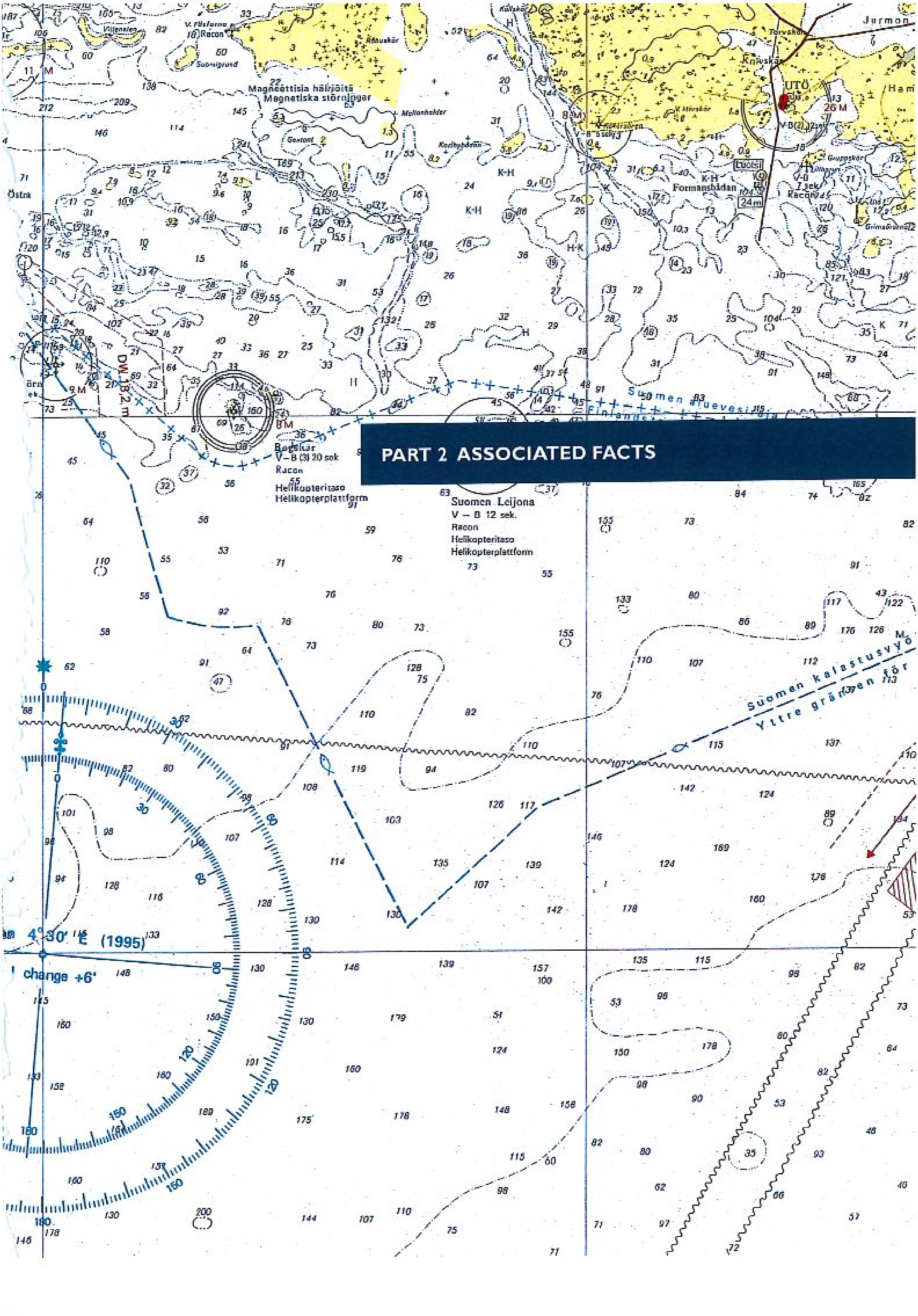
PART 2 ASSOCIATED FACTS



CHAPTER 9

INTERNATIONAL CONVENTIONS, LEGISLATION, REGULATIONS AND CO-OPERATION

9.1 International co-operation and conventions

Shipping is an international activity and co-operation to enhance safety and uniformity has long been in progress. Extensive international co-operation evolved, however, only after the United Nations' decision to create an Inter-Governmental Maritime Consultative Organisation (IMCO). The first working meeting of the Organisation was held in 1959.

