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STRENGTH AND FAILURE ASSESSMENTS OF PARTS FROM MV ESTONIA

Fred Nilsson and Hans Öberg

1. BACKGROUND

An account is given in this report of studies performed at Kungliga Tekniska Högskolan at the Department of Solid Mechanics in order to determine the failure mechanisms and to estimate collapse loads of certain parts of the visor locking and pivoting devices.

a) Metallographic and fractographic investigation of different parts of the bow visor hinge and locking system. The parts examined were the three lugs of the bottom lock mounted on the hull, parts of the pivoting joint and parts of the side lock. In the following the three plates will be numbered 1, 2 and 3, respectively, where the number 1 designates the one located closest to the hydraulic actuator. The purpose of these investigations was to determine the failure mechanisms of the three plates. These investigations were performed at the Department of Materials Science and are reported separately in [1]-[2].

b) Tensile testing of material taken from plate 1 of the bottom lock mounted on the hull in order to determine the tensile properties of the material.

c) Estimate of failure load of the lock plates mounted on the hull.

d) Mechanical testing of material from the visor pivoting point.

e) Charpy impact testing of material from visor beam.

f) Estimate of collapse loads of the visor pivoting point.

A summary of the testing activities performed the Department of Solid Mechanics is given in Appendix A. In Appendix B an inventory of the parts presently stored at Kungliga Tekniska Högskolan is given.

2. FRACTOGRAPHIC INVESTIGATION OF BOTTOM LOCK PLATES

The findings of the metallographic and fractographic investigations are documented in separate reports [1]-[2]. The main result from examination of the material from the bottom lock plates is that

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the fractures surfaces exhibit a typical appearance of shear fracture due to an overload. Shallow cracks (1 mm) were detected along the weld between lugs and housings. The character of these cracks has not been determined. The same conclusions were arrived at for the material from the visor pivoting point. There is no basis for a conclusion that pre-existing defects at the hinges had a significant influence on the failure.

3. Tensile testing of bottom lock material

A tensile specimen (numbered 3037 in the internal test account of the department) was cut from plate 1 of *the bottom lock* (situated closest to the hydraulic actuator). The cross section was 14,0 mm x 30,3 mm, that is rather close to the broken ligaments that were roughly 15 mm x 35 mm. The specimen was loaded using the 500 kN MTS testing machine of the department.

The failure load was 177 kN which is proportional to a stress of 417 MPa which is then taken as the ultimate tensile strength σ_u. This value is in reasonable accordance with the expected behaviour of the material. A stress-displacement diagram is enclosed (Fig. 1). The displacement shown in the diagrams is the sum of the elongation of the specimen and of the fixtures and the testing rig. From Fig. 1 the yield stress can be estimated to 230 MPa.

The cross section after break was 9,3 mm x 22,5 mm. A 50 mm long gage length elongated to 68,3 mm during the test. This corresponds to an average strain of 36,6%.

Two standard tensile specimens with a circular cross section were also cut out from the lug and tested. The object of this part of the testing was to determine the yield and the ultimate strength of the material according to standard procedures. The two tests yielded virtually identical information and the stress versus strain behaviour is shown in Fig. 3. The yield strength was determined to 243 MPa and the ultimate tensile strength to 407 MPa. This is in reasonable accordance with the previously described testing on rectangular specimens.

