SUPPLEMENT No. 506

Metsaveer Jan: MV ESTONIA Accident Investigation. Calculation of Load-Carrying Capacity of the Bow Visor Locks.

Tallinn Technical University.

Tallinn 1996.

TALLINN TECHNICAL UNIVERSITY

MV ESTONIA ACCIDENT INVESTIGATION

CALCULATION OF LOAD-CARRYING CAPACITY OF THE BOW VISOR LOCKS

by

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Tallinn 1996

1. LOAD-CARRYING CAPACITY OF THE ATLANTIC LOCK

The Atlantic lock (bottom lock) consists of a locking bolt, guide bushing and support bushing. The lock was fixed to the vessel by three lugs. One lug attached to the visor was locked by the bolt (Figure 1).

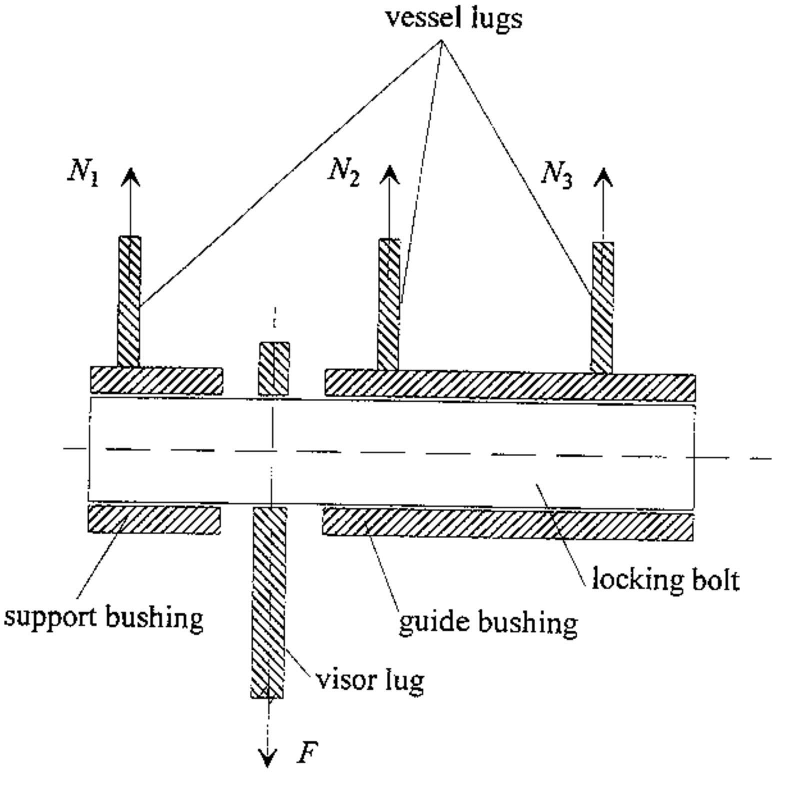

Figure 1.

On calculations we start with the following assumptions:

1. As the bottom lock was not manufactured in the vessel, but was mounted in finished shape, then we have reason to suppose that both bushings were sufficiently co-axial, i.e., well centered and all clearances with equal magnitude, and that all the three lugs which were fixed to the vessel started to carry loads simultaneously.

2. Damage observations showed that the locking bolt was not deformed significantly during the accident. Thus, we can consider the bolt as a rigid member, and only lugs as deformable.

3. Taking into account that the deformations of lugs can be quite large (20-25 mm), and that usually weld joints can not be deformed in such extent, we start from assumptions, that the limit value of one lug consists of the contributions of the weldings at ultimate strength and the contributions of the lug at yield stress.

A. Determination of the load-carrying capacity of one lug.

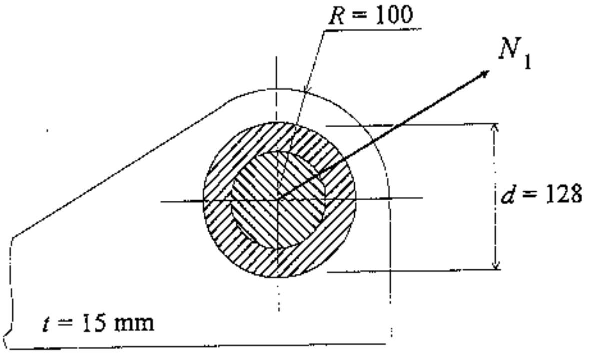

Figure 2.

Supposing that contribution of the lug N_1 is divided equally between the two halves of the lug (Figure 2), we get the contribution of the lug

$$N_{1l} = 2A\sigma_y$$

where σ_y is the yield stress, and A is the failure area of one half of the loop. With σ_y=243 MPa and $A = 15 \cdot 36 = 540$ mm² we have the contribution of the lug

$$N_{1l} = 0.26 \text{ MN}.$$

The contribution of the weldings between the bushing and lug consist of contributions of both side weldings in tension zone.

$$N_{1w} = 2\tau_u 0.7k\pi d/2$$

where τ_u=290 MPa is the ultimate shear strength of the weldments, k=3 mm is the side of weldings and d=128 mm is the diameter of the bushing. Therefore, the contribution of the weldings is

$$N_{1w} = 0.24 \text{ MN}$$

and the total value of the load-carrying capacity of one lug is

$$N_1 = 0.50 \text{ MN}$$

Investigations carried out in VTT show that the ultimate strength of the weldments were considerably higher than the ultimate strength of the plating. If we take that the ultimate strength of the weldments were two times higher than the ultimate strength of the plating, then we get

$$N_{1w} = 0.48 \text{ MN}$$

and the total value of the load-carrying capacity of one lug is

$$N_1 = 0.74 \text{ MN}$$

After the weldings are failed, the stress in lug grows up to the ultimate strength $\sigma_u = 417\text{MPa}$. The load-carrying capacity of one lug in this case is

$$N_1 = 2A\sigma_u = 0.45 \text{ MPa}.$$

B. Load carrying capacity of the assembly of lock.

Forces acting on each lug can be determined using a computation scheme (Figure 3), in which bars 1 - 3 represent deformable lugs and the rigid beam represents the locking bolt.