The authority of the Organisation was expanded in 1982 and its name was changed to the International Maritime Organisation (IMO). IMO has its permanent administrative office in London and consisted in September 1994 of 149 Member States.

Heading the IMO is its Assembly, which meets once every second year. A Council normally meets twice each year. The Council acts as the IMO's governing body and consists of 32 elected Member States. The IMO is a technical organisation and most of its work is carried out in a number of committees and sub-committees. The structure of the Organisation is subject to changes as new demands arise.

The Organisation's two most important technical bodies are the Maritime Safety Committee (MSC) and the Marine Environment Protection Committee (MEPC).

The MSC, which is responsible for all safety matters except marine pollution, has the following sub-committees with specific areas of expertise:

- Ship Design and Equipment
- Stability and Load Lines and Fishing Vessels' Safety
- Fire Protection
- Safety of Navigation
- Bulk Liquid and Gases
- Dangerous Goods, Solid Cargoes and Containers
- Standards of Training and Watchkeeping
- Flag State Implementation
- Radio Communications and Search and Rescue

The work of the MSC is generally identified by its goal of fostering and enhancing several international conventions related to maritime safety. The result is reflected, inter alia, in the International Convention for the Safety of Life at Sea (SOLAS), the International Convention on Load Lines (ILLC), the International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW), the Convention on the International Regulations for Preventing Collisions at Sea (COLREG) and the International Convention on Tonnage Measurement of Ships.

Conventions enter into force when they have been ratified either by a specified number of Contracting Governments, or Contracting Governments with a combined merchant tonnage constituting not less than a specified percentage of the gross tonnage of the world's merchant fleet.

Most of the conventions are continuously under development as the work within the IMO progresses and is updated by Amendments, and as new issues need attention whenever deemed appropriate by Contracting Governments. Amendments to technical requirements and regulations enter into force automatically after a certain period and are binding on states which have ratified the Convention itself. A number of minimum performance standards, guidelines, interpretations and other recommendations are issued as Assembly Resolutions. These are recommended for implementation but are not binding on Member States unless explicitly referred to in the texts of the Conventions.

The 1960 SOLAS convention, the first to be adopted under the auspices of the IMCO, entered into force in 1965. It replaced earlier conventions of 1914, 1929, and 1948. The present version was adopted in 1974 and entered into force in 1980. The Convention has been, and continues to be, modified and amended and two Protocols (1978 and 1988) have been adopted to respond to increased safety needs and to allow for technical development. Amendments made in

1988, known as "SOLAS 90" increased the requirements as to damage stability of new passenger ships and in 1992 similar requirements were extended to existing passenger ships.

IMO Conventions do not generally have retroactive effect and the requirements applicable to a ship are therefore those which were in force at the time the ship was built. However, in recent years certain requirements have been made applicable retroactively for existing ships.

Problems related to the effective implementation and application of IMO's instruments by certain member states have been recognised by the Organisation and a special sub-committee on Flag State Implementation has been established to develop ways of ensuring compliance with the Conventions and other relevant instruments.

In response to the ESTONIA accident and upon the initiative of the Secretary-General of the IMO, a Panel of Experts was set up in December 1994, under the supervision of a Steering Committee, open to all Member Governments and international organisations concerned. The Panel's task was to review all safety aspects of ro-ro ships and advise the MSC of any action required (Chapter 19).

Telecommunication at sea is regulated by rules and regulations issued by another UN organisation, the International Telecommunication Union (ITU). This body co-ordinates the global telecommunication networks and services and is responsible for regulating the standards of all kinds of telecommunication. A committee within ITU deals with all matters related to radio communication, including allocation of frequencies and the technical properties of transmissions for maritime radio. It lays down performance standards for maritime radio equipment and also issues certificates for the personnel of ship stations and ship land stations. ITU publishes the International Radio Regulations and many maritime radio catalogues, e.g. the List of Coast Stations, the List of Ship Stations, the List of Radio Determination and Special Service Stations.