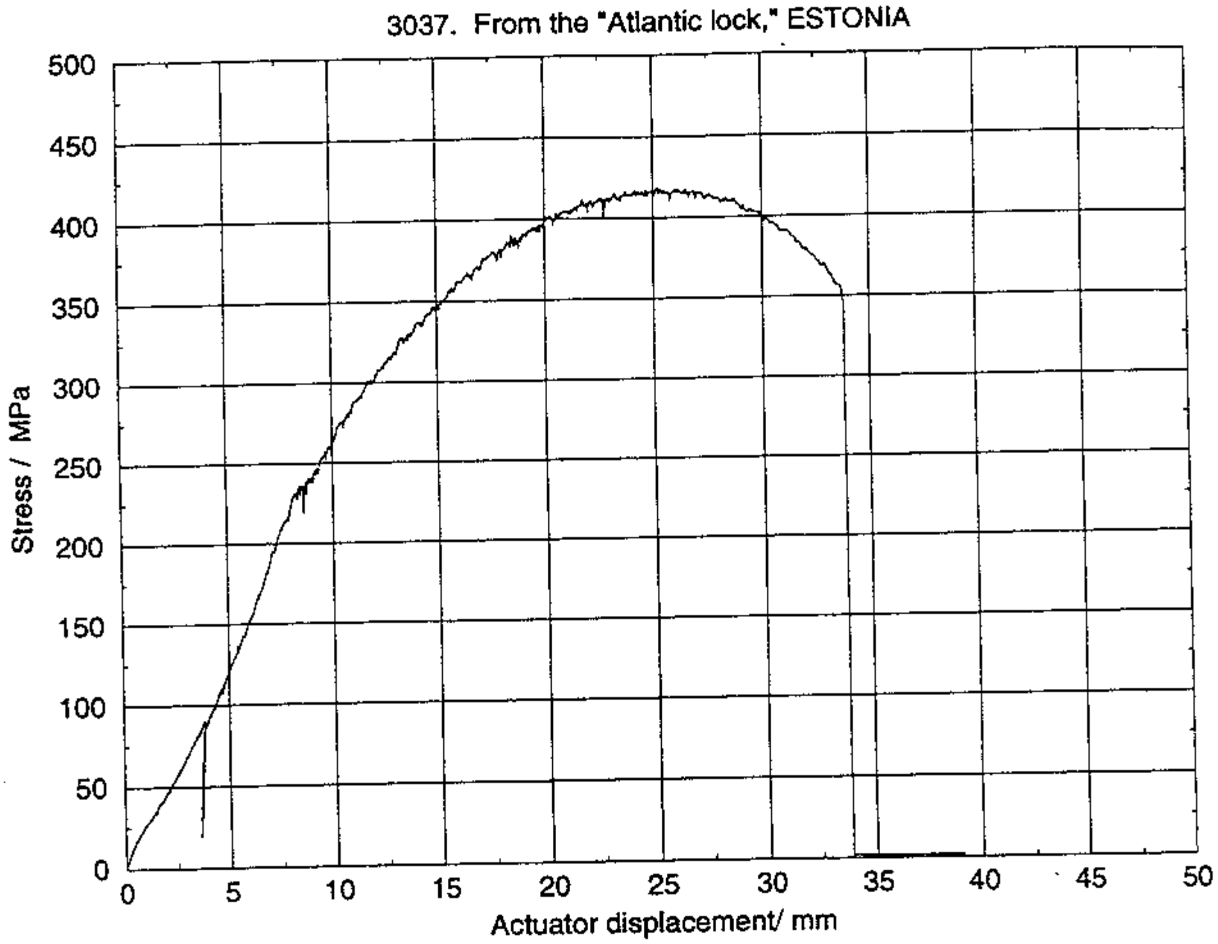


Fig. 1. Tensile testing of bottom lock material, rectangular specimen.