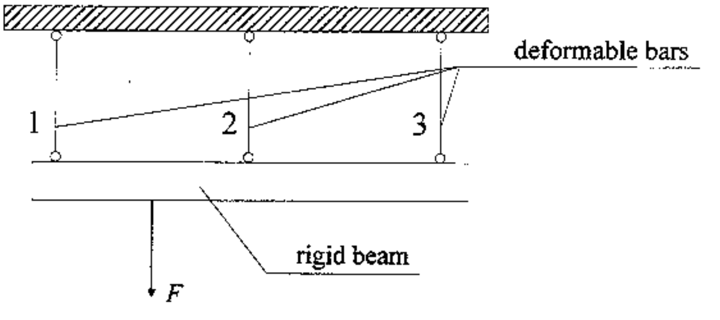

Figure 3.

By applying the force F, bars 1 - 3 will extend by quantities u_1, u_2, and u_3, and corresponding internal forces N_1, N_2, and N_3 will appear in these bars (Figure 4).

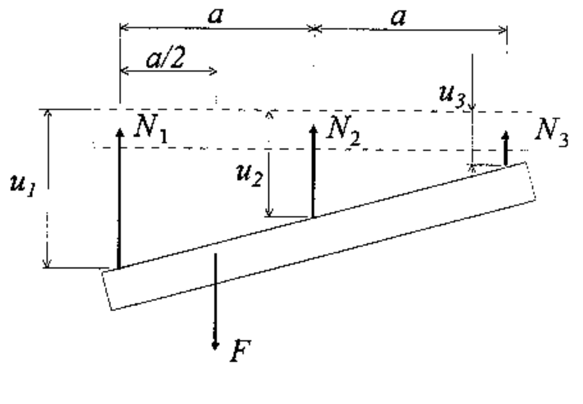

Figure 4.

Since the beam is rigid and the distance between forces N_1 and N_2 is equal to the distance between N_2 and N_3, then $u_1 - u_2 = u_2 - u_3$, and following this $N_1 - N_2 = N_2 - N_3$, or

$$N_1 - 2N_2 + N_3 = 0.$$

By adding here the equations of equilibrium,

$$N_1 + N_2 + N_3 = F,$$
$$N_2 a + N_3 2a - F\frac{a}{2} = 0,$$

we get a set of three equations, that has the following solution:

$$N_1 = \frac{7}{12}F, N_2 = \frac{4}{12}F, N_3 = \frac{1}{12}F.$$

Thus we get $F = 1.71N_1$.

However, if the visor lug is not on equal distance from vessel lugs, but is closer to the separate support bushing (lug 1), then the force N_1 is even greater. In the extreme case, when the visor lug is against the support bushing, then the force holding the visor is $F = 1.53N_1$.

That kind of force distribution is valid, when the system behaves linearly. With the increase of force F the limit will be reached, from which the displacement u_1 and force N_1 will not increase proportionally. In the limit case, if the $\varepsilon - \sigma$ diagram is horizontal, only the displacement u_1 increases and the force N_1 remains constant. If the horizontal part of the $\varepsilon - \sigma$ diagram is long enough and the force F is applied at equal distance from neighboring lugs, then the displacement u_1 increases until the force N_2 reaches its limit that equals to force N_1. At the same time force N_3 decreases continuously and approaches to zero when force N_2 approaches to force N_1. In that case the force distribution is as shown in Figure 5.

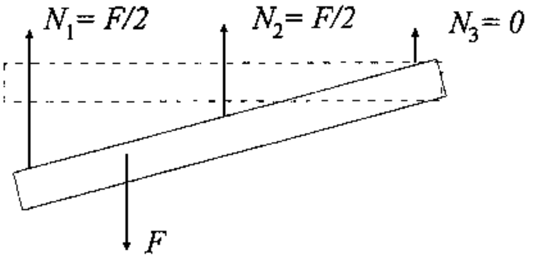

Figure 5.

It seems as the beam would have been turned over the application point of force N_3 $(u_3 = 0)$. If the visor lug is against the separate support bushing and the material of two fixing lugs is in plastic state, then $N_1 = 0.55F$ and $F = 1.83N_1$.

Thus, in case of actual $\varepsilon - \sigma$ diagram the most loaded lug is subjected to a force in the range of $N_1 = (0.65 \div 0.55)F$, and the force holding the visor is $F = (1.53 \div 1.83)N_1$.
Resulting from this in the case, if the ultimate strength of the weldments were equal to the ultimate strength of the plating, the load-carrying capacity of the atlantic lock is

F = 0.80 ... 0.90 MN.

and in the case, if the ultimate strength of the weldments were two times higher than the ultimate strength of the plating, is

F = 1.15 ... 1.35 MN.

and its moment about the axis of visor hinges *M*= *F* . *l*, where the arm *l*=6.25 m, are respectively

M =5.0 ... 5.6 MNm, or

M =7.2 ... 8.4 MNm.

2. LOAD-CARRYING CAPACITY OF THE SIDE LOCK

The side locks are similar to the atlantic lock, but they are loaded in different directions and therefore the failure took place in another way. The visor lugs of both side locks have been torn out of the aft bulkhead of the visor, leaving rectangular holes in the bulkhead. The design of the visor lug and the aft bulkhead of the visor are presented in figure 6. The lug is welded to the plating of the bulkhead, which is reinforced by one horizontal and two vertical stringers. The failure surfaces of the side locking are shown in figure 7. Dimensions of the rectangular hole in the bulkhead plating are approximately 390 x 80 mm.

