RULES

PUBLICATION 17/P

STRENGTH ANALYSIS OF HULL STRUCTURE
OF ROLL ON/ROLL OFF SHIP

April
2021

Publications P (Additional Rule Requirements) issued by Polski Rejestr Statków complete or extend the Rules and are mandatory where applicable.

GDAŃSK

Publication No. 17/P – Strength Analysis of Hull Structure of Roll-on/Roll-off Ship – April 2021 is an extension of the requirements contained in *Part II – Hull* of the *Rules for the Classification and Construction of Sea-going Ships*.

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1 GENERAL

1.1 Introduction

1.1.1 For the design of ro-ro ships, documentation of which is subjected to the approval of PRS, the "Rules for the Classification and Construction of Sea-going Ships" (further referred to as the „Rules") require a strength analysis of hull structure to be carried out.

1.1.2 The hull structure strength analysis shows that in all, described below, design load conditions (in Chapter 2 and in 5.3), the stresses in the chosen sections will not exceed the values prescribed by the Rules.

1.1.3 Acceptable results of strength analysis carried out in accordance with the procedure given in the present Publication, as well as compliance with the requirements of the relevant Chapters of the Rules, will be the basis for the PRS approval of hull structural documentation

1.1.4 Strength analysis is usually related to fragments of particular hull structures (sides, bottom, decks, bulkheads) or their combinations. It is generally related to the primary supporting member systems of these structures considered as 2- or 3- dimensional bar systems (frameworks or grillages) or 3-dimensional FE models, where plate and beam- or bar-shaped finite elements are used (see 1.2.1).

1.1.5 Any calculation method or computer programme that takes into consideration the effects of bending, shear, axial and torsional deformations may be applied in strength analysis. The FEM calculations with the use of finite elements mentioned in 1.1.4 fulfil the requirement.

1.1.6 The present Publication contains guidelines for carrying out stress analysis of cross-sections of primary supporting members of roll-on/roll-off ships or other ships without standard watertight transverse bulkheads in the cargo region.

1.2 Strength analysis procedure

1.2.1 For ro-ro ships constructed before the year 2021 and ships constructed from the year 2021, having length L_0 < 120 m and not more than two fixed cargo decks above freeboard deck, with regularly spaced transverse frames and without partial bulkheads and large hatches in cargo part, simple FE models (2-dimensional frameworks or grillages), acc. to the method defined in 1.2.2, are permitted for the performance of strength analysis of the primary supporting member system in the cargo part of the ship.

For ro-ro ships having a length of $L_0 \geq 120$ m or with thecomplex hull structure other than specified above, the strength analysis of the hull girder system in cargo part requires the use of FE model of the whole ship hull, according to the requirements of Chapter 5. The requirements of Chapter 5 apply, in particular, to the calculation of the primary supporting member system stresses, for a ship in heeled condition, i.e. during the extreme roll.

PRS may also require the use of the FE model of the whole hull (together with superstructure) for „ro-pax" ships, for strength assessment of the superstructure during hull general bending.

1.2.2 The method referred to in 1.2.2 to 1.2.6, and in Chapters 2 to 4 enables to perform necessary calculations for 3-dimensional structures with the use of 2-dimensional calculation models (2-dimensional frameworks and grillages). Situations where the application of such a method is permitted are defined in 1.2.1.

Fig. 1.2-1 shows a scheme of the procedure for strength analysis of primary supporting members of ro-ro ship with pillars, supporting the deck structures directly on the double bottom.

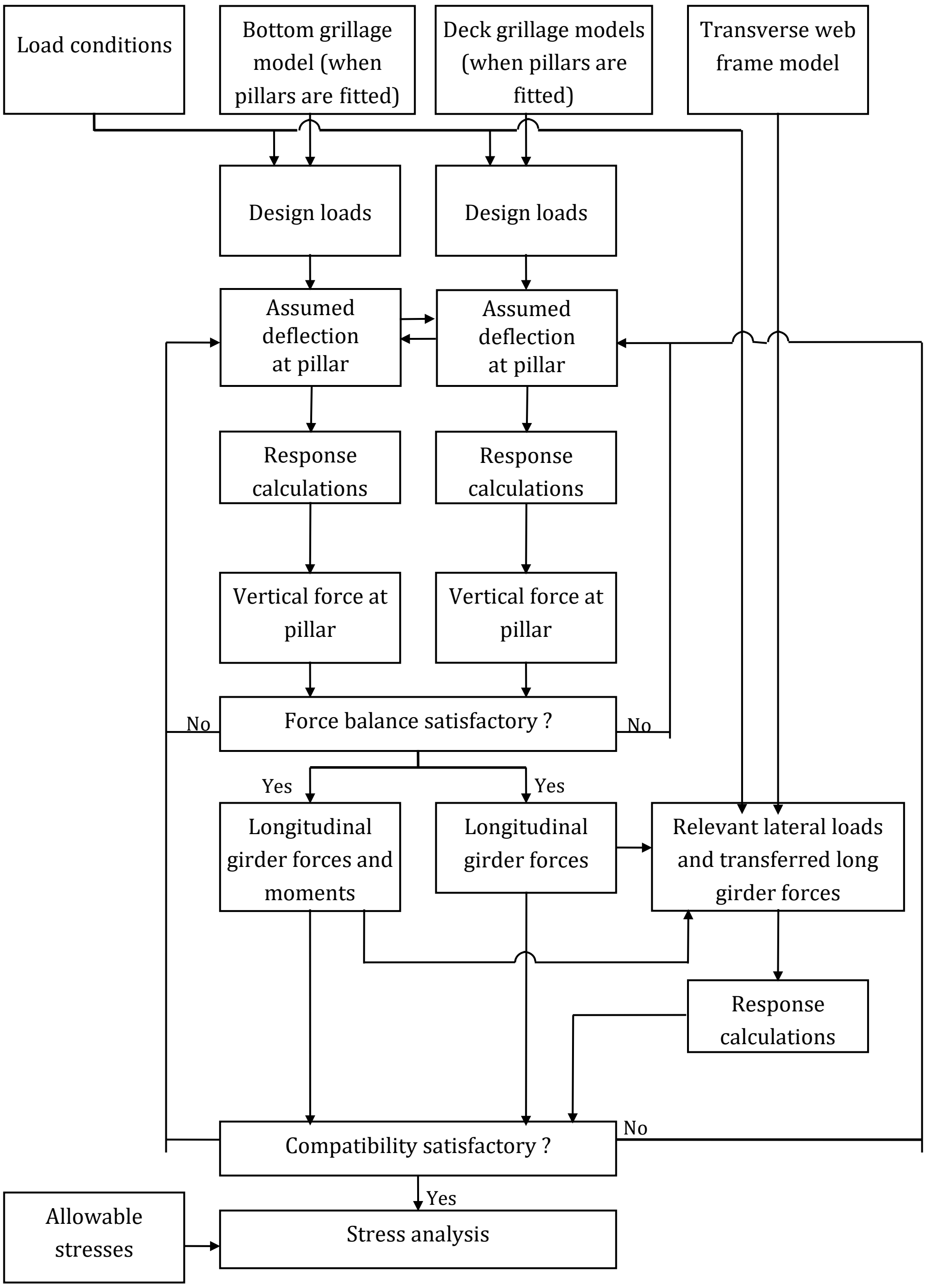


Fig. 1.2-1
Strength analysis procedure of roll-on/ roll-off ship (applied 2-dimensional framework or grillage models)

1.2.3 The design loads to be applied to particular structural members may be derived from the load conditions given in Chapter 2. Additional load conditions may be required in order to investigate the local strength of decks and double bottom.

1.2.4 For the load conditions, SO1 – SO5, the complete transverse section of the hull, is to be, in general, investigated.

1.2.5 Where pillars are fitted along the ship's centre plane, the unsymmetric load conditions SO6 and SO7 are to be investigated for individual decks and bottom.

For designs with no longitudinal discontinuities, such as pillars, simple procedures involving only modelling of transverse web frames may be applied.

1.2.6 If pillars are fitted at regular intervals over the whole length of the cargo region, modelling analysis of the bottom and deck (grillages) will be necessary in addition to the analysis of transverse web frames. These additional calculations involve an iteration process to obtain interaction between framework and grillage models. The iteration process is to be carried out until the compatibility between the forces and displacements in transverse web frames and grillages of decks and bottom has been proved satisfactory.

