by strength reserves with general requirements, which generally correspond to series of products with known successful design cases;

Note②: Characterized by strength reserves with higher requirements, which generally correspond to first products, or users have higher safety requirements for the product than conventional products;

R_e ——yield strength of the material, see 4.18.1.3 of the IGC Code.

3.2.4.3 For inner bulkhead plates of Type C tank, the FE stress criteria are as follows:

- $\sigma_{e\_membrane} \le 1.0f$ for areas beyond structural connections
- $\sigma_{eL\_membrane} \le 1.25f$ for local areas of structural connections, see also note①.

where: $\sigma_{e\_membrane}$ ——element equivalent stress derived from the stress components of the membrane stress of the considered area, i.e. to be taken as mid-surface equivalent stress of the element in the FE result at that point;

$\sigma_{eL\_membrane}$ ——element equivalent stress derived from the stress components of the membrane stress for the local area of structural continuities, i.e. to be taken as mid-surface equivalent stress of the element in the FE result at that point;

f —— see 3.2.4.2;

Note①: The coefficient, 1.25, may be modified by the Administration or CCS considering the design concept, configuration of the structure, and the methodology used for calculation of stresses.

3.2.4.4 For stiffening rings, bulkhead girders and stiffener webs of Type C tank, the FE stress criteria of the plate elements are as follows:

- $\sigma_{e\_membrance} \le 1.25f$, see also 3.2.4.3 note①;
- $\sigma_{eg\_membrane} \le 3.0f$

where: $\sigma_{e\_membrane}$ ——element equivalent stress derived from the membrane stress component of the web element, i.e. to be taken as mid-surface equivalent stress of the element in the FE result at that point;

$\sigma_{eg\_membrane}$ ——element equivalent stress derived from the membrane stress component of the web element taking into account the secondary equivalent stress action, i.e. to be taken as mid-surface equivalent stress of the element in the FE result at that point;

f —— see 3.2.4.2.

3.2.4.5 For stiffening rings, bulkhead girders and stiffener face plates of Type C tank, the FE stress criteria of the plate or beam elements are as follows:

- $\sigma_a \le 1.25f$, see also 3.2.4.3 note①;
- $\sigma_{ag} \le 3.0f$

where: σ_a ——axis stress of plate or beam element lengthwise, i.e. to be taken as element axis stress in the FE result;

σ_{ag} ——axis stress of plate or beam element lengthwise taking into account the secondary equivalent stress action, i.e. to be taken as element axis stress in the FE result;

f —— see 3.2.4.2.

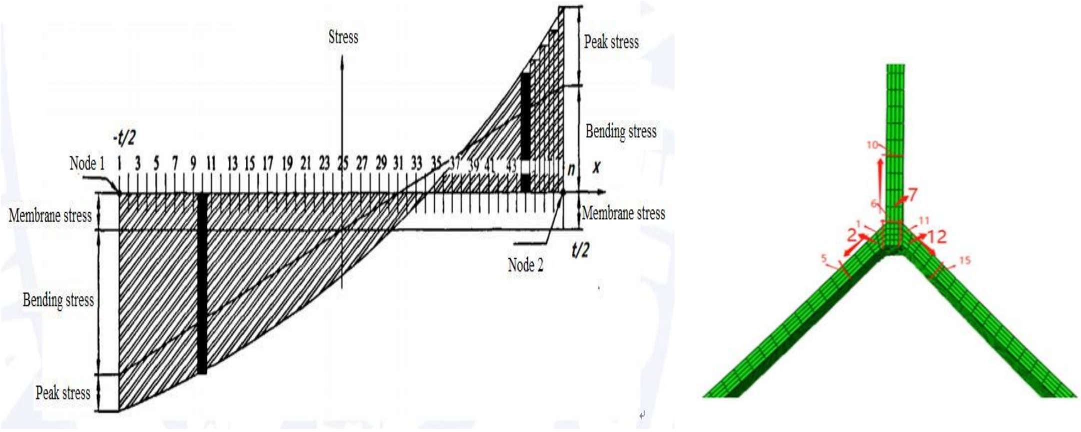
3.2.4.6 For structural members outside Type C tank, such as saddle support, stop flats, press-wood, etc., strength check is to be carried out in accordance with Sections 4 and 5, Appendix 2, PART TWO of ISC Rules for Construction and Equipment of Ships Carrying Liquefied Gases in Bulk.