The calculations are started with the following assumptions:

1. In the bulkhead plating between the lug and vertical stringers there were shear stresses oriented both perpendicularly to the plate (vertical stringers) and along it. Because of very high stiffness of the visor lug, the first ones are taken to be linearly distributed along the failure surface. Shear stresses oriented along the plate are not very big and they are taken to be constant.

2. Because of the low bending stiffness of the bulkhead plating, the primary failure took place in the horizontal stringer. The maximum shear stress in bulkhead plating is taken to be $\alpha\tau_u$, where τ_u is the ultimate shear stress of plating material and α is the variable parameter.

3. Because of the very high longitudinal and very low transverse stiffness of the horizontal stringer only the in-plane forces of stringers are taken into account.

The load-carrying capacity of the horizontal stringer is

$$F_h = \sigma_u^h A,$$

where σ_u^h is the ultimate tensile strength of the material of the horizontal stringer, $\sigma_u^h = 476$ MPa, and A is the cross section area of the broken part of horizontal stringer, $A = 10 \cdot 80 = 800\ \text{mm}^2$.

Thus we obtain

$$F_h = 0.38\ \text{MN}$$

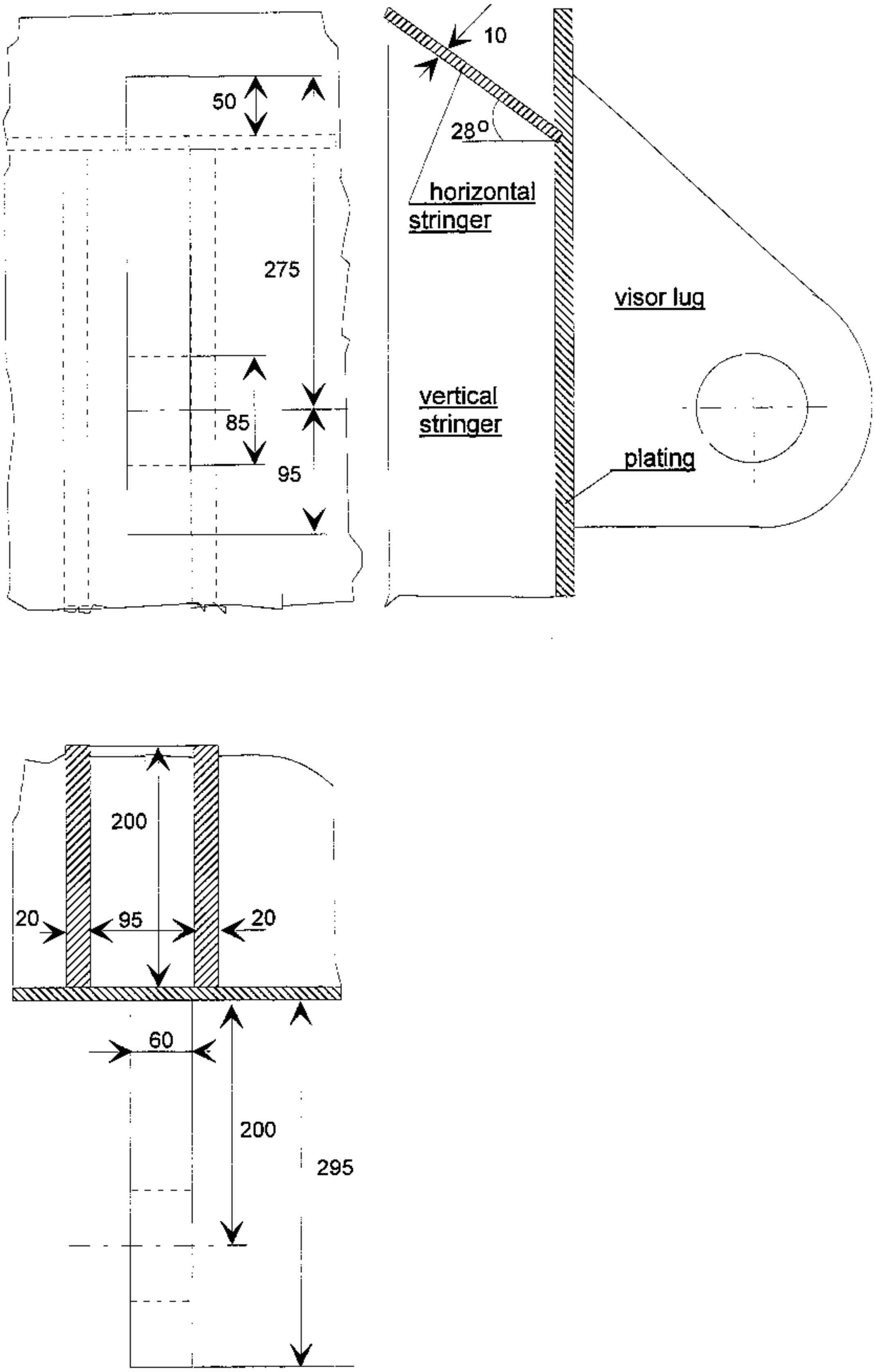

Figure 6. Design of the side locking

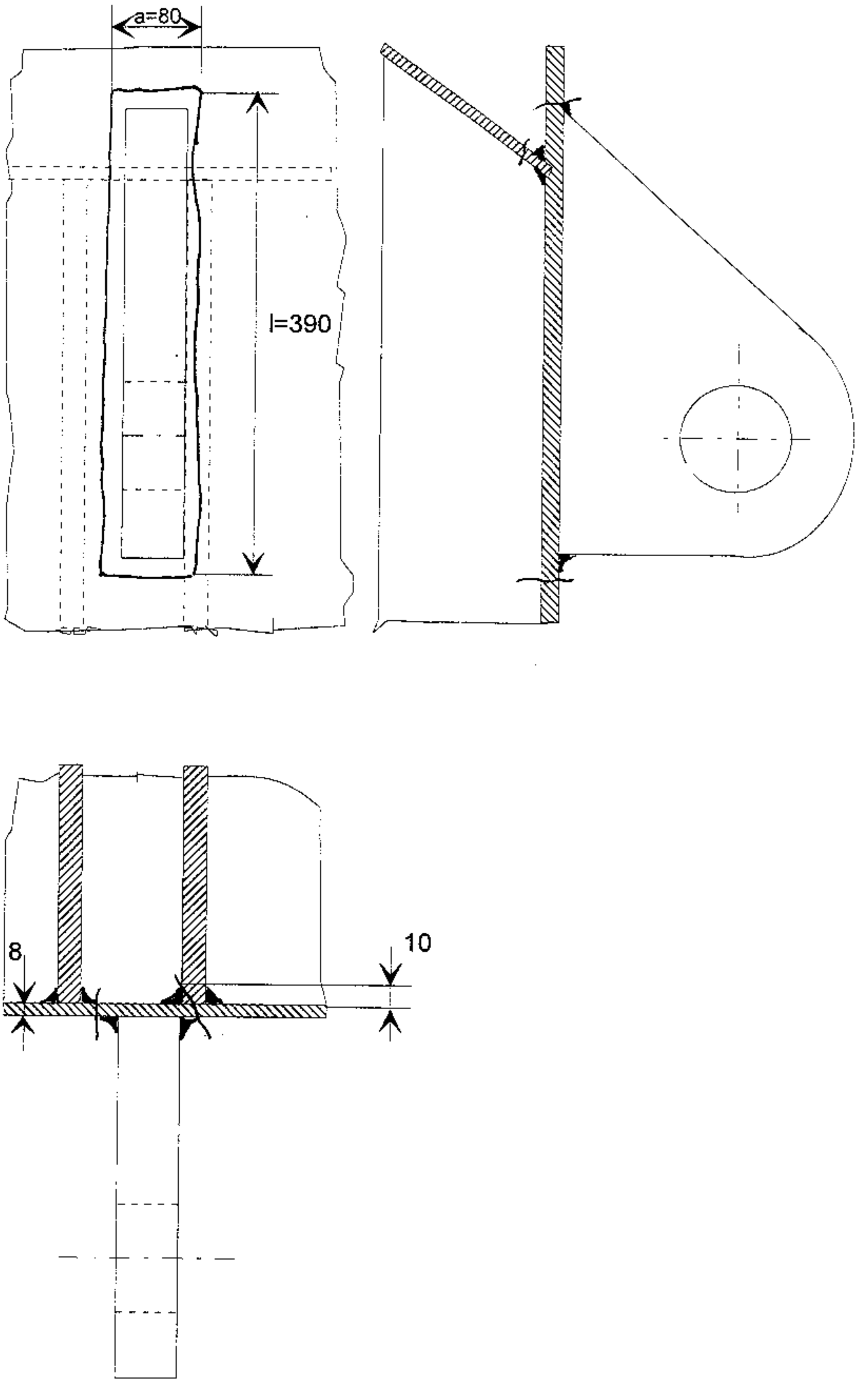

Figure 7. Failure surfaces of the side locking

The load-carrying capacity F of the side locking device can be determined from equilibrium equations of the lug, (see figure 8).

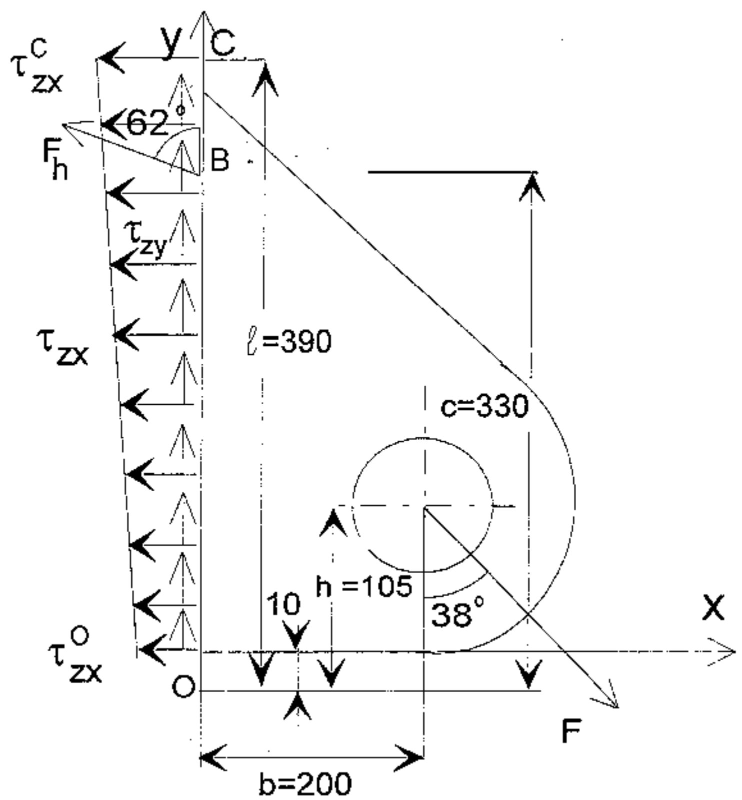

Figure 8.