1.3 Definitions

1.3.1 Symbols not mentioned in the following list are given in connection with appropriate formulae.

L – length of the ship, in m;
B – breadth of the ship, in m;
H – depth of the ship, in m;
T – draught, in m;
δ – block coefficient,

For details, see 1.2.1, *Part II – Hull* of the *Rules,*

v – maximum service speed at draught T, in knots;

h_{dp} –height of double bottom, in m;

E – modulus of elasticity (Young's modulus), in MPa, $E = 2.06 \cdot 10^5$ MPa may be taken for steel;
g = 9.80665 m/s^2 – standard acceleration of gravity;

C_W – wave coefficient;
a_V – combined vertical acceleration, in m/s^2;
a_T – combined transverse acceleration, in m/s^2;
Φ_A – roll angle (amplitude of roll)in radians;
Θ_A – pitch angle (amplitude of pitch) in radians.

For details, see Chapter 17, *Part II– Hull* of *the Rules,*

1.3.2 Units

SI – units (the units of the International System of Units (SI)), as well as other units not covered by the system and permitted temporarily for use, are adopted in the present Publication.

The following SI – units are used in the Publication:
mass unit – tonne [t];
length unit – millimetre [mm], centimetre [cm] or metre [m];
angle unit – radian [rad];
time unit – second [s];
force unit – newton [N] or kilonewton [kN];
pressure unit – kilopascal [kPa];
stress unit – megapascal [MPa];
intensity of cargo mass distribution – tonne per square meters [t/m^2].

Attention is to be paid to the units used in computer programmes. They may differ from those listed above.

2 LOAD CONDITIONS

2.1 Maximum cargo on the lower part of section, upright condition (LC1)

2.1.1 This condition, shown in Fig. 2.1-1, may be decisive for the strength of the double bottom and lower deck.

It should be noted that in this condition, the upper decks are also loaded.

The total sum of static cargo load on the considered section need not exceed the buoyancy on the same section. For this purpose, the loads on the upper decks need not be taken as the maximum permissible values.

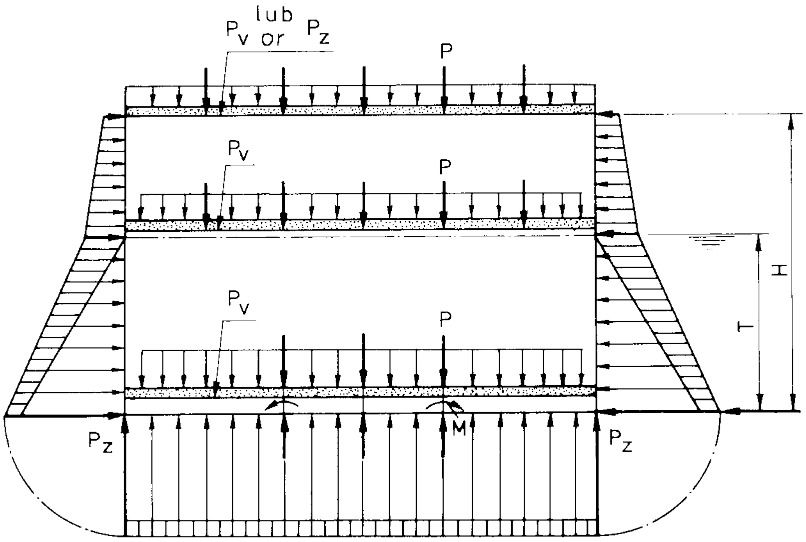
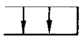


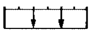
Fig. 2.1-1 Load condition SO1

Explanations to the figures:

 – load $q_0(g + 0.5a_v)$, [kPa], due to structure weight

 – load $q_1(g + 0.5a_v)$, [kPa], due to uniformly distributed cargo

 – transferred forces and moments from an adjacent structure

 – sea pressure P_z, combined (static and dynamic)

2.1.2 The design pressures due to cargo loads (including the mass of structures) shall be determined from the formula:

$$P_v = (g + 0.5a_v)(q_0 + q_1) \text{ [kPa]} \quad (2.1.2)$$

q_1 – intensity of cargo mass distribution, in t/m^2;
q_0 – intensity of structure mass distribution, in t/m^2.

For accommodation decks, the intensity of mass distribution ($q_0 + q_1$) may be taken equal to 0.4 t/m^2 .

2.1.3 The design sea pressures P_Z, in kPa, are to be determined for full draught, including dynamic sea pressures, from the formulae given in 16.2 *Part II – Hull* of the *Rules for the Classification and Construction of Sea-going Ships*.

For the weather deck, the greater of the values – the sea pressure or the pressure due to cargo – is to be applied. In both cases, the mass of the structure is to be taken into consideration.

2.2 Maximum cargo on the lower part of section, heeled condition (SO2)

2.2.1 This condition, shown in Fig. 2.2-1, may be decisive for the strength of the bottom, sides, pillars between decks and lower decks.

The cargo distribution on the considered section is to be the same as for load condition SO1.

Symbols are adopted according to Fig. 2.1-1.

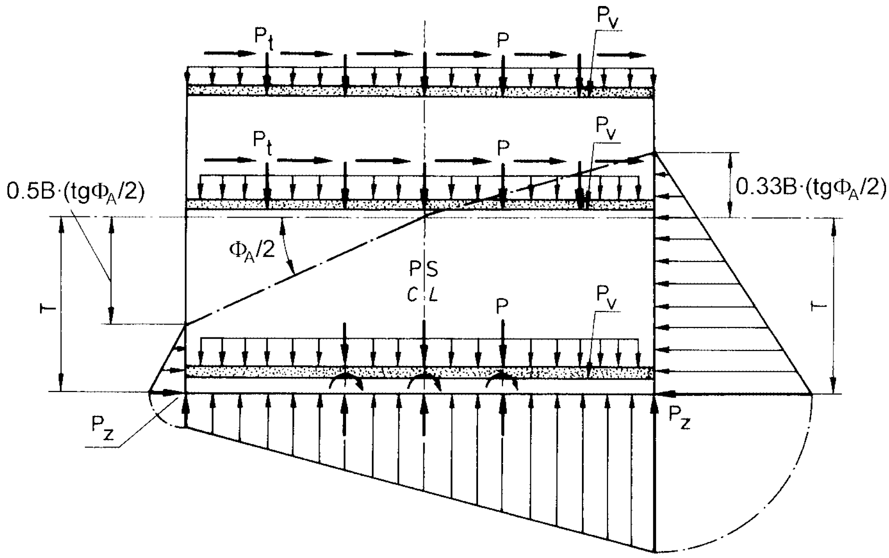


Fig.2.2-1 Load condition SO2

2.2.2 The design pressures due to cargo (including the mass of structures) are to be assumed as acting at an oblique angle to the deck.

The pressure components in the ship's vertical direction (according to the hull co-ordinate system) are to be taken as:

$$P_v = g(q_0 + q_1) \text{ [kPa]} \qquad (2.2.2\text{-}1)$$

The pressure components in the ship's transverse direction (according to the hull co-ordinate system) are to be taken as:

$$P_t = 0.67 a_T (q_0 + q_1) \text{ [kPa]} \qquad (2.2.2\text{-}2)$$

q_0, q_1 – as defined in 2.1.2.

In the case of different cargo loads in specified areas, the mean value of q_1 for the whole deck area may be applied.

Where movable decks for the carriage of vehicles are used, the pressure components (in the ship's transverse direction) due to the mass of vehicles and their cargo, determined in accordance with 2.2.2-2, are to be taken into consideration and are to be applied in accordance with real conditions of the decks supports.

2.2.3 The design sea pressures are to be determined for full draught, corrected for the effects of wave form and roll.

The pressure at the bilge for the emerged side is to be determined from the formula:

$$P_Z = 10T - 5B \cdot tg\frac{\Phi_A}{2} \text{ [kPa]} \qquad (2.2.3\text{-}1)$$

For the position $T - 0.5B \cdot tg\frac{\Phi_A}{2}$ [m], above the baseline, $P_Z = 0$ is to be taken.

The pressure at bilge for the submerged side is to be determined from the formula:

$$P_Z = 10T - 3.3B \cdot tg\frac{\Phi_A}{2} \text{ [kPa]} \qquad (2.2.3\text{-}2)$$

For the position $T + 0.33B \cdot tg\frac{\Phi_A}{2}$ [m], above the baseline, $P_Z = 0$ is to be taken.

Between the positions specified above, the value of P_Z is to be varied linearly.

If, at the above-specified pressure distribution, the weather deck is partially submerged, then the sea pressure on the weather deck may be disregarded when cargo loads are applied.