Another UN organisation, the International Labour Organisation (ILO), deals with certain matters relating to shipping, such as crew accommodation, working conditions and health.

The Commission of the European Communities has also taken action to increase safety at sea, primarily by urging its Member States to be more active in IMO's work towards higher safety standards, requirements for increased port state control and other efforts made to reduce accidents related to human error.

The Organisation for Economic Co-operation and Development (OECD) has expressed concern about safety at sea and has also stressed that ships must comply with international requirements. The use of sub-standard ships in transport is regarded as unacceptable from the point of view of economic equality since it leads to distortion of competition.

Regional co-operation between the states surrounding the Baltic Sea led to the Helsinki Convention for the Protection of the Marine Environment of the Baltic Sea Area, HELCOM 1974, which entered into force in 1982. The Convention is, however, insofar it addresses shipping, binding only upon ships flying the flags of the Baltic Sea states. IMO has issued a recommendation that the Convention should also be respected by ships of other nationalities.

An agreement, the Paris Memorandum of Understanding (MOU) on Port State Control, which was concluded in 1980 by the Maritime Authorities of 14 European states, took effect in 1982. This agreement provides for port state control with a view to ensuring that, without discrimination as to flag, foreign merchant ships visiting the ports of a Member State comply with the standards laid down in the relevant instruments. The MOU requires, among other things, that a Member State achieves an annual total of inspections corresponding to 25 per cent of the estimated number of individual foreign merchant ships entering its ports during a 12-month period. Such inspection is primarily a visit on board to check the relevant certificates and documents and, in case of doubt, to carry out a more detailed inspection.

Similar agreements have subsequently been adopted in other regions as well. IMO's Assembly resolution A787(19) recommends inter alia that Member States also include operational checks on the competence of the crew during port state control inspections.

9.2 National maritime administration and legislation

The United Nations Conference on the Law of the Sea (UNCLOS) stipulates that the flag state has the main responsibility for enacting legislation to ensure the safety of its ships. States that have ratified a Convention are required to introduce the Convention's requirements into their own national legislation or to make equivalent arrangements. Some nations have added requirements over and above those of the Conventions. The general philosophy is, however, that the minimum requirements should be stringent enough for world-wide acceptance. A state's national regulations apply only to ships flying the flag of that state.

Conventions normally permit the administration of a state to delegate certain functions, required by the Convention, to authorised organisations, usually classification societies. Nevertheless, the responsibility for ensuring the ships' compliance with Convention requirements remains entirely with the state administration on whose behalf the organisations act.

The Estonian administration

The Estonian National Maritime Board has four departments: General Department, Maritime Safety Department, Coast Guard Department (until 17 April 1995) and Lighthouse and Hydrography Department.

The Maritime Safety Department consists of the Fleet Section and two sections with service functions, Ship Control Service and Pilot Service.

The Ship Control Service, which was established in April 1994, consists of eight sections, Navigation and Communications Section, Technical Section and six Harbour Master Sections (five sections on the coast, and one on inland waterways). The Pilot Service is responsible for pilotage in the Estonian inland sea.

The main tasks of the Coast Guard Department are the search for and rescue of humans at sea, the localisation and combating of pollution at sea, surveillance of the purposeful exploitation of Estonian waters and surveillance of ships' safety.

The Fleet Section is responsible for the maintenance of the fleet of the Estonian National Maritime Administration.

The Maritime Board has authorised six classification societies, all members of IACS (on IACS see 9.3), to perform statutory surveys under the SOLAS, MARPOL, Load Line, Tonnage and COLREG Conventions and to issue the related certificates.

The Finnish administration

The Finnish Maritime Administration consists of the Head Office and four Maritime Districts. The Maritime Administration is an independent body reporting to the Ministry of Transport and Communications. The Head Office is divided into five departments, one of which is the Maritime Safety Department.

The Maritime Safety Department supervises that ships are properly constructed, equipped, manned and operated. The department takes care of international co-operation related to ship safety and marine pollution.