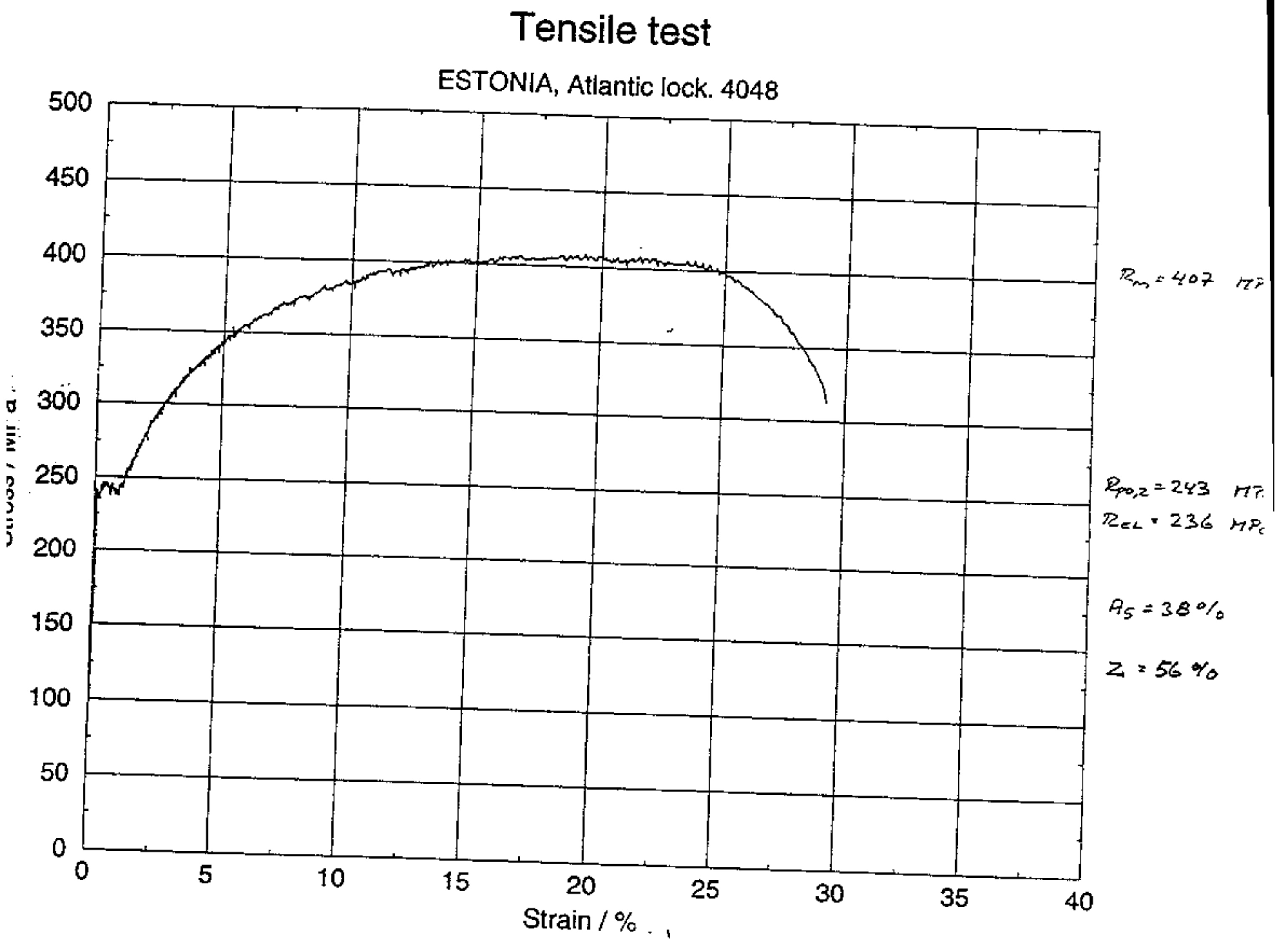


Fig. 2. Tensile testing of bottom lock material, standard cylindrical specimen.

4. Estimate of collapse loads of bottom lock plates

The collapse load for each plate is estimated in the following way. Each of the three plates exhibits two fracture surfaces having the overall appearance of tensile failure through a shearing mechanism similar to that of the performed tensile test. It is then simply assumed that at the point of failure the fracture surfaces resist by a purely normal load equal to the area of each fracture surface times the ultimate tensile strength σ_u. Possible in plane shearing forces will probably not be of any greater significance. Sketching the missing piece of a plate we then obtain the force geometry from Fig. 3.