2.3 Maximum cargo on the upper part of section, upright condition (SO3)

2.3.1 This condition, shown in Fig. 2.3-1, may be decisive for the strength of double bottom and higher decks.

All cargo spaces, except those above the double bottom, are to be considered loaded to the maximum.

If the total sum of static cargo loads exceeds the buoyancy on the same section, the loads on lower decks may be reduced. If this condition is unrealistic for stability reasons, adjustments to this condition are to be made and submitted for consideration.

2.3.2 The design pressures due to cargo and design sea pressures are to be calculated as for SO1 condition.

Symbols are taken according to Fig. 2.1-1.

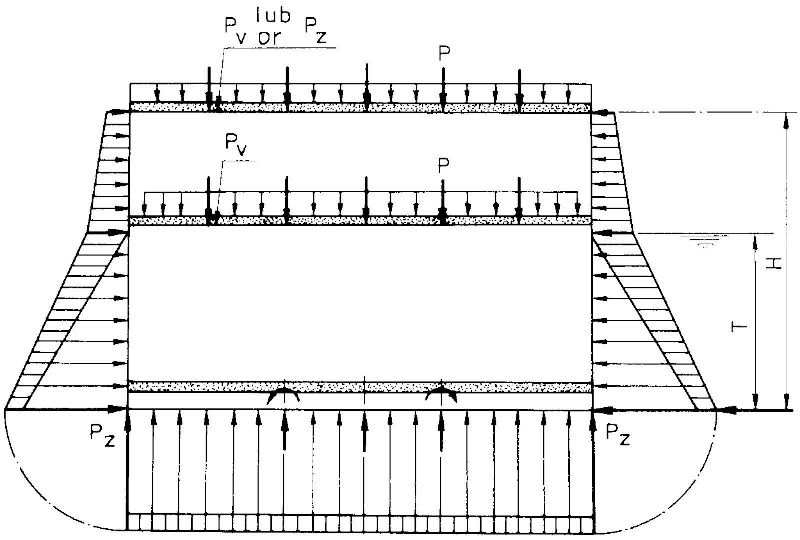


Fig. 2.3-1 Load condition SO3

2.4 Maximum cargo on the upper part of section, heeled condition (SO4)

2.4.1 This condition, shown in Fig. 2.4-1, may be decisive for the strength of the double bottom, higher decks, pillars between decks, as well as the strength of the ship sides. The cargo distribution on the section is to be the same as for SO2 condition.

Symbols are taken according to Fig. 2.1-1.

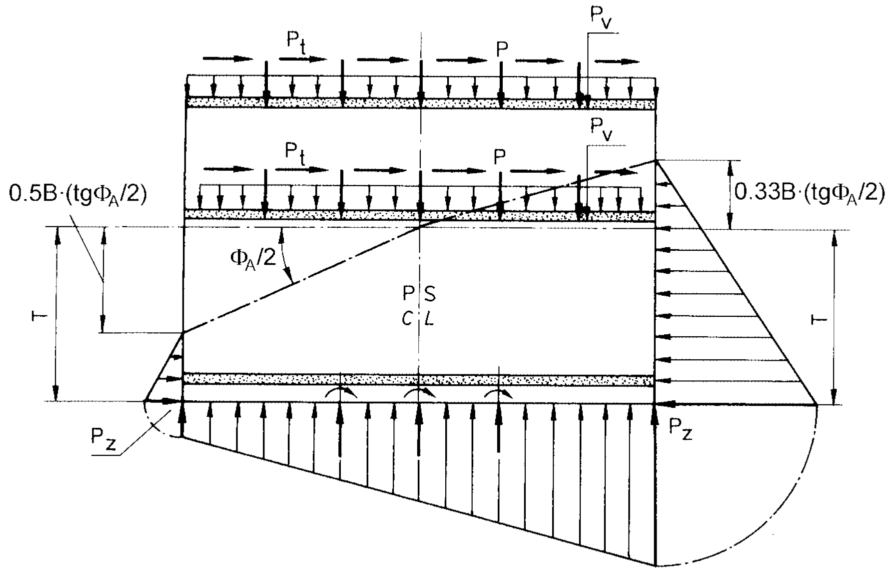


Fig. 2.4-1 Load condition SO4

2.4.2 The design pressures due to cargo and design sea pressures are to be calculated as for SO2 condition.

2.5 Ballast condition (SO5)

2.5.1 This condition, shown in Fig. 2.5-1, may be decisive for the strength of the double bottom in ships with pillars supporting decks.

The design pressures due to the mass of deck or double bottom structures are to be calculated as for SO1 condition. For the decks, the value of q_1 is to be taken as zero. Double bottom tanks for bunker are to be considered empty. Ballast shall be placed in double bottom tanks.

Symbols are taken according to Fig.2.1-1.

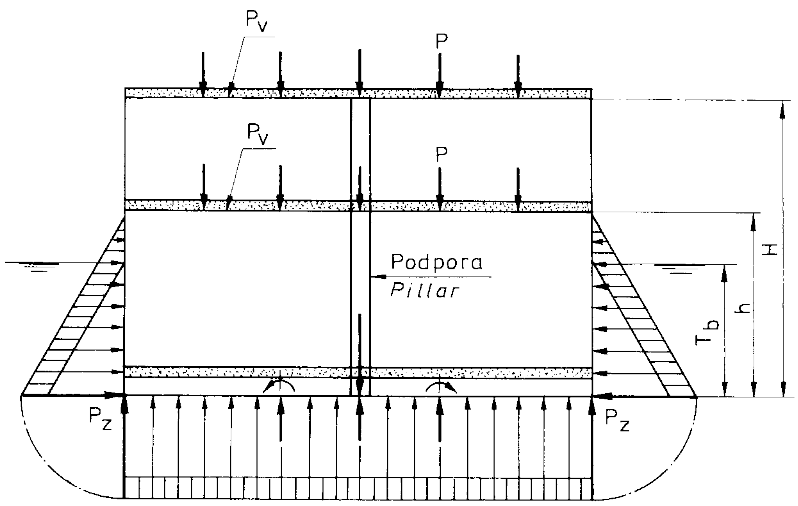


Fig. 2.5-1 Load condition SO5

2.5.2 Design bottom pressure P_Z, in kPa, is to be determined, taking into consideration dynamic components. Pressures dynamic components are to be determined from the formulae given in *Part II – Hull*, of the *PRS Rules*, substituting to them draught *T*. Static pressures are to be determined for draught T_b.

At position $h = T_b + 0.1P_{Tb}$ above the baseline, $P_Z = 0$ is to be taken. P_{Tb} denotes P_Z at $z = T_b$ ($z = 0$ is to be taken at the baseline).

Linear variability of the pressures is to be taken along the ship side, between levels $z = T_b$ and $z = h$ (Fig.2.5-1).

2.6 Transversely unsymmetric deck load (SO6)

2.6.1 This condition, shown in Fig. 2.6-1, is applicable only to strength analysis of deck grillage supported by pillars.

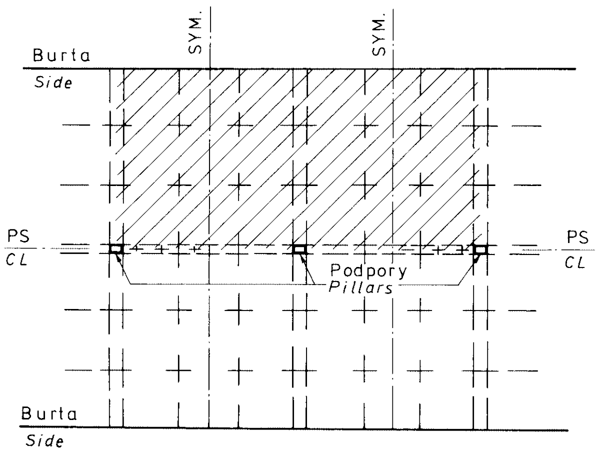


Fig. 2.6-1 Load condition SO6

2.6.2 The loads are to be calculated as for SO1 condition.

2.7 Longitudinally unsymmetric deck load (SO7)

2.7.1 This condition, shown in Fig. 2.7-1, is applicable only to strength analysis of deck grillage supported by pillars.