$$\sum F_x = 0 \rightarrow F\sin 38^0 - F_h \sin 62^0 - \frac{1}{2}(\tau_{zx}^0 + \tau_{zx}^c)2\ell t_p - (\tau_{zx}^0 + \tau_{zx}^c)at_p - \frac{1}{2}(\tau_{zx}^0 + \tau_{zx}^B)ct_s = 0,$$

$$\sum F_y = 0 \rightarrow F_h \cos 62^0 - F\cos 38^0 + \tau_{zy}(2a + 2\ell)t_p + \tau_{zy}ct_s = 0,$$

$$\sum M_0 = 0 \rightarrow F_h \sin 62^0 c - F\sin 38^0 h - F\cos 38^0 b + 2\tau_{zx}^0 t_p \ell \frac{\ell}{2} + 2\frac{1}{2}(\tau_{zx}^C - \tau_{zx}^0)\ell t_p \frac{2\ell}{3} +$$

$$+\tau_{zx}^C a t_p \ell + \tau_{zx}^0 c t_s \frac{c}{2} + \frac{1}{2}(\tau_{zx}^B - \tau_{zx}^0)ct_s \frac{2c}{3} = 0 \ldots\ldots \tau_{zx}^B = \tau_{zx}^0 + \frac{\tau_{zx}^C - \tau_{zx}^0}{\ell}c$$

Here: τ_{zy} is a constant shear stress, $\tau_{zx}^0, \tau_{zx}^B, \tau_{zx}^C$ are values of linear shear stress in points 0, B and C respectively, dimensions ℓ, b, h are presented in Fig. 8, and further, t_p is the thickness of plating, $t_p = 8$ mm and t_s is the height of the broken part of the vertical stringer, $t_s = 10$ mm (Fig. 6), and a is the width of the rectangular failure hole in plating of the visor, a=80 mm (Fig. 7).

For getting the closed system of equations we use the strength condition in point C

$$\sqrt{(\tau_{zx}^c)^2 + (\tau_{xy})^2} = \alpha\tau_u,$$

For shipbuilding steels, the ultimate shear strength assumed to be approximately 0.6 times ultimate tensile strength,

$$\tau_u = 0.6\,\sigma_u^p\ ,$$

where σ_u^p is the tensile ultimate strength of plating steel, $\sigma_u^p = 454$ MPa.
Thus we obtain

$$\tau_u = 272\ \text{MPa}\ .$$

From presented system of equations we can determine the load carrying capacity of the side locking device F, as the function of the parameter α.

α	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
F MN	0.55	0.69	0.83	0.97	1.10	1.23	1.36	1.49	1.62	1.75

For evaluation of the value of the parameter α we proceed from assumption that the horizontal stringer fails then, when the stress in plating grows up to yield stress. Then the parameter α is about 0.7 and the load-carrying capacity of the side lock without damages is

F= 1.35....1.40 MN.

As the arm from the force F to the hinges axis equals a = 4.1 m, then the lifting moment is

M=Fa=5.5...5.7 MNm.

In these calculations we supposed that there were no cracks in structure and that the shear stresses are distributed linearly along the failure surface. By observations on the recovered bow visor we can not say with full certainty, whether the cracks in the structure existed or not. If there were cracks, then the load-carrying capacity of the side lock might have been considerably lower. As the side lock is statically undetermined complicate structure, it is difficult to say, which was the real distribution of the shear stresses and which was real value of the parameter α. The real distribution of the shear stresses before the failure may in fact have not been linear and the parameter α somewhat different. Consequently, the calculated load-carrying capacity is only the approximate value for this force. The real load carrying capacity of the side lock is probably lower.

For comparison we estimate also the load carrying capacity F of the weldments, assuming the side of the weldments k = 8 mm. For that we have three equilibrium equations of the lug in the form (see Fig. 9):

$$\sum F_x = 0 \rightarrow F\sin 38^0 - (\tau_{zx}^c + \tau_{zx}^0)0.7ka - (\tau_{zx}^c + \tau_{zx}^0)0.7kl = 0$$

$$\sum F_y = 0 \rightarrow 2\tau_{xy}(l + a)0.7k - F\cos 38^0 = 0$$

$$\sum M_0 = 0 \rightarrow \tau_{zx}^c 0.7kal + 2\left[\tau_{zx}^0 l^2/2 + (\tau_{zx}^c - \tau_{zx}^0)l^2/3\right]0.7k - F(b\cos 38^0 + h\sin 38^0) = 0.$$

The values of dimensions a, l, b, h are indicated on Fig. 9.

Adding the strength condition to failure in point C

$$\sqrt{(\tau_{zx}^c)^2 + (\tau_{zy})^2} = \tau_u.$$

we get the closed system of equations.