The department is divided into the Ship Inspection Section and Ship Technical Section. The Inspection Section handles seafarers' competence, manning, lifesaving, navigation and radio matters. The Technical Section handles construction, stability, load line, fire safety, tonnage measurement, dangerous cargoes and pollution prevention matters. The department is manned by 35 persons.

There are 25 inspectors, organised in four districts, for surveys of Finnish flag vessels and for port state control of foreign ships.

Finland has authorised four classification societies, belonging to IACS, to carry out surveys for compliance with the SOLAS, MARPOL and Load Line conventions.

The Swedish administration

The Swedish Maritime Administration, with headquarters in Norrköping, is organised into six departments, one of which is the Maritime Safety Inspectorate.

The Maritime Safety Inspectorate is headed by the Director of Maritime Safety, appointed by the Government. The Inspectorate has approximately 140 employees, of whom just under half work in the head office. The rest are divided between the regional Inspectorate Areas and the Rotterdam office.

The Inspection Department at head office was at the time of the ESTONIA accident divided to four sections: the Ship Technical Section, the Ship Operational Section, the Investigating Section and the Planning Section. An international secretariat within the department handles international matters related to safety and marine pollution prevention, including co-ordination of Sweden's participation in the work of IMO. The organisation has subsequently been expanded with a pollution prevention section and a quality section.

Inspection and related works have largely been delegated to the regional Inspectorate Areas.

The Administration has authorised five classification societies, members of IACS, to perform surveys and inspections required by the SOLAS, Load Line and MARPOL Conventions. The right to issue the relevant certificates has in some cases been delegated to the classification society and in other cases been retained by the Administration.

The master of the ship is required by law to report incidents on a standard form to the Marine Accident Investigation Section.

9.3 Classification societies

The first classification society was formed in the mid-18th century to give underwriters independent information about the condition of ships intended to be insured. Several other classification societies were formed at the beginning of the 19th century.

The main purpose of a classification society is to perform neutral surveys and inspections. A classification society is engaged for a given ship by the shipowner from the design stage of the newbuilding, through the construction phase and subsequently throughout the life of the ship. A classification, carried out by a recognised society, is normally a requirement of insurance companies. A classification society's requirements, valid at the time of building a vessel, generally apply to the vessel throughout her life. Retroactive application of new requirements has not been practised although some movement in that direction has recently taken place.

Classification societies are generally organised as non-profit organisations and charge shipyards and shipowners for their services at cost. A classification society performs independent research into ship design and safety for the development of appropriate rules.

Classification societies are also involved, depending on their resources, competence and world-wide coverage, in performing, on behalf of administrations, the statutory surveys required by the various international conventions. The arrangements are agreed between the national administration in question and the society and define the level of delegation and issuance of certificates.

The eleven major classification societies have a co-operative organisation, the International Association of Classification Societies (IACS), which co-ordinates the policy of the societies, co-ordinates exchange of experience and technical knowledge and issues unified recommendations for the standard to be applied in essential technical matters. Bureau Veritas is one of the members of IACS. Several other, national, classification societies exist which are not members of IACS and which do not qualify for such membership.

Classification societies have from time to time and in particular at the beginning of the 1990s been criticised regarding the quality and integrity of their work. The IACS has therefore developed a quality assurance concept which all the member societies must comply with. Individual classification societies have also instituted extensive internal training and development of work procedures in order to increase the effectiveness of their work.

9.4 The relationships between owner, shipyard, administration and class

Ships have traditionally been built in close co-operation between the owner, the shipyard, the flag administration and the classification society. Before a building contract is signed, an outline specification is developed by the owner or the yard or both parties together. After a contract has been agreed a detailed building specification is developed by the two parties in co-operation. This specification is sufficiently detailed to specify all essential features of the newbuilding, but is still flexible enough to allow the yard to find practical design solutions.

The yard produces drawings for the newbuilding. Major drawings are examined by the classification society for compliance with its building requirements and – where applicable and based on authorisation – with international conventions. The owner has the right to examine all drawings in which he might have an interest. Revisions to the drawings are often made during this work which eventually results in drawings approved by the owner and the classification society.

Drawings specifying the safety and accommodation standard will also normally have to be approved by the flag state administration.