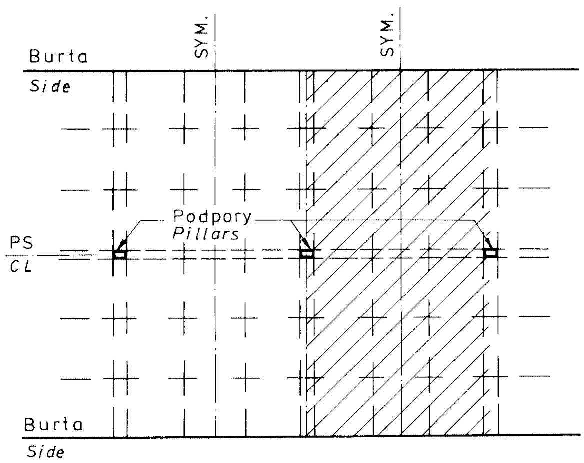


Fig.2.7-1 Load condition SO7

2.7.2 The loads are to be calculated as for SO1 condition.

2.8 Deck loaded with concentrated forces (SO8)

2.8.1 This condition is applicable only to strength analysis of deck grillage (or to the transverse plane framework) to allow for concentrated forces from a pile of containers or from other cargo.

2.8.2 Loads are to be calculated for the maximum permissible mass of pile of containers and the mass of the structure, including vertical accelerations calculated in accordance with 2.1.2.

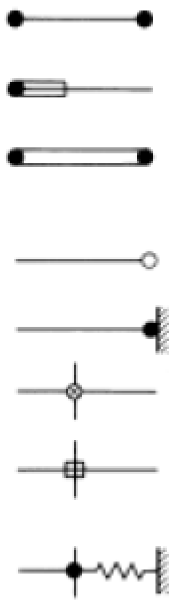
3 MODELLING OF STRUCTURE

3.1 General

3.1.1 For structures where the transverse strength members are supported only at the ship sides, one model of the transverse web frame structure will be sufficient.

3.1.2 If the deck and the double bottom are designed with pillars and longitudinal girders in addition to the transverse web frames, force distribution from an adjacent structure to the transverse web frame in question is to be considered. This can normally be calculated by 2-dimensional grillage models.

3.1.3 The correlation between forces and displacements in the individual 2-dimensional grillage models is to be satisfactory. Symbols used in the description of the models are given in Fig. 3.1-1.



element (bar) between nodes

rigid end of element

rigid element

element with symmetry conditions at end (grillage model)

fixed node

node with vertical support (grillage model)

node with pillar support (grillage model)

node with linear in plane restraint (linear spring able to be displaced in grillage or framework plane)

Rys.3.1-1
Symbols used in schemes of structure calculation models

3.1.4 Structures in the way of openings for ramps, lifts, etc., may be analysed on the basis of modified 2-dimensional models. Necessary modifications will be considered in each particular case.

3.2 Transverse web frames

3.2.1 Figs. 3.2-1 and 3.2-2 show typical models of a transverse web frame at pillars and between pillars when centreline pillars are fitted. The model is to extend from side to side to allow for unsymmetric load conditions.

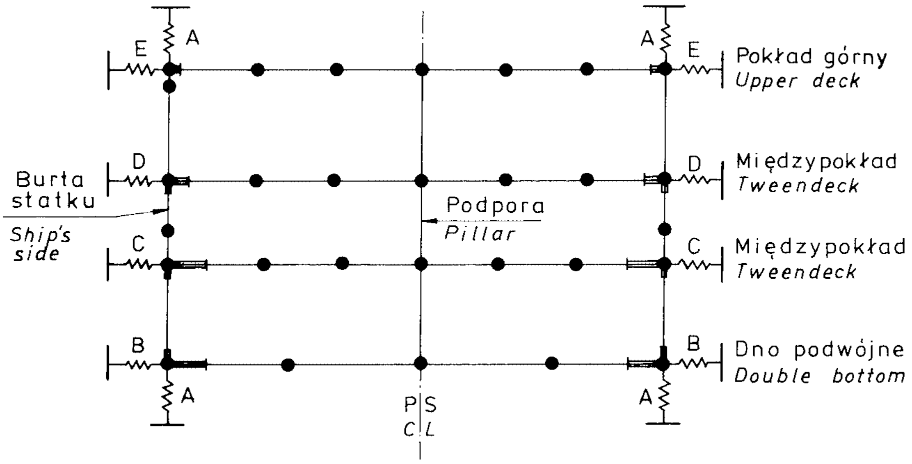


Fig.3.2-1 Transverse web frame at pillars

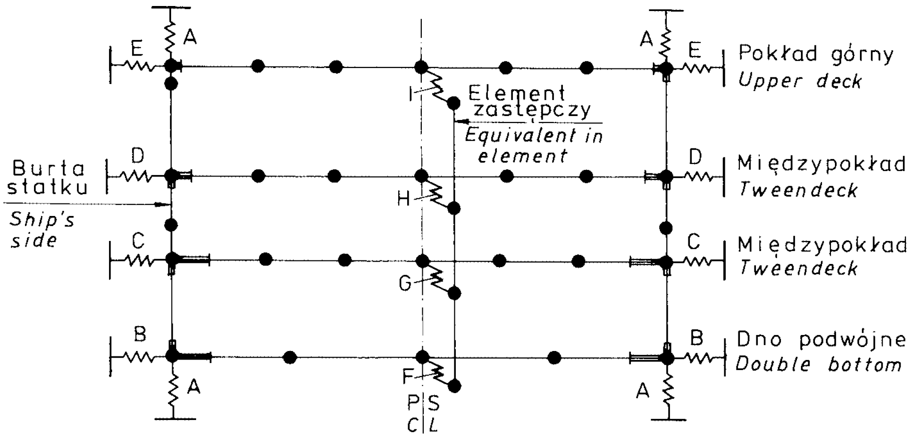


Fig.3.2-2 Transverse web frame between pillars

3.2.2 Vertical and horizontal supporting springs corresponding to the stiffness of ship's sides and decks are to be applied.

For transverse web frames in the mid-part of hull compartment of length l specified below, the stiffness coefficients for spring pillars A, B, C, D and E may be calculated from the formula:

$$K = \frac{0.5 \cdot E}{\frac{l^2}{S_r}\left(\frac{5 \cdot l^2}{384 \cdot I} + \frac{2.6}{8 \cdot A_s}\right)} \qquad (3.2.2\text{-}1)$$

l – distance between effective transverse bulkheads; the value l, taken for calculations, is not to be greater than 0.9 L;

S_r – transverse web frames spacing;

I – actual moment of inertia of that part of hull cross-section, within mid-part of hull compartment of length l, which acts as the spring support: ship side (spring A) and deck or bottom (springs B, C, D, E), calculated against the neutral bending axis, taking into account effective strake areas (parts of decks and bottom cross sections – for spring A and those of side structures and longitudinal bulkheads – for springs B, C, D, E).

A_s – actual shear area of that part of hull cross-section, within mid-part of hull compartment of length l, which acts as the spring support: of ship's side and longitudinal bulkhead (if any) (spring A) and of bottom or deck (springs B, C, D, E).

For frames situated outside the mid-part of hull compartment of length l, the stiffness coefficients K, defined as above, may be calculated from the below formula:

$$K = \frac{0.5 \cdot E \cdot I \cdot S_r}{l^4\left[\frac{1}{24}\frac{x}{l} - \frac{1}{12}\left(\frac{x}{l}\right)^3 + \frac{1}{24}\left(\frac{x}{l}\right)^4\right] + 2.6\frac{I}{A_S}l^2\left[\frac{1}{2}\frac{x}{l} - \frac{1}{2}\left(\frac{x}{l}\right)^2\right]} \quad (3.2.2\text{-}2)$$

where:

x – distance to the fore end of hull compartment of length l; other symbols are defined as in formula 3.2.2-1.

3.2.3 Transverse web frames between pillars are normally connected to the pillar by a longitudinal centre plane deck girder. In 2-dimensional model, this connection may be represented by springs F, G, H and I. The stiffness coefficient of these springs may be calculated from the formula:

$$K = \frac{E}{nk_1\left(\frac{l^3}{384 \cdot I} + \frac{2.6l}{8 \cdot A_S}\right)} \quad (3.2.3\text{-}1)$$

l – distance between pillars;
I – actual moment of inertia of the girder;
A_s – transverse (shear) section of the girder;
n – number of transverse web frames between pillars;
k_1 – factor determined from Table 3.2.2.

