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An Analysis of the Reasons of the Failure of the Locking Devices of MV Estonia.

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AN ANALYSIS OF THE REASONS OF THE FAILURE OF THE LOCKING DEVICES OF MV ESTONIA

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Every technical expert study of an accident has the following main objectives:

1. To certify whether the design and calculations of the device/mechanism were correct;

2. To certify whether the construction of the device/mechanism was in accordance with the technical conditions (specifications);

3. To certify whether the regular technical inspections of the device/mechanism had been correctly arranged and carried out;

4. To present recommendations for the prevention of similar accidents.

The Technical Experts Group of the Joint Accident Investigation Commission of M/V Estonia consisted of the following experts at the Meeting of the Commission which took place in Stockholm on February 27-28 in 1996:

Estonia:

August Ingerma	Expert
Jaan Metsaveer	Expert

Finland:

Tuomo Karppinen	Member of the Commission
Klaus Rahka	Expert

Sweden:

Börje Stenström	Member of the Commission
Mikael Huss	Expert

Two opinions concerning the matter of strength and failure of the locking devices of MV Estonia were formed at the meeting of the Technical Experts Group:

Opinion No. 1 (Supported by J. Metsaveer, T. Karppinen, K. Rahka, B. Stenström, M. Huss):

The strength of the locking devices of the bow visor is estimated on the basis of static loads. The failure took place as a result of 2 - 5 overload, so it was a static failure. The fact that the ship had been in operation for 14 years is overlooked.

Opinion No. 2 (Supported by A. Ingerma, V. Strizhak):

The strength of the locking devices of the bow visor is estimated on the basis of alternating cyclic load. The failure took place as a result of cyclic load, i.e. it was a fatigue failure [1], hereby we also present the strength calculations of the side lock.

Arguments contradicting the concept of static failure:

1. The theoretical technical calculations [3, 4] and model simulations [5] and the measurements of the pressure of sea forces on the bow visor [6] contribute to the statement that there exists alternating cyclic load from sea forces to the bow visor. The greatest forces had the following range:

Horizontal force:	FX = 7.7 MN (770 Tons).
Side force:	FY = 2.7 MN (270 Tons).
Vertical force:	FZ = 7.7 MN (770 Tons).

The opening moment of the bow visor relative to the hinges was YM = 35.4 MNm.
During the 3 hours of experimentation conditions under which the opening moment induced by the sea load was sufficient to exceed the closing moment created by the gravity of the bow visor were observed approximately 50 times. This was at a significant wave height of 4.3 m and at the speed of 14.5 knots.

Conclusion:

THE LOCKING DEVICES WERE OPERATING AT AN ALTERNATING LOAD.

2. The failure of the locking devices and their components on MV DIANA II, the sister ship of MV ESTONIA on Jan. 16th, 1993. This failure is a classical example of fatigue failure, where the breaking originated from the weakest locking device -- the welds of the side locking devices.

Conclusion:

THE FAILURE OF THE LOCKING DEVICES WAS A FATIGUE FAILURE.

3. On the 3rd of January, 1994, an inspection of the locking devices on MV DIANA II was carried out [7].

During the inspection the following clearances were measured between the lockbolt and the eye:

'The Atlantic lock' -- 35 mm, aft direction;
stb side lock -- 20 mm, fwd direction;
portside side lock -- 40 mm, aft direction.

Such increases in clearances occur during operation only due to alternating loads.

Furthermore, the differences in the amounts and directions of the wear indicate that:

3.1. The distribution of load on the locking devices is not uniform. The distribution of the load cannot be determined as the entire locking installation is not statically determined.

3.2. Some of the welds of the locking devices are subject to pressure and some to traction as the expansion of the eye in the aft direction indicates the direction of the opening of the bow visor and the expansion in the forward direction indicates the closing direction of the bow visor.

Conclusion:

THE FORCES ACTING ON THE LOCKING DEVICES ARE OF INDETERMINATE VALUE AND DIRECTION I. E. A STATICALLY UNDETERMINED SYSTEM. INITIAL DAMAGE SUCH AS THE FORMATION OF A FATIGUE MICROCRACK AND ITS FURTHER DEVELOPMENT INTO A MACROCRACK IS POSSIBLE, WHEN THE SEALOAD IS DIRECTED TO CLOSE OR OPEN THE BOW VISOR, INDEPENDENT OF THE DIRECTION OF THE FORCE.