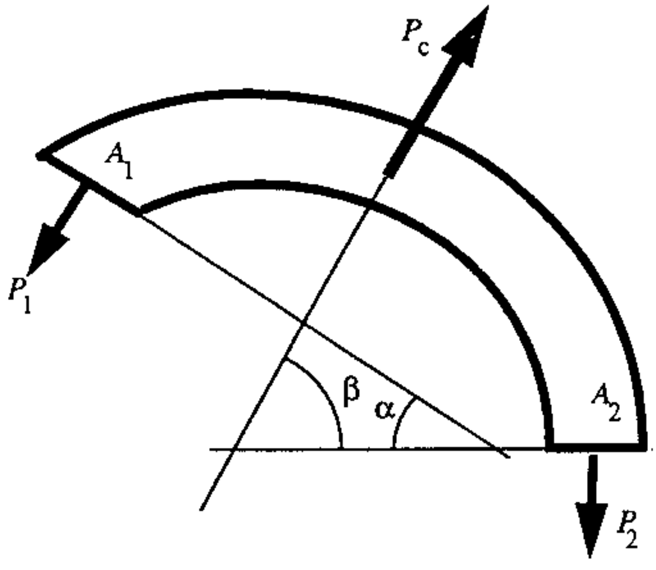


Fig. 3. Assumptions for calculation of the collapse load

The areas A_1 and A_2 and the angle α between the fracture surfaces are measured from the fractured parts. The loading angle β is assumed unknown and is determined by equilibrium considerations. Expressing equilibrium in the horizontal and vertical directions, respectively, we obtain

$$P_c \cos\beta = P_1 \sin\alpha \tag{1}$$

$$P_c \sin\beta = P_1 \cos\alpha + P_2 \tag{2}$$

With $P_1 = A_1\sigma_u$ and $P_2 = A_2\sigma_u$ we can solve for the critical load and the loading angle as

$$P_c = \sigma_u (A_1^2 + A_2^2 + 2A_1A_2\cos\alpha)^{1/2} \tag{3}$$

$$\beta = \arccos\left(\frac{A_1\sigma_u}{P_c}\sin\alpha\right) \tag{4}$$

The different measured quantities and the calculated results are given in Table 1. Two different values of the tensile strength have been used. The lower and more realistic one is formed by taking the average of the yield and the ultimate tensile strength, respectively, while the upper bound value in the table is obtained by using the ultimate tensile strength. In the last row the contribution from the different plates has been summed. The total load bearing capacity of the lock is not, however, necessarily equal to the sum of the limit loads in Table 1. This sum is rather an upper bound to the total capacity. The problem is statically indeterminate and if there is sufficient clearance for deformation, one of the plates may have failed before the others.