Table 3.2.2

n	1	2	3	4	5	6	7	8	9	10	>10
k_1	2.00	1.50	1.33	1.25	1.20	1.18	1.14	1.12	1.11	1.10	1.0

If spring supports are not available in the software used, the spring may be replaced by a “spring element” with cross-sectional area:

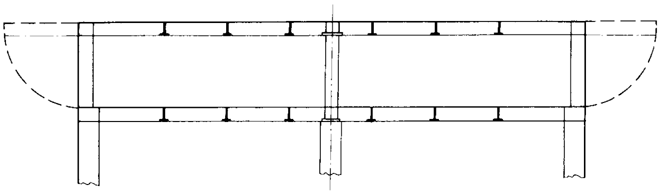
$$A = \frac{Kl_S}{E} \quad (3.2.3\text{-}2)$$

l_s – length of “spring element”.

3.3 Deck and bottom structures

3.3.1 A typical deck design and corresponding model are shown in Fig. 3.3.1. This model may be used for the analysis of load conditions SO6 and SO7. In addition, the force distribution in the deck or bottom longitudinal girders may be determined for load conditions SO1 - SO5 and applied to the transverse web frame model given in Fig. 3.2-1. This applies when pillars are used to support the deck and bottom structure. The compatibility of forces and displacements at the intersections between the web frame and grillage models may be difficult to obtain when the number of longitudinal girders is large. In this case, it may be more convenient (or necessary) to apply a 3-dimensional model combining web frame models and grillage models.

a) Typical deck structure (transverse section)



b) Grillage model (upper deck), including ship sides unfolded

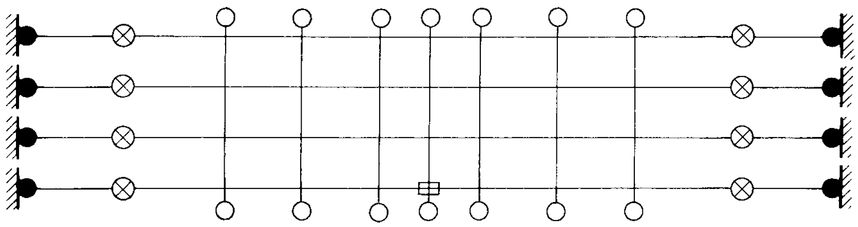


Fig. 3.3-1 Deck structure

Fig.3.3-2 Deflections of transverse web frame under angle of heel

Pre-set displacement of boundary nodes in grillage model

Fig. 3.3-3 Racking

The grillage model of deck structure for load condition S08 (in some cases 2-dimensional model may be sufficient) is to include such part of the deck area, which would adequately represent the heterogeneity of loads and the symmetry of the structure.

3.3.2 The node supported by a pillar is to be given rotational spring stiffness in x- and y-direction, calculated from the formula:

$$K_r = \frac{E}{\frac{l}{4I} + \frac{3.9}{A_s l}} \text{, moment unit/rad} \quad (3.3.2.)$$

l – length of a pillar;
I – relevant moment of inertia of pillar (in x- or y- direction);
A_s – relevant shear area of a pillar (in x- or y- direction).

It should be noted that for tween decks, the value of K_r is to be taken as the sum of stiffness of pillars above and below the deck considered.

3.3.3 The node supported by a pillar in each grillage model is to be given pre-set vertical displacement corresponding to the deflection (relative displacement) obtained in the successive transverse web frame calculation.

For the loading conditions SO2 and SO4, the transverse boundary nodes of grillage are to be given similar pre-set displacement corresponding to the deflections due to racking between the decks (see Fig. 3.3-3).

4 STRESS ANALYSIS

4.1 General

4.1.1 Permissible girder stresses given in *Part II – Hull* of the *Rules*, Section 14.4, are to be complied with.

4.1.2 The stability factor (usage factor) η of pillars is to comply with:

$$\eta = \frac{\sigma_a}{\sigma_c} \le \frac{0.7}{1+\frac{l}{i}} \quad (4.1.2)$$

where:

$$\frac{0.7}{1+\frac{l}{i}} \ge 0.3$$

σ_a – calculated compressive stress;
σ_c – critical buckling stress of pillar; it may be calculated according to 13.7, *Part II – Hull* of the *Rules*;
l – length of pillar, in m;
i – radius of gyration, in cm.

4.1.3 The stability factor (usage factor) for plating acting as girder flange is to comply with:

$$\eta = \frac{\sigma_a}{\sigma_c} \le 0.87 \quad (4.1.3)$$

σ_a and σ_c – see 4.1.2.

4.2 Strength of cross joints

4.2.1 The flange discontinuity at cross joints of highly stressed girders is to be normally compensated by brackets. If brackets are not possible, e.g. between deck transverse and ship's side vertical girders, high shear stresses in the web area combining the girders may occur.

The design shear stress may normally be taken as the average of stresses calculated from the formula:

$$t = 10\frac{P_{m1} - Q_{s2}}{A_{s2}} \text{ [MPa]} \quad (4.2.1\text{-}1)$$

and

$$t = 10\frac{P_{m2} - Q_{s1}}{A_{s1}} \text{ [MPa]} \quad (4.2.1\text{-}2)$$

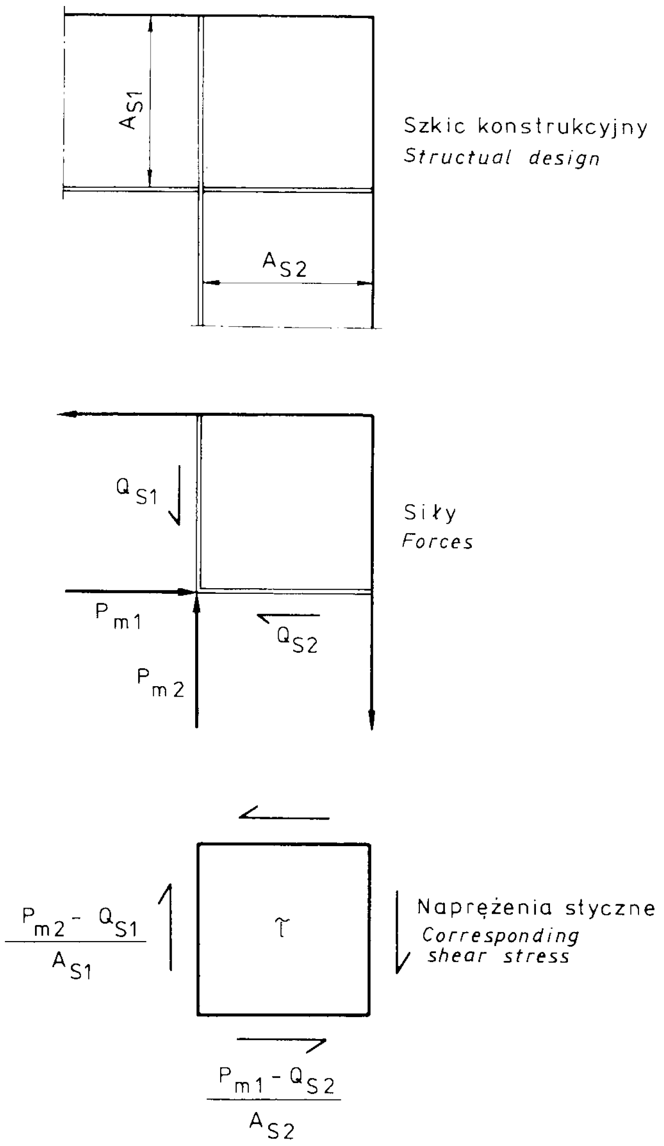


Fig.4.2-1 Stress analysis of cross joint

Q_s – shear force at girder web, in kN;
P_m – longitudinal force in girder flange, in kN;
A_s – girder shear area, in cm^2.

5 STRESS ANALYSIS WITH FE MODEL OF THE WHOLE SHIP HULL

5.1 Analysis purpose and scope

5.1.1 The analysis performed in accordance with the requirements of this Chapter is aimed mainly at the assessment of stress level in the transverse web frame system made by deck transverses, web frames and divisions (or partial bulkheads), which compensates transverse cargo loads in heeled conditions (so-called racking) – see also 1.2.1.

For that purpose, the use of the FE model of the whole ship hull is required, in accordance with the requirements of 5.2 and 5.3.

5.1.2 The FEM calculations with the whole ship hull may also be required by PRS for the assessment of capacity and strength of „ro-pax" ships superstructure, in general bending conditions (see 5.2.3 and 5.3.3), and the strength of the primary supporting member system of decks, sides and pillars, instead of calculations with grillage and framework models, as defined in Chapter 3 (see 5.2.2 and 5.3.2).