4. The edges of the lug of the Atlantic lock of the bow visor has clear traces of hammering (ledges caused by hammering) on both sides (3.7 and 4.3 mm) in fwd direction. Hammered ledges can only be caused by a great number of impacts between the bolt and the lug.

The expansion of the eye in the forward direction as much as 5 mm [8] and the existence of hammered ears indicates the existence of a numerous cyclic load in the closing direction of the bow visor. Cracks were discovered in the weld joint between the hinge beams of the bow visor and the support bushing.

In the expert opinion [11] the calculated failure load of the bow visor (given the failure stress $\sigma_u = 400$ N/mm^2) was 95 tons. It is also pointed out that the appearance of the fracture surfaces suggests that some welding repairs have been carried out and that the plate material of the lug of the side lock has a tendency of delamination due to the fabrication process. It is also pointed out in [11] that the actual load carrying capacity of the side locking device was therefore significantly less than the calculated value of the failure load of 95 tons.

The divers estimated the clearance between the lockbolt and the eye to be 10 mm [17].

Conclusion:

THE INCREASE OF THE CLEARANCES AND THE FORMATION HAMMERED LEDGES IS POSSIBLE ONLY IF THERE EXIST CYCLICAL IMPACT LOADS. THE SIDE LOCK HAS BEEN PREVIOUSLY REPAIRED BY WELDING AND THUS IT IS NOT POSSIBLE TO RULE OUT THE PRIOR EXISTENCE OF FATIGUE CRACKS.

5. The analogous failures of locking devices on RO-RO passenger ferries operating on the Baltic Sea indicate the existence of alternating cyclical loads and clearances between the lockbolts and the eyes. The clearances increase during operation accompanied by an increase in the lack of uniformity in the distribution of the load, causing the failure of the lock. The incomplete lists include 8 marine accidents involving Finnish and Swedish RO-RO ships (mainly passenger ferries) during the years 1973-1993 that were due to damage to the locking devices of their bow visors. Four accidents occurred within the year of the construction. The conclusion to be drawn from this is that the locking system with clearances used in Scandinavia (one bottom lock/Atlantic lock and two sidelocks) is too small and poorly designed due to the clearances, sooner or later resulting in damage or maritime accident.

Yet it has been pointed out that on 30% of the ships inspected the bow visor locking devices have cracks or deformations. We know that a crack is a tension concentrator with the factor 3÷50. This means that the further development of the crack (which is the load-carrying capacity of the detail) shall progress with force that is 3÷50 smaller. This proves once more that the attachment devices are operating under alternating loads and that the calculations should be made on fatigue strength. In the former Soviet Union (from 1975 onwards) the RO-RO type ships had a locking system without clearances - a forced locking system consisting of a screw and a nut - and the total number of locks was fourteen, of those ten bottom locks and four side locks. There is no information concerning damages to the locking devices. Estonian Shipping Company has four ships of this kind and they have all been in operation for 20 - 22 years.

Conclusion:

THE LOCKING DEVICE SHOULD BE A FORCED LOCKING SYSTEM WITHOUT CLEARANCES.

6. Neither the shipyard nor the Bureau Veritas have presented the strength calculations during design. Therefore the quality of the design can not be verified.

Conclusion:

EITHER THE STRENGTH CALCULATIONS WERE OMITTED OR, THE GENERAL LOW QUALITY OF CALCULATIONS MADE IT IMPOSSIBLE TO PRESENT THEM.

7. During the construction two vertical stiffeners were welded to the (back of the plating) of the lug of the side lock. Calculations are omitted.

The welding of such vertical stiffeners into the back plating of the eye of the side lock does not increase the load carrying capacity of the side lock neither practically nor theoretically, as the flow of force through the eye of the side lock and the plating of the eye goes through the weld joint. Thus the weld joint remains the weakest point of the flow of force.

The strength of a fillet weld joint is determined by the thickness of the thinner detail (t) determining the leg of the weld joint k (k = t). The thickness of the plating is the thinner part of the weld joint t = 8 mm. This is also the basis for strength calculations.

It can not be determined and is also irrelevant whether the failure takes place in the weld joint or in the plating metal.

Conclusion:

THE INSPECTOR EVALUATED THE WEAKNESS OF THE SIDE LOCK ACCORDING TO HIS OWN EXPERIENCE AND THE REINFORCEMENT WAS CARRIED OUT ESTIMATING BY EYE.