Table 1: Geometry data and estimated collapse loads

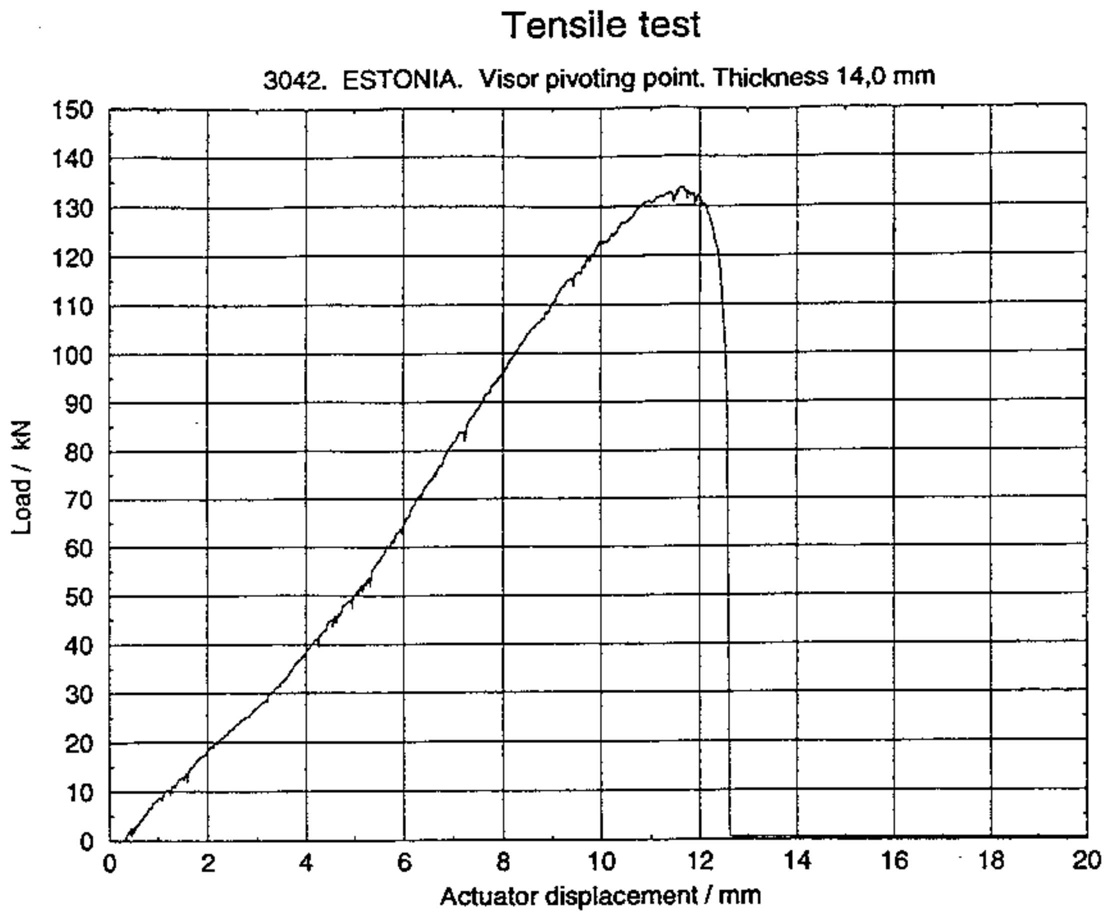
Plate	A_1/mm^2	A_2/mm^2	$\alpha/°$	$\beta/°$	P_c/tons	P_c/tons upper bound	Upper bound of collapse together with weld
1	525	525	28	76	33	43	79
2	980	495	82	33	38	49	85
3	480	1050	25	82	49	63	99
Sum					120	155	263

In these calculations no account has been taken of the welds between the plates and the bushing. The load bearing capacity of these welds is very uncertain. The visual impression is that the welds were of poor quality and unfortunately no direct measurement of their load bearing capacity is possible. An estimate was, however, made in the following way. Assuming that these welds had the same strength properties are corresponding parts tested from the visor pivoting point as described in section 4 below. The load bearing thickness of the welds at the bottom lock plates was on average 4 mm (measured along the fusion line) in comparison with the 12 mm thickness of the welds from the visor pivoting point. A simple proportioning then gives that the load bearing capacity of the bottom lock welds should be 4/12 of the load bearing capacity per unit length of the welds subjected to testing. Calculating the total force on an area projected from a semi circle gives a force of 36 tons per plate. This contribution has been added in the right-most column of Table 1. It should be kept in mind that this is a very uncertain figure in view of the uneven quality of the welds.

5. MECHANICAL TESTING OF MATERIAL FROM THE VISOR PIVOTING POINT

Two slices, numbered 3042 and 3043, were cut from the *visor pivoting point*. The thicknesses of the slices were 14,0 mm and 13,9 (3043). The welded joints were loaded using equipment mentioned above. The results are shown in two diagrams enclosed (Fig. 4).