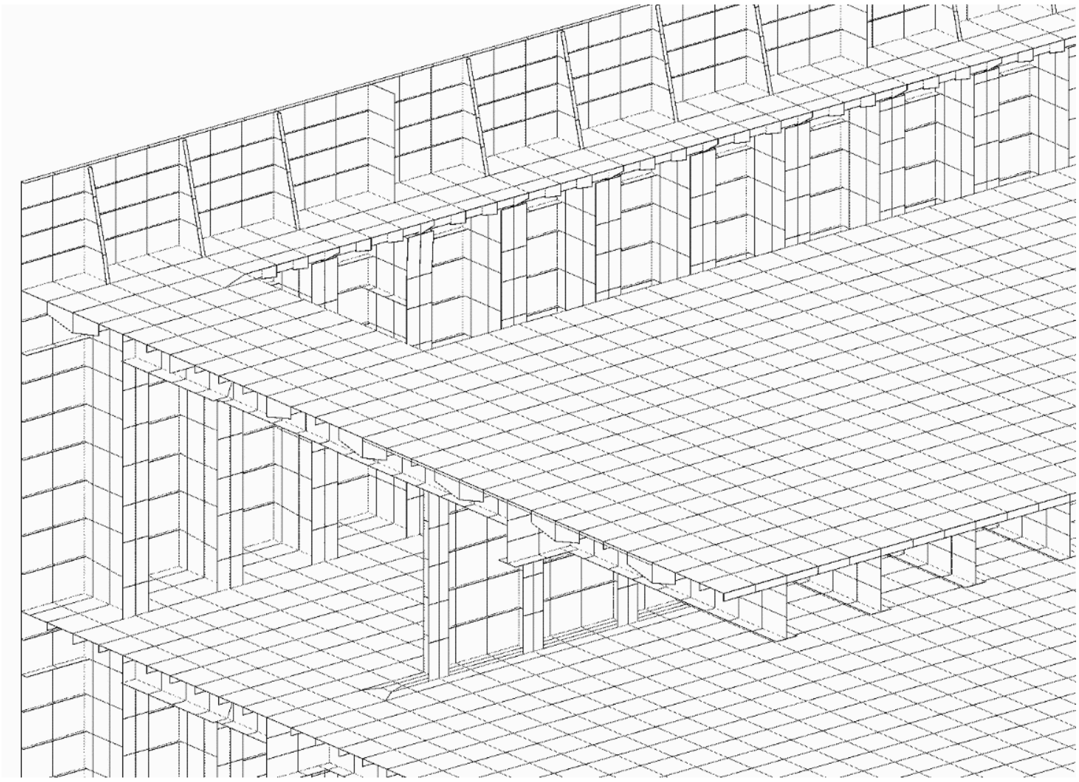
5.2 Finite elements in FE model of the whole ship hull

5.2.1 FE model for strength analysis for ship in heeled condition (racking)

5.2.1.1 It is recommended to apply the FE model of the whole ship hull with the use of plate finite elements for modelling plating (decks, sides, bulkheads, etc.) and frame webs. T-beam flanges may be modelled by the bar or beam finite elements. Plating stiffeners shall be modelled with the use of beam elements, taking into account eccentricity of stiffener cross-section centre of gravity in relation to the plating. General modelling principles (type, size and elongation of finite elements, method of considering openings/cutouts in primary supporting member webs, modelling brackets, etc.) shall be applied in accordance with paragraph 14.4.2 of the *Rules for the Classification and Construction of Sea-going Ships*, *Part II – Hull*.

Such finite element mesh will be further defined as ***a standard mesh***.

5.2.1.2 An example division into finite elements of a part of the ro-ro ship hull structure (standard finite element mesh) is shown in Fig. 5.2-1.



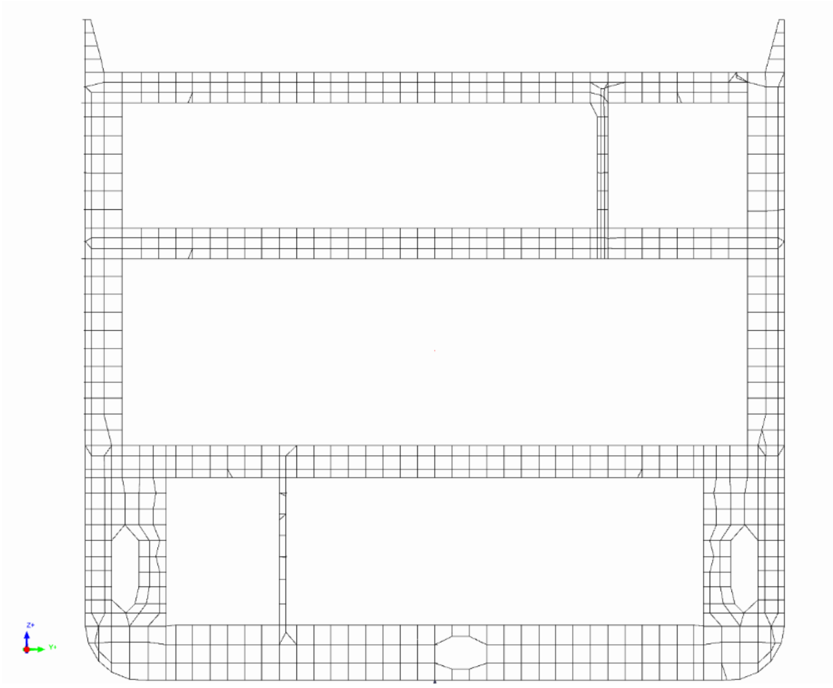


Fig. 5.2-1 Example of the standard mesh

5.2.1.3 Alternatively, the FE model of the ship hull may include areas modelled with the standard mesh (see 5.2.1.1) and those modelled with elements of bigger size (i.e. with the use of the so-called „coarse mesh").

The use of standard FE mesh (acc. to 5.2.1.1) is obligatory for the midship part (for the length not less than ship's breadth *B*), and the FE model shall take into account hatch openings in decks for transfer of vehicles between cargo decks.

Depending on the space arrangement of the ship, PRS may require the application of standard FE mesh also in other hull regions (e.g. at ship ends, where stern doors/ramps or watertight doors in collision bulkhead are installed).

In regions with coarse modelling, the requirements of 14.6.2.3 of the *Rules for the Classification and Construction of Sea-going Ships*, *Part II – Hull*, are to be applied.

The above means that the plating may be modelled by plate elements of edge length equal to web frame spacing in the longitudinal direction and transversely to longitudinal girders spacing, however not longer than 1.5 web frame spacing.

Plating stiffeners in this region may be concentrated (a few pieces at a time) and located along the edge of plate elements.

The girder webs may be modelled by one row of finite elements (along ~~with~~ the member depth) and their flanges – by bar or beam elements.

Small openings in the primary supporting member webs may be generally disregarded in the FE model. Passage openings may be taken into account by the use of equivalent thickness of the web.

Sufficient transition zones, divided into finite elements to allow for a smooth transition from standard to coarse mesh, shall be provided between the modelled region using standard mesh (according to 5.2.1.1.) and the regions with coarse mesh applied.

The above method of (example) hull division into finite elements is shown in Fig. 5.2-2. The figure shows only a part of the ship bottom and side.

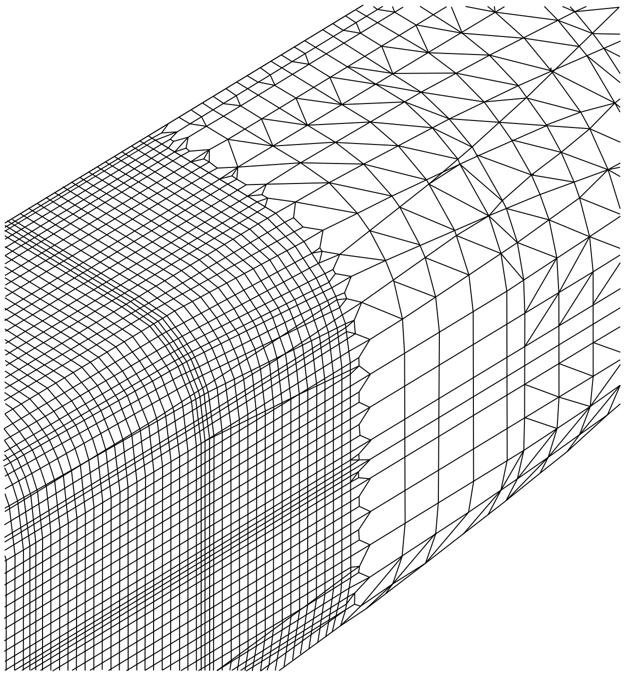


Fig. 5.2-2
Regions of hull sides and bottom modelled with the use of standard mesh and coarse mesh

Note: the level of stresses calculated with the use of FEM, in ship heeled condition (”racking”) is assessed in accordance with requirements of 5.4.1 only in the regions where standard FE mesh is applied in the FE model.