3.2.4.7 Stress linearization

For solid elements, stress linearization is generally used to obtain membrane stress, bending stress and surface stress component. Stress linearization may be carried out according to recognized technical standards or as follows:

(1) for modelling requirements for solid elements, see 3.2.2.2 and 3.2.2.3.

(2) Stress categories and linearization are shown in Figure 3.2.4.7. Stress linearization may be carried out using method based on stress integral. The main steps for calculating membrane equivalent stress σ_m and membrane + bending equivalent stress $\sigma_{m+b}^{Top/Bottom}$ of the element are as follows:



(a) (b)

Figure 3.2.4.7 Stress categories and stress linearization

① determine the location of the stress categorization line along the thickness direction, see Figure 3.2.4.7(b);

② extract 6 stress components σ_{ij} (i=1, 2, 3; j=1, 2) of the nodes on the stress categorization line as the interpolation function values of stress distribution on the stress categorization line, then equally divide the stress categorization line into n (e.g. n=40) parts, and then obtain the stress tensors $\sigma_{i\,j,1}$, $\sigma_{i\,j,2}, \ldots \sigma_{ij,n}, \sigma_{ij,(n+1)}$ of the (n+1) equal diversion points on the stress categorization line by interpolation;

③ calculate the membrane stress tensor$\sigma_{ij,m}$:

$$\sigma_{ij,m} = \frac{1}{t}\int_0^t \sigma_{ij} dx$$

④ calculate the bending stress tensor$\sigma_{ij,b}$:

$$\sigma_{ij,b}^{\text{Top/Bottom}} = \pm\frac{6}{t^2}\int_{-t/2}^{t/2} \sigma_{ij} x dx$$

where: $\sigma_{ij,b}$——6 bending stress components at ends of the stress categorization line;

t ——thickness, as shown in Figure 3.2.4.7(a);

x ——distance from the equal diversion point to the middle of the thickness .

⑤ calculate the combination $\sigma_{ij,\ m+b}$ of the membrane stress component and bending stress component:

$$\sigma_{ij,\ m+b}^{\text{Top/Bottom}} = \sigma_{ij,\ m} + \sigma_{ij,\ b}^{\text{Top/Bottom}}$$

⑥ calculate equivalent stress at mid/neutral plane and top/bottom plane in way of ends of the stress categorization line based on the membrane and membrane+bending stress component:

$$\sigma_m = \sqrt{\frac{1}{2}[(\sigma_{11,m} - \sigma_{22,m})^2 + (\sigma_{22,m} - \sigma_{33,m})^2 + (\sigma_{33,m} - \sigma_{11,m})^2 + 6(\sigma_{12,m}^2 + \sigma_{23,m}^2 + \sigma_{31,m}^2)]}$$

$$\sigma_{m+b}^{\text{Top / Bottom}} = \sqrt{\frac{1}{2}\left\{(\sigma_{11,\ m+b}^{\text{Top / Bottom}} - \sigma_{22,\ m+b}^{\text{Top / Bottom}})^2 + (\sigma_{22,\ m+b}^{\text{Top / Bottom}} - \sigma_{33,\ m+b}^{\text{Top / Bottom}})^2 + (\sigma_{33,\ m+b}^{\text{Top / Bottom}} - \sigma_{11,\ m+b}^{\text{Top / Bottom}})^2 + 6\left[(\sigma_{12,\ m+b}^{\text{Top / Bottom}})^2 + (\sigma_{23,\ m+b}^{\text{Top / Bottom}})^2 + (\sigma_{13,\ m+b}^{\text{Top / Bottom}})^2\right]\right\}}$$

where: σ_m——membrane equivalent stress, see Figure 3.2.4.7(a);

$\sigma_{\text{m+b}}^{\text{Top/Bottom}}$ ——membrane+bending equivalent stress of Top/Bottom plane in way of ends on the stress categorization line, see Figure 3.2.4.7(a).