Welding defects could be seen in the broken welds. In spite of that, the load carrying capacity of the welds was good compared to that of the net section.



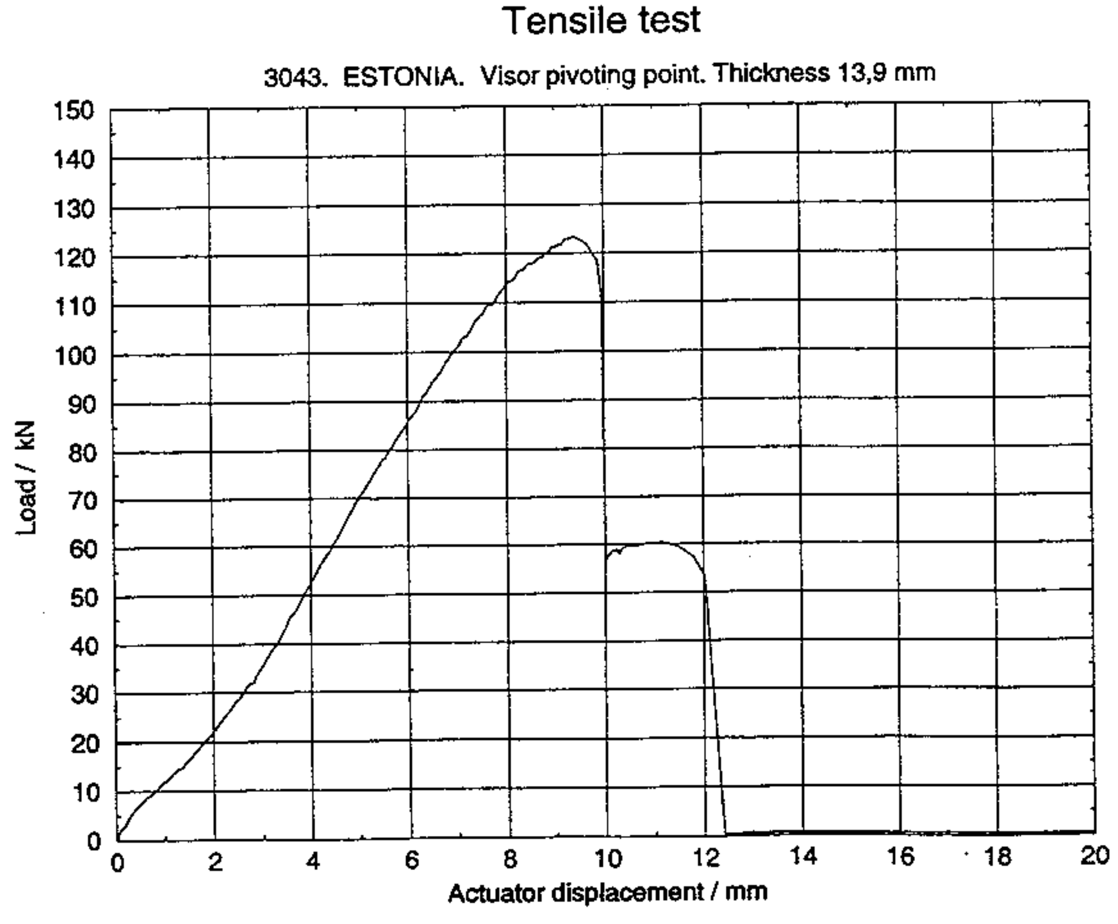


Fig. 4. Load vs displacement from testing of welds from visor pivoting point.

6. IMPACT TESTING OF VISOR BEAM MATERIAL

Impact testing using standard Charpy specimens machined from the visor beam was carried out in order to establish the toughness properties. The results from testing at different temperatures are shown in. The main conclusion is that the material possesses adequate toughness properties in the temperature interval considered.