5.2.2 FE model for strength analysis of primary supporting members of decks, sides and pillars (upright ship)

5.2.2.1 The FE model with standard FE mesh (see 5.2.1.1) may be applied for the analysis of load cases required in Chapter 2, which formally concern framework and grillage FE models required for an upright ship (loading conditions SO1, SO3, SO5, SO6, SO7, SO8).

The FE model for the assessment of structural strength in regions indicated in Chapter 2 may be a part of the FE model of the whole hull.

Alternatively, a model may be applied of hull part situated between frame sections spaced on each side from the region where the stress level is assessed by a distance not less than the region length.

Loading of FE model shall comply with the requirements of 5.3.2, and the stress level shall be assessed to criteria defined in 5.4.2.

5.2.3 FE model for hull general strength analysis

5.2.3.1 FE model with standard FE mesh, as defined in 5.2.1.1, may be used for the general strength analysis of the ship, using loading defined in 5.3.3. The assessment of the level of calculated stresses is performed according to 5.4.3.

5.2.3.2 The analysis of general strength may use the FE model with a „coarse” mesh of finite elements, defined in 5.2.1.2.

The loading defined in 5.3.3 shall then be applied. The level of calculated stresses is assessed in accordance with 5.4.3.

5.2.3.3 In way of superstructure situated in the midship part, the FE model shall consider openings for doors and windows.

If many window openings are situated close to each other, fragments of superstructure walls between neighbouring windows shall be modelled with finite ~~fine~~ elements. In such a case, it is sufficient to use at least one row of finite elements between the windows, unless the spacing of windows edges is greater than the length of sides of plate elements required for standard FE mesh (see 5.2.1.1). In this case, vertical and horizontal stiffenings of walls shall be considered, with at least the use of beam elements with their neutral sectional axis displaced from the plating. In the FE model, the position of the stiffenings may be slightly changed to have them situated on the edges of plate elements~~,~~ that model wall plating.

In ~~the~~ way of steps (ends of side or internal walls) of the superstructure or deckhouse and in the region of expected greatest stresses at the edges of window openings, PRS may additionally require the application of locally more dense FE mesh of squares not larger than 50 x 50 mm, in order to reflect with sufficient accuracy the shape of opening corners (see the requirements for local FE models given in 14.7 of the *Rules for the Classification and Construction of Sea-going Ships, Part II – Hull*).

The level of stresses determined in regions where such more dense FE mesh has been applied shall be assessed according to the requirements of 5.4.3.2 or 5.4.3.3.

An example fragment of the FE model in the region of windows is shown in Figs. 5.2-1 and 5.2-2.

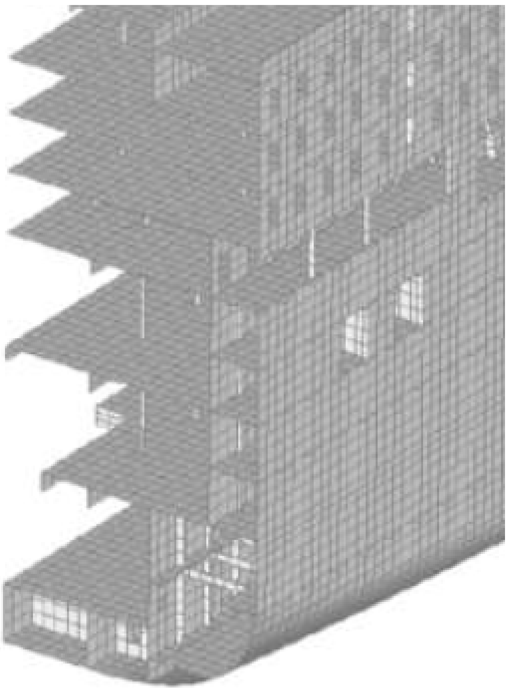


Fig.5.2-3
Example application of standard FE mesh in the region of openings for windows or doors

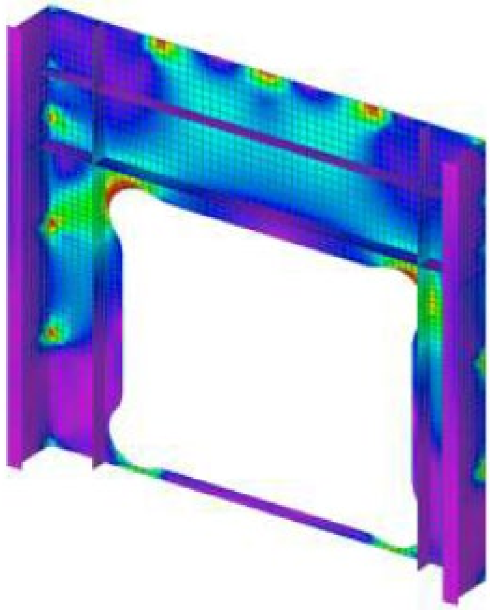


Fig. 5.2-4 An example of more dense FE mesh in the region of a window

5.3 Loads and supports

5.3.1 Strength analyses in the ship heeled condition („racking”)

5.3.1.1 For particular transverse sections, loads required for load conditions SO2 and SO4 (see Chapter 2) are to be assumed.

Maximum local load value (pressure of uniformly distributed cargo or load due to vehicles, cargo trays, etc.) shall be applied, according to ship design and *Loading Manual* of the ship.

If the load due to cargo on loaded decks or internal bottom, in SO2 or SO4 condition, distributed along the whole length of the ship cargo space, exceeds the value corresponding to the ship capacity, the non-loaded deck segments having an appropriate length and situated possibly symmetrically against the loaded midship region shall be located in regions of bow and stern.

5.3.1.2 The FE model of the whole ship hull shall be approximately balanced.

The model ~~shall~~ may be balanced through the application, to ship sides and bottom, continuous loads q_y, q_z and q_M (in [N/m]), which can compensate hull internal loads and external loads (water pressure) – see Fig. 5.3-1.

During development of the FE model, in order to determine the values of loads q_y, q_z and q_M , the hull shall be divided longitudinally into at least 20 segments of similar length, and the internal and external loads shall be applied so that they are sectionalized to successive segments.

Subsequently, the load within each segment shall be reduced, e.g. to a point at the ship bottom, in the centre plane, in the middle of segment length, to achieve forces P_y, P_z and torque M_x (Fig. 5.3-1).

Continuous load q_y evenly distributed along the segment length balances the force P_y, continuous loads q_z balance the force P_z and continuous loads q_M balance the torque M_x.

It is recommended to apply continuous loads q_z and q_M along the lines determined by points A_1 and A_2, i.e. in the middle of the side section between the internal bottom and the lowest deck (Fig. 5.3-1).

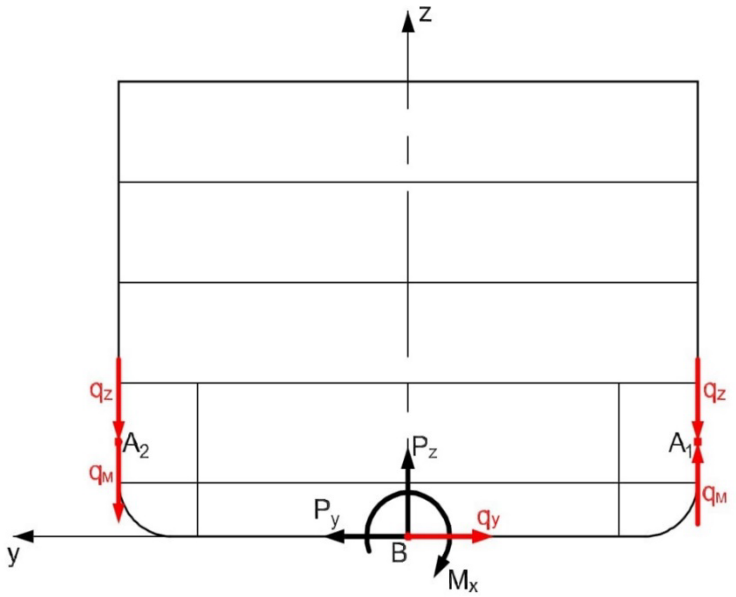


Fig. 5.3-1 Balance method for FE model of the whole ship hull

5.3.1.3 PRS may accept another method of FE model balancing, than the one presented in 5.3.1.2, upon the proposal of ship designers, if the method does not result in determining inaccurate values of hull structure stresses.