3.2.5 Stress singularity and strain criteria

3.2.5.1 If a sharp angular shape is formed due to the simplification of the detailed outline in modeling, such as the Y-connection, the local structural stiffness will be abrupt in the finite element solution, resulting in the divergence of the stress calculation results of the first (or first row) element at the intersection of the structure, and the phenomenon of the divergence of the stress calculation results still exists even increasing the mesh density of the element, which does not represent a true stress response. This situation is called "stress singularity" and the point is also called "stress singularity", as shown in Figure 3.2.5.1.

Stress singularity is particularly sensitive in terms of the structure of curved/column plate shell.

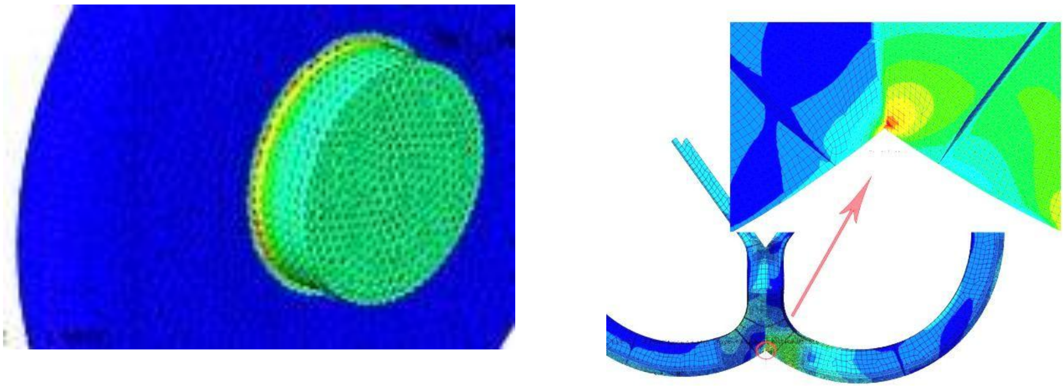
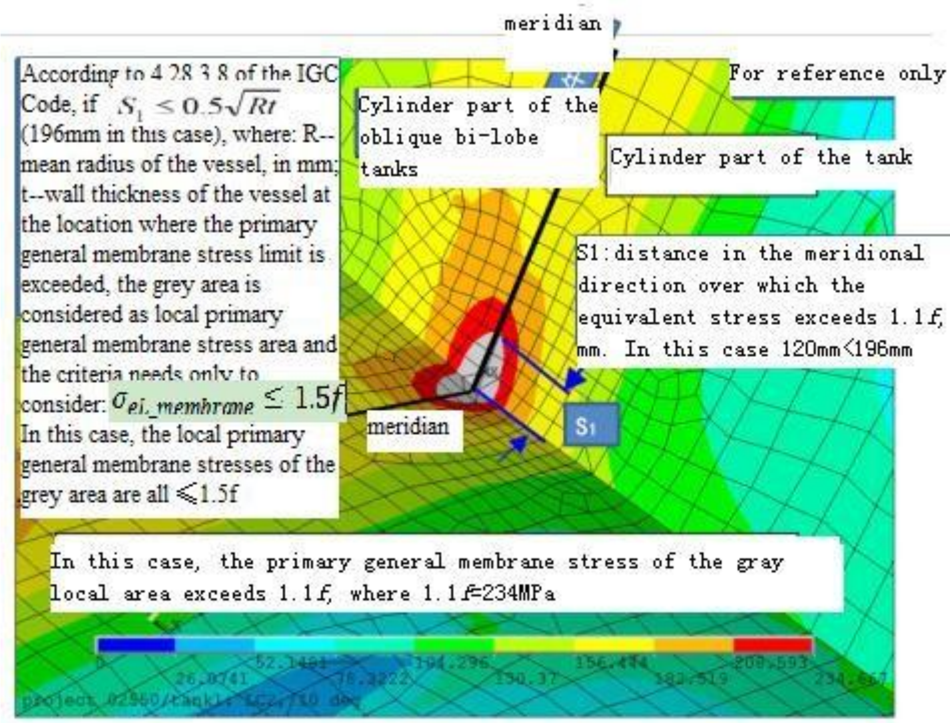