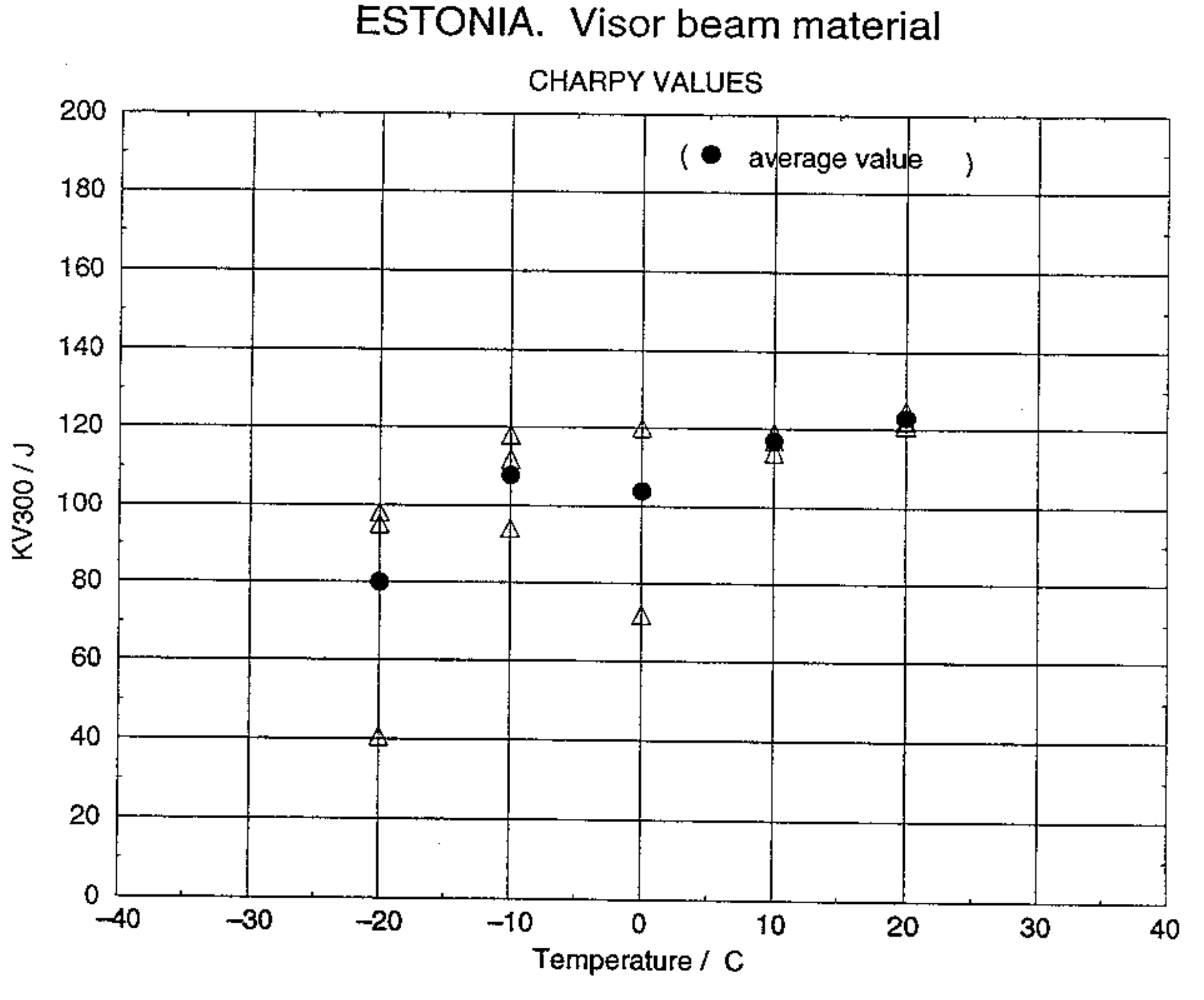


Fig. 5. Charpy impact toughness.