5.3.1.4 The model with a balanced load according to the requirements of 5.3.1.2 shall be properly supported. Possible option for non-displaced supports assumes zero values of displacements u_x , u_y or u_z in some nodes of the FE model in x, y, z directions of the ship coordinate system (Fig. 5.3-2).

Zero values of displacements:
$u_y = 0,\ u_z = 0$ – in point (node) A_1 (at the bottom, in aft region);
$u_x = 0,\ u_y = 0,\ u_z = 0$ – in point B (at the bottom, in the centre plane, in bow region);
$u_z = 0$ – in point A_2 (at the bottom, in aft region).

Points A_1 and A_2 are arranged symmetrically against the symmetry plane.

The rotation angles of nodes in the FE model in points A_1, A_2 and B are not to be restricted.

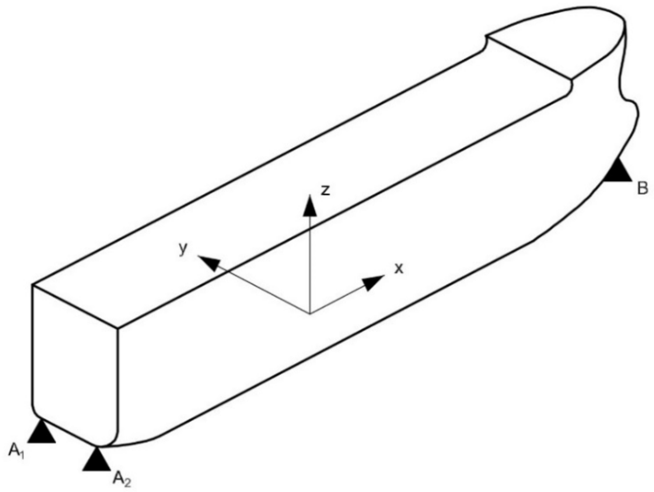


Fig. 5.3-2 Fixed supports in FE model of the whole ship hull

5.3.2 Strength analyses of primary supporting members of decks, sides and pillars (upright ship)

5.3.2.1 The FEM analysis shall consider loads defined in Chapter 2 (other than in load conditions S02 and SO4, covered by 5.3.1).

5.3.2.2 The ship hull region where the strength of the primary supporting member system is analyzed, shall be modelled with the use of standard FE mesh (see 5.2.1.1). Other hull regions may be modelled with the use of coarse FE mesh (see 5.2.1.2).

If the FE model includes coarse modelled regions, the stress analysis made in accordance with 5.4.2 covers fragments of a structure modelled with the standard mesh, spaced at least 0.5B (B – ship's breadth) from the segments with coarse modelling.

5.3.2.3 Alternatively, the FE model may be a hull segment being a part of full-length ship model (not less than required in Chapter 2 and not less than 2B, where B is the ship's breadth), which includes structure extending between the bottom and the uppermost deck.

The stress analysis made according to 5.4.2 covers the structure region situated at least 0.5B from the segment ends.

5.3.2.4 In stress calculations of the primary supporting member system (FE models), the effect of general bending on stress level in longitudinal girders may be disregarded, by the assumption that the ship sides at the internal bottom are supported in the vertical direction ($u_z = 0$ and displacements related to the other five degrees of freedom of nodes are not restricted – see displacement symbols referred to in 5.3.1.4).

Additionally, the support $u_y = 0$ shall be applied in two points at the ends of the hull model or hull segment model, in the symmetry plane, at the ship bottom. Displacements related to the other five degrees of freedom of the FEM nodes are not restricted, except the application of an additional support $u_x = 0$ at one of the above two nodes.

Normal stresses due to general bending may be determined with the use of the whole ship (beam model) or by general bending analysis made according to the requirements of 5.3.3, and subsequently added to the stresses calculated by FEM in accordance with this paragraph 5.3.2 (see also 14.5.3 and 15.1.1.2 of the *Rules for the Classification and Construction of Sea-going Ships, Part II – Hull*).

5.3.3 Hull general strength analysis

5.3.3.1 In the FE model defined in 5.2.3, the load shall be applied, which will approximately ensure along ship's hull the value of bending moment required in Chapter 15 of the *Rules for the Classification and Construction of Sea-going Ships, Part II – Hull*, used there to determine the required hull section modulus (combined still water bending moment M_s and wave bending moment M_w).

It is particularly important to achieve a possibly precise value of $M_s + M_w$ in the midship part of the hull.

In this case, local loads (the own weight of structure ~~weight~~, external pressures and cargo/stores loads) are not directly considered, however, appropriately chosen continuous load similar to the load q_z, used in accordance with 5.3.1.2, shall be applied along the ship sides.

In this case, the condition of zero value of total vertical ship load due to loads q_z shall by fulfilled.

The transverse (shear) force in the hull shall not cause excessive values of permissible shear stresses in shell plating, according to criteria defined in Chapter 15 of the *Rules for the Classification and Construction of Sea-going Ships, Part II – Hull.*

5.3.3.2 The ship hull shall be supported as defined in 5.3.1.4.

5.3.3.3 PRS may accept methods of loading and supporting the FE model proposed by hull designers, which are alternative to those defined in 5.3.3.1 and 5.3.3.2, provided the accuracy of calculated normal stresses due to general bending is found sufficient.

5.4 Stress analysis

5.4.1 Ship in heeled condition („racking")

5.4.1.1 For the regions of the FE model subjected to stress analysis, where standard FE mesh has been applied (see 5.2.1.1 and 5.3.1), the strength criteria defined in 14.5.3.1 of the *Rules for the Classification and Construction of Sea-going Ships*, *Part II – Hull* shall be fulfilled.

In this case, checking the level of normal stresses in longitudinal girders, including hull general bending stresses, according to 14.5.3.2 of the *Rules for the Classification and Construction of Sea-going Ships*, *Part II – Hull*, is not obligatory.

5.4.2 Strength analysis of the primary supporting members of decks, sides and pillars

5.4.2.1 The analysis covers the stress level in regions modelled with the use of standard FE mesh (see 5.2.1.1), according to 5.3.2.

For the stresses calculated without considering hull general bending stresses (see 5.3.2.4), the strength criteria defined in 14.5.3.1 of the *Rules for the Classification and Construction of Sea-going Ships*, *Part II – Hull* are obligatory.

For longitudinal girders, criteria for normal stresses considering hull general bending stresses defined in 14.5.3.2 of the *Rules for the Classification and Construction of Sea-going Ships*, *Part II – Hull* shall be additionally fulfilled. The calculation method of the stresses is defined in 5.3.2.4.

5.4.3 Hull general strength analysis

5.4.3.1 The analysis covers the level of normal stresses (along ship axes) in deck and bottom plating modelled for FEM analysis in accordance with the requirements of 5.2.3 and loaded in accordance with the requirements of 5.3.3.

The average normal (membrane) stresses in plate elements situated in areas corresponding to required sizes of plate elements of a coarse mesh (defined in 5.2.1.2) are not to exceed 175k, MPa (k – strength coefficient of used steel – see 2.2.1.2 of the *Rules for the Classification and Construction of Sea-going Ships*, *Part II – Hull*).

5.4.3.2 In the way of steps (ends) of sidewalls of superstructure or deckhouse and in way of doors and windows in those walls, where PRS may require the application of more dense FE mesh (see 5.2.3.3), the permissible level of membrane equivalent stresses in the centres of plate elements having dimensions not more than 50 mm x 50 mm and of main stresses at the edges of the opening, amounts to 310k, MPa – see 14.7.2.4 of the *Rules for the Classification and Construction of Sea-going Ships*, *Part II – Hull.*

5.4.3.3 If a more dense FE mesh is used for the fatigue strength assessment of structure in stress concentration areas referred to in 5.4.3.2, in accordance with the requirements of *PRS Publication 45/P – Fatigue Strength Analysis of Steel Hull Structure* (plate elements of side length approximately equal to the plate thickness), the assessment covers average stresses in the areas approximate size 50 mm x 50 mm (see 14.7.2.4 of the *Rules for the Classification and Construction of Sea-going Ships, Part II – Hull*).

List of amendments effective as of 1 April 2021

Item	*Title/Subject*	*Source*
5	Stress Analysis with FE Model of the Whole Ship Hull	PRS R&B