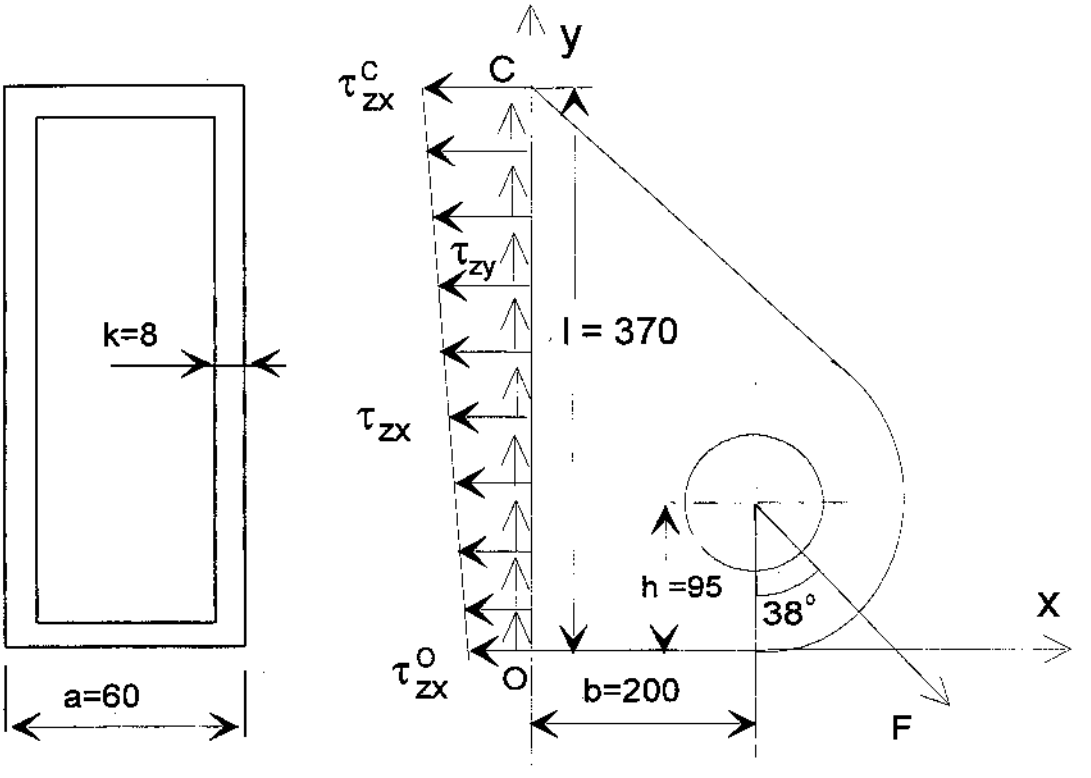

Figure 9.

Usually for weldments the value of the ultimate shear stress is assumed to be

$$\tau_u = (0.65...0.70)\sigma_u = (0.65...0.70) \cdot 454 = 295...318 \text{ MPa}$$

and the solution of the system of equations (for $\tau_u = 318\text{MPa}$) is:

F=0.741 MN; τ_{zx}^c =294 MPa; τ_{zx}^0 =-105 MPa; τ_{zy} =121 MPa.

Thus the load carrying capacity of the weldments of the side lock at k=8 mm is

F=0.7...0.75 MN.

The real ultimate strength of weldments may be considerably higher than the ultimate strength of plating. If the ultimate strength were two times higher, then the load carrying capacity of weldments would be 1.40 - 1.50 MN and if at the same time the side of weldments were a little bigger, then the load carrying capacity of weldments would be even higher. This may be the reason why the weldments really did not fail.

3. CALCULATION OF REACTIONS OF THE BOW VISOR LOCKING DEVICES.

A. Assumptions.

1. During the long life of the ship, the wear abolish differences of clearances in different locking devices and therefore all locking devices take the load simultaneously.

2. Reactions of the atlantic and side locks are directed parallel to ξ axes.

3. The displacement u between the visor and hull, caused by sea loads, are distributed linearly

$$u = u_0 + \varphi\eta - \gamma y$$

where the unknown quantities u_0, φ, γ are the displacement and the angles of rotation about axis y and η, respectively, and η, y are the coordinates (see figure 10).

4. All locking devices deform linearly, i.e.,

$$F_h = ku_h,\ \ F_a = k_a u_a,\ \ F_s = k_s u_s$$

where F_h, F_a, F_s are the reactions, u_h, u_a, u_s, the displacements and k, k_a, k_s the stiffness of the hinges, atlantic lock and side locks, respectively.

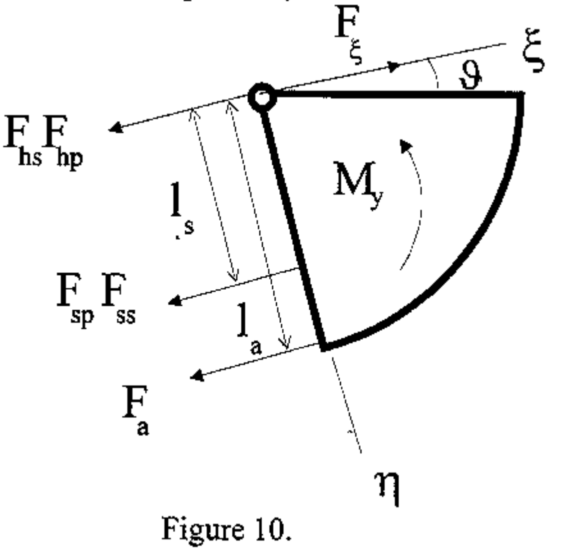

Figure 10.

B. Calculation formulae.

If we denote $\alpha = k_a / k$, $\beta = k_s / k$, then the displacements and reactions in hinges, side locks and atlantic lock will be the following:

a) in port side hinge:
$u_{hp} = u_0 + \gamma l; F_{hp} = ku_0 + k\gamma l;$

b) in starboard hinge:
$u_{hs} = u_0 - \gamma l; F_{hs} = ku_0 - k\gamma l;$

c)in port side lock:
$u_{sp} = u_0 + \gamma l + \varphi l_s;\ F_{sp} = \beta k u_0 + \beta k \gamma l + \beta k \varphi l_s;$

d) in starboard lock::
$u_{ss} = u_0 - \gamma l + \varphi l_s;\ F_{ss} = \beta k u_0 - \beta k \gamma l + \beta k \varphi l_s$

e) in atlantic lock:
$u_a = u_0 - \gamma y_a + \varphi l_a;\ F_a = \alpha k u_0 - \alpha k \gamma y_a + \alpha k \varphi l_a.$