7. ESTIMATE OF COLLAPSE LOADS OF THE VISOR PIVOTING POINT

The same approach as for the bottom lock plates was used to calculate the collapse load of the visor pivoting point with the difference that the load bearing capacity of the welds this time was taken into account from the beginning. The experimental results from the testing described in sect. 5 were used for this assessment. The fracture modes of the four plates were so similar so that each plate is treated in the same way. This leads to a collapse load estimate 3 477 kN (the weld contribution is 2 143kN) which is 354 tons. In total the four plates are thus estimated to sustain at most 1 416 tons.

8. References

1. K. Pettersson, P.-O. Söderholm and N. Lange, "Metallographic and fractographic examinations of samples from mv Estonia", Department of Materials Science and Engineering, Division of Mechanical Metallurgy, Royal Institute of Technology, 1994-04-12.

2. K. Pettersson, and P.-O. Söderholm, "Notes from metallographic and fractographic examinations of samples from mv Estonia", Department of Materials Science and Engineering, Division of Mechanical Metallurgy, Royal Institute of Technology, 1996-02-27.

APPENDIX A. Testing performed at the Department of Solid Mechanics, KTH

95-01-11

Tensile tests, plate specimens 3037, material from the bottom lock.

Tensile tests, slices of the visor hinge and bushing, 3042 and 3043. The weld between the visor lug material and the bushing was loaded.

Charpy testing of the visor lug plate (4525), portside hinge, starboard lug plate.

95-03-30

Tensile testing of material from the bottom lock, specimen number 4048 and 4049.

95-10-05

Production of fracture surfaces in the visor material. Two specimens were made of the visor material cut out near the hinge. Specimen 4331 was fatigued and specimen 4332 was broken by a static load. The purpose was to produce fracture surfaces in the material in a controlled way to enable a comparison with the real fracture surfaces.

APPENDIX B. Inventory of parts

MS indicates storage at the Department of Materials Science

SM indicates storage at the Department of Solid Mechanics

Number indicates marking on detail.

Number	*Part*
4525	The visor. Portside hinge. SM.
4526	The visor. Starboard hinge. SM
4527	The visor. Part of a bushing, unknown which. SM
4528	The visor. A minor art of the bushing. SM
4529	The visor. A thin part of the bushing including welds and visor lug material. SM
4530	The visor. Stempost. Portside shell plate. SM
4532	The visor. Stempost. Starboard shell plate. SM.
4533	The visor. Stempost. Thick part, folded into the hull. SM.
4534	The visor. As 4533 but from a lower position. SM.
4535	Visor shell plate, starboard. SM
4536	Visor bottom deck plate, portside. SM
4537	Bottom bracket. SM
4538	Bottom of visor / lower part of visor shell plate. Starboard. SM
4539	
4540	
4541	The portside plate (1) of the bottom lock close to the actuator. SM.
4542	The middle plate (2) of the bottom lock. SM.
4543	The starboard plate (3) of the bottom lock including a part of a supporting plate. SM
4544	Side lock? SM.
4545	The visor. The brass bushing. SM:
4546	The visor. part of the bushing. SM.
4547	The visor. Part of the bushing cut from detail 4546. SM.
4548	Starboard visor hinge, portside lug plate. Detail from fold at upper side of the hole. MS.
4549	Starboard visor hinge, portside lug plate, upper fracture surface. MS.
4550	The visor. Bushing covering plate. SM.
4551	Starboard side lock. MS 3a1.
4552	Part cut from 4551. MS 3a2.

4553 Part cut from 4551. MS 3a3.

4554 Portside side lock. MS 3b1.

4555 Stempost. Detail cut out between 4533 and 4534, divided into 6 parts. MS.

4556 Starboard visor hinge, starboard lug plate, upper fracture surface. MS.

Details from Mare Balticum

Hinge. Brass bushing. KP.