Figure 3.2.5.1 Stress singularity and stress singular point

3.2.5.2 For stress singularity in very small areas of structural discontinuity, the following treatment methods are recommended:

(1) for stress singularity on the tank shell of Type C tank, special strength check method may be carried out according to 4.28.3.8 of the IGC Code; see notes to Figure 3.2.5.2(1);

(2) for other areas, such as supporting brackets in way of saddles, longitudinal bulkhead plates, stress singularity may be omitted subject to ISC agreement. Instead, the stress of the first element after the stress singularity is to be taken as the reference value, see notes to Figure 3.2.5.2(2).

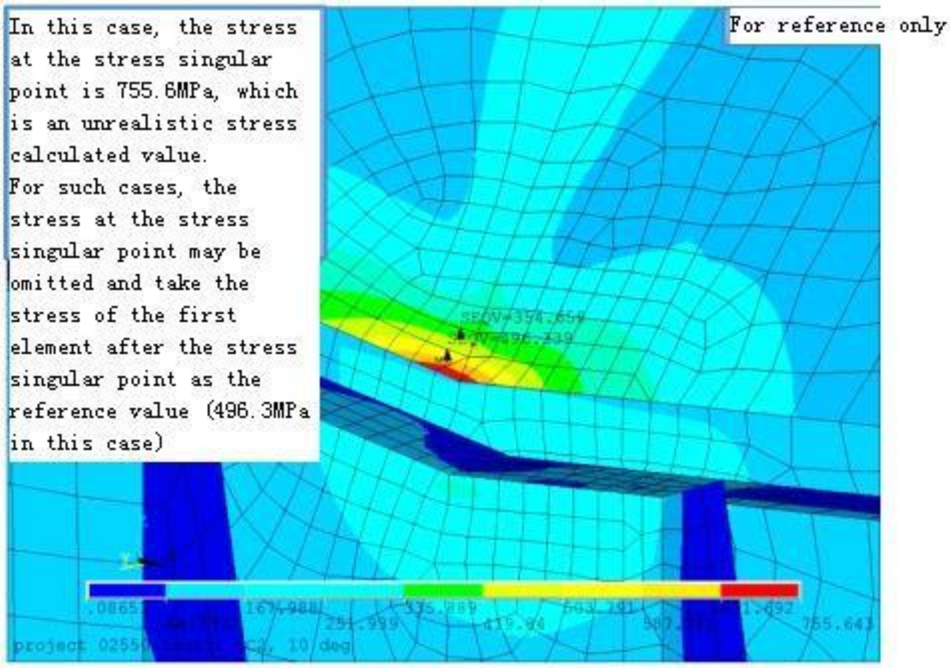


According to 4.28.3.8 of the IGC Code, if $S_1 \le 0.5\sqrt{Rt}$ (196mm in this case), where: R--mean radius of the vessel, in mm; t--wall thickness of the vessel at the location where the primary general membrane stress limit is exceeded, the grey area is considered as local primary general membrane stress area and the criteria needs only to consider: $\sigma_{ei\_membrane} \le 1.5f$ In this case, the local primary general membrane stresses of the grey area are all ≤1.5f

S1: distance in the meridional direction over which the equivalent stress exceeds 1.1*f*, in mm. In this case 120mm<196mm

In this case, the primary general membrane stress of the gray local area exceeds 1.1*f*, where 1.1*f*=234MPa

Figure 3.2.5.2(1) Notes to check method of the tank body according to 4.28.3.8 of the IGC Code