8. In expert studies [9, 10, 11, 12, 16] where the basis for evaluation is failure under static stress, the methods of classical strength calculation have been used. Thus the ultimate stress (σ_u) of materials was used as basis for calculations. Furthermore, the strength of weld joints as the weakest parts of a structure is calculated using the failure stress of the base material. The concentration factor K = 2.5...4.5 present in weld joints and the calculable failure cross-section (0.7 of the length of fillet leg) are not taken into account. Weld joints must be calculated at shear stress $\tau = 0.6\sigma$. The coefficient of safety for locking devices is not taken into account. The generally recognized foundations for engineering calculations are missing. The purpose of such calculations remains unclear. They should be included in the final report so that they can be applied and verified by everyone.

The expert studies [9, 16] is incomprehensible from an engineer's viewpoint.
The expert study [10] contains calculational errors.
The calculations in the expert study [11], where the remaining strength of the welds, with a prior crack, of the base of the attachment area of the hydraulic actuators, the concentration factor caused by the crack has not been taken into consideration.
Model simulations (mock-up) [12] of the side locks have been performed. The simulations were based on static traction and the obtained failure load is 870...2140 kN (87...214 tons). The strength calculations were not presented and can therefore not be evaluated.
These simulations result in comparative data on laboratory models. The results can not be transposed to reality as the mechanisms of static and fatigue failure are completely distinct and not comparable. It must also be taken into

consideration that the MV ESTONIA was in operation for 14 years before the shipwreck.

Conclusion:

THE THEORETICAL CALCULATIONS BASED ON THE SCIENCE OF THE STRENGTH OF MATERIALS DO NOT PROVIDE A BASIS FOR EVALUATING THE STRENGTH OF REAL LOCKING DEVICES.

9. The calculations of forces affecting the bow visor [3, 4] and experiments [5, 6] confirm their cyclical nature, causing the fatigue failure of the details of the locking devices.
The failure has the following phases:
I — the formation of a fatigue microcrack, the existence of which is not always possible to determine after the failure;
II — as the microcrack has a large concentration factor of K = 3...50 [13], further development of the crack will take place under lesser tensions/compressions;
III — final failure.

Weld joints are especially sensitive to alternating cyclical loads. In general practice the permitted shear stress of weld joints subject to cyclical alternating stress is τ = 50...90 N/mm^2 [14, 15]. Using the above values, we get the calculable [1] load bearing capacity of the side lock as the weakest locking device F = 88...159 MN (8.8...15.9 tons).

Conclusion:

THE SIDE LOCKS ARE UNDERSIZED (THE CALCULABLE FORCE BEING 100 TONS) BY A FACTOR OF 100/8.8...100/15.9 = 11.4...6.3.

10. As all of the above will give rise to a discussion with the proponents of static failure, it would be prudent to render a written critical evaluation on each of the points presented above.

Conclusion:

PLEASE SUBMIT A MOTIVATED EVALUATION IN WRITING.

11. FINAL CONCLUSIONS

Answers to the basic problems of the expert study.

1. Was the construction of the device/mechanism in accordance with the technical conditions (specifications).

As the locking system of the bow visor is a statically undetermined system, the distribution of forces on the locking devices is of indeterminate direction and magnitude.
The locking devices of the bow visor are subject to alternating cyclical load, thus the strength calculations should be made (to fatigue).
Strength calculations are absent from the design. The designed locking devices have clearances, the side locks are undersized.

Conclusion:

THE QUALITY OF THE DESIGN IS LOW, FAILURES ARE INEVITABLE.

2. Does the device/mechanism comply to technical specifications.

There is no data on weld joints. Actual dimensions are not in accordance with the drawings [2, p 23]. The gaps in the beams of the hinges were cut by welding.

Conclusion:

DURING CONSTRUCTION DRAWINGS WERE NOT ADHERED TO AND INEXACT TECHNOLOGY WAS USED.

3. Was the technical inspection correctly arranged and carried out.

There were no criteria or norms for the normal operation of the locking devices. The clearances in the locking devices on DIANA II were not paid attention to after Jan 16th, 1993 and after the incident with DIANA II the inspections were not extended to other vessels' locking devices. There was no information on analogous damages to other ships (7 incidents) on the Baltic Sea.

Conclusion:

THE IMPLEMENTATION OF TECHNICAL INSPECTIONS WAS INADEQUATE AND INCOMPETENT.

4. Recommendations for the prevention of similar accidents.

The use of locking devices without clearances, such as screw-mechanisms is recommended.

It is recommended to set forth criteria and norms for the normal operation of locking devices and to inform the IMO and the IACS of the failures of the locking devices and to carry out an analysis of the reasons of all the failures.

Tallinn, March 13th, 1996

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