Here 2l is the distance between the hinges and side locks, $l = 3.40$ m, the distances from hinge axis (y-axis) to atlantic and side locks are $l_a = 6.25\text{m}$, $l_s = 4.10\text{m}$, respectively, and the transverse distance to atlantic lock is y_a=0.4 m.
For finding three unknown parameters $ku_0, k\gamma, k\varphi$ we have three equations of the visor equilibrium :

$$F_{hp} + F_{hs} + F_{sp} + F_{ss} + F_a = F_\xi$$
$$F_{sp}l_s + F_{ss}l_s + F_a l_a = M_y^*.$$
$$F_{hp}l - F_{hs}l + F_{sp}l - F_{ss}l - F_a y_a = M_\eta$$

where,

$$F_\xi = F_x \cos\vartheta - (F_z + W)\sin\vartheta,$$
$$M_y^* = M_y - M_W$$
$$M_\eta = M_z \cos\vartheta + M_x \sin\vartheta$$

Here: $\vartheta = 15^0$ is the angle between axes x and ξ, quantities F_x, F_z, M_x, M_y, M_z are the sea load components and $W = 0.55\text{MN}, M_W = 2.0\text{MNm}$ are the weight of the visor and its moment about y axis.

From this equations we get:

$$(2 + 2\beta + \alpha)ku_0 + (2\beta l_s + \alpha l_a)k\varphi - (\alpha y_a)k\gamma = F_\xi,$$
$$(2\beta l_s + \alpha l_a)ku_0 + (2\beta l^2{}_s + \alpha l^2{}_a)k\varphi - (\alpha y_a l_a)k\gamma = M_y^*,$$
$$-(\alpha y_a)ku_0 - (\alpha l_a y_a)k\varphi + \left[2(1+\beta)l^2 + \alpha y_a^2\right]k\gamma = M_\eta.$$

If the port side lock is failed then the equations take a from:

$$F_{hp} + F_{hs} + F_{ss} + F_a = F_\xi$$
$$F_{ss}l_s + F_a l_a = M_y^*$$
$$F_{hp}l - F_{hs}l - F_{ss}l - F_a y_a = M_\eta.$$

Thus for determination unknown parameters $ku_0, k\gamma, k\varphi$ we have three equations:

$$(2 + \alpha + \beta)ku_0 + (\alpha l_a + \beta l_s)k\varphi - (\beta l + \alpha y_a)k\gamma = F_\xi$$
$$(\alpha l_a + \beta l_s)ku_0 + (\alpha l_a^2 + \beta l_s^2)k\varphi - (\beta l l_s + \alpha y_a l_a)k\gamma = M_y^*$$
$$-(\beta l + \alpha y_a)ku_0 - (\beta l l_s + \alpha y_a l_a)k\varphi + \left[(2+\beta)l^2 + \alpha y_a^2\right]k\gamma = M_\eta$$

C. The results.
The calculated reactions of atlantic and side locks F_a, F_{sp}, F_{ss} and full reactions of hinges R_{hp}, R_{hs}, which are directed forward and down, are presented in Figure 11 and 12 as function of stiffness ratio k_s / k_a for five different stiffness ratio values k / k_a in two different combinations of sea loads. The results are presented in two cases: a) if all locking devices are in order (above);