In this case, the stress at the stress singular point is 755.6MPa, which is an unrealistic stress calculated value.
For such cases, the stress at the stress singular point may be omitted and take the first stress of the first element after the stress singular point as the reference value (496.3MPa in this case)

Figure 3.2.5.2(2) Notes to strength check method of stress singularity of other parts according to 4.28.3.8 of the IGC Code

3.2.5.3 Recognized methods or the following strain criteria and assessment methods may be used as alternative to 3.2.5.2, subject to agreement of ISC:

(1) First, an "elastoplastic analysis" is performed using a recognized nonlinear structural analysis procedure and strain criteria are applied. Steps of implementation are as follows:

① Take into account the strain hardening effect of the elastoplastic behavior of the material, enter/establish a multi-linear stress-strain curve of the material in the program, which is to include at least the (stress, plastic strain) coordinates of the following 3 points and see Figure 3.2.5.3:

- $(R_e, 0)$
- $(\sigma_{0.2}, 0.2\%)$
- (Rm, ε_{Rm})

where: R_e, Rm ——see 4.18.1.3 of the IGC Code;

$\sigma_{0.2}$ —— stress corresponding to 0.2% plastic strain, in MPa;

ε_{Rm} —— plastic strain when stress reaches R_m;

The actual test value of stress-strain of the material is permitted subject to CCS agreement.

② The elastoplastic finite element analysis of the model is re-performed (in order to ensure the convergence quality, it is recommended to take the local model extended only with the local region near the stress singularity for analysis, and if so, the boundary conditions of the displacement or force obtained in advance from the whole model analysis are to be assigned to the edge of the local model).

(2) Then, the strength of stress singularity element is to be checked using one of the following

criteria:

① 0.2% residual plastic strain criteria;

② ultimate load criteria;

③ maximum principal strain criteria.

where: ① 0.2% residual plastic strain criteria: the maximum plastic strain value of the element is to be controlled within 0.2%;

② ultimate load criteria: the original load P_0 is gradually loaded by elastoplastic method until the plastic collapse is reached; read the loaded value P_1; obtain the permissible ultimate load $P_2 = \frac{2}{3}P_1$, and satisfying $P_0 \leq P_2$;

③ maximum principal strain criteria: the maximum principal strain value is to be controlled as follows:

$$\begin{cases} \leq 5\% & \text{for shell elements} \\ \leq 2\% & \text{for other elements} \end{cases}$$

(3) Where the stress singularity element and the adjacent area are solid elements, in general, strain cannot be read directly. Structural strain values at stress singularities can be obtained by quadratic extrapolation in conjunction with strain linearization, if necessary, according to recognized methods (e.g. EN13445-3).

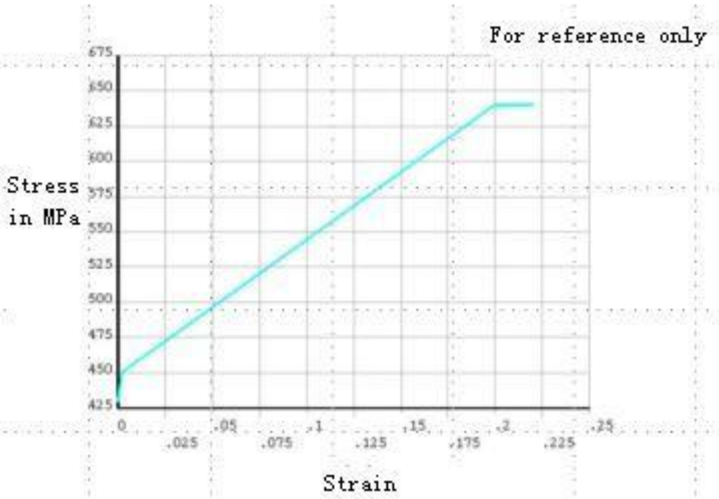


Figure 3.2.5.3 Plastic stress-strain curve of a certain material