$F_x = -6.3MN, F_z = -6.3MN, M_x = 7.4MNm, M_y = 20.0MNm, M_z = 2.5MNm.$

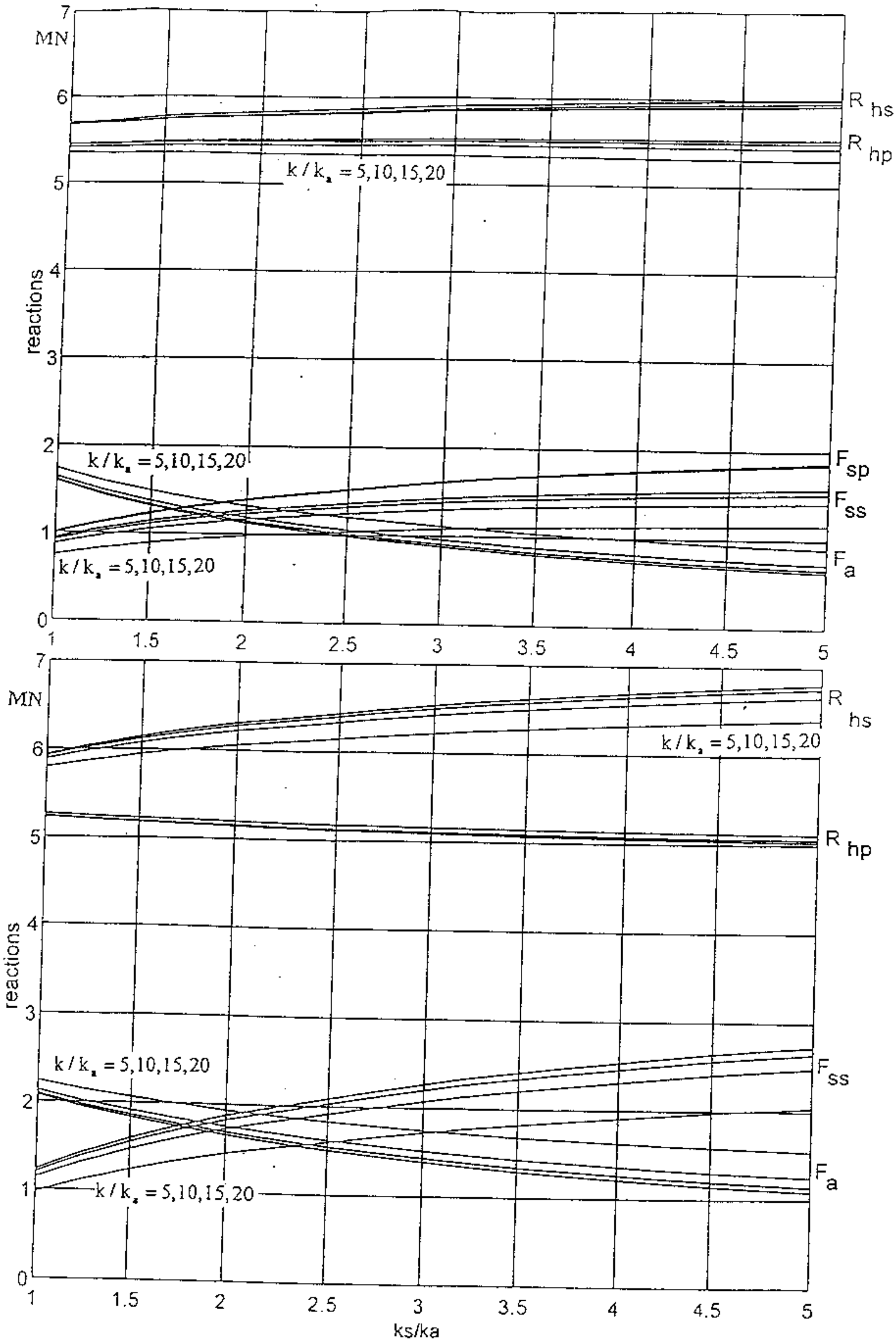

Figure 11.

$F_x = -5.4MN, F_z = -5.4MN, M_x = 5.0MNm, M_y = 15.5MNm, M_z = 2.0MNm.$

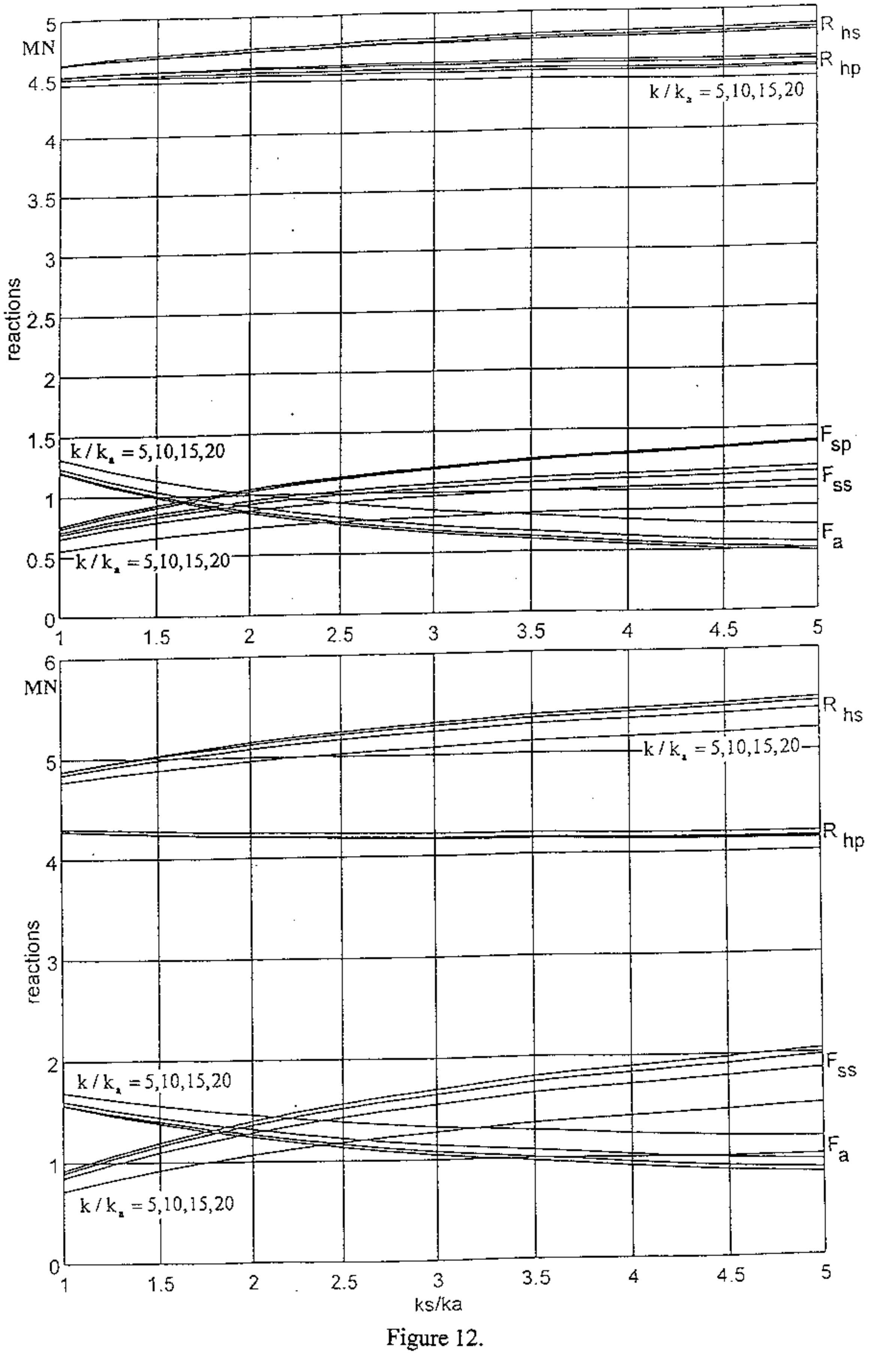

Figure 12.