The shipyard builds the ship according to the approved drawings. Due to the complexity of a large ship and the fact that often only one ship is to be built to the drawings, drawings for every detail are not in practice produced. Some details are therefore often left open to the workmanship of the yard and the inspection by the classification society and the owner.

Attendance by the classification society during the building normally also includes inspection of important subcontractors' products at their works. Inspection at the yard includes general visual inspection of all essential work for compliance with approved drawings and detailed inspection or non-destructive testing of items that may call for such attention. The surveyor at the yard is the representative of the classification society. The surveyor's task is to ascertain that the ship is built according to the rules but normally, however, he is not in a position to make detailed examination of every small section of the ship. The responsibility for adequate workmanship and compliance with the approved plans and drawings still remains with the shipyard.

The owner may have his own inspectors and will often have more inspection capacity on a particular newbuilding than the classification society has. The owner's inspectors will often perform detailed inspection of the workmanship and will also cover areas where the classification society has no specific requirements. The owner's inspection team often includes the captain and the chief engineer who are selected to become the master and the chief engineer of the ship when delivered.

When the ship is completed, sea trials take place in accordance with a programme agreed between the yard, the owner and the classification society. After successful trials and any required supplementary work, the ship is delivered to the owner. The yard will be closely related with the ship during a subsequent guarantee period, normally one year.

The classification society will follow up the ship in accordance with its requirements and practice. The work is often divided into annual portions on a rolling time schedule of maximum five years. The annual surveys are made in conjunction with annual dockings of ships for which this frequency is required, or in conjunction with afloat underwater surveys of ships for which this procedure has been approved.

The co-operation between the classification society and the owner is a commercial one, designed to assist the owner to obtain a ship of good class and to demonstrate during the life of the ship that the standard required by the rules is maintained.

9.5 The impact of the HERALD OF FREE ENTERPRISE accident on the development of safety regulations

In 1987, the ro-ro passenger ferry HERALD OF FREE ENTERPRISE capsized and foundered just outside Zeebrugge Harbour, Belgium, with heavy loss of life. The vessel had left the harbour with the bow doors open. When the ship increased speed, the bow wave exceeded the freeboard and water started to enter the lower vehicle deck through the open bow doors. In less than two minutes, at least 500 t of water had accumulated on the vehicle deck and the vessel capsized.

Though ro-ro vessels had been lost prior to the HERALD OF FREE ENTERPRISE disaster, this accident drew renewed attention to the need for improving the safety of ro-ro vessels. Problems of the inadequate stability of such vessels when damaged had long been recognized, but the need for practical and efficient transport seems to have taken priority over safety considerations.

The HERALD OF FREE ENTERPRISE accident triggered an intense world-wide discussion on all aspects of ro-ro safety. Improved damage stability standards for existing vessels were being proposed with the aim of introducing these internationally via the IMO network of convention requirements.

In the discussion, the large, open vehicle space near the waterline was generally considered the main problem with regard to damage stability in the design of ro-ro ferries. If the external watertight integrity of the vehicle space is breached, unfavourable circumstances may initiate an ingress of water to the vehicle deck. Water is free to flow over the unsubdivided deck and large free surfaces are quickly formed, leading to the loss of stability and to list. In a heeled condition, the free surface is reduced and some stability is regained, but usually a small list is enough to immerse the car deck. Progressive flooding is likely to start and the list quickly develops to a capsize.

The risk of collision was considered the most serious threat to the watertight integrity of the vehicle space though statistically ro-ro ships had been involved in few collisions. Numerous other possible ways of losing watertight integrity were listed including weather damage due to wave forces. The research was directed to generating data to support the development of new damage stability standards for ro-ro passenger ferries, but other subjects were also studied. As far as the Commission is aware, very little attention was paid to the wave impact forces on the bow doors and the strength of the locking devices.

One of the main items emerging from the discussions following the HERALD OF FREE ENTERPRISE accident was the very modest formal requirements for the damage stability of passenger ships in the final stage of flooding. A damaged ro-ro passenger vessel with a minimum freeboard and transverse residual metacentric height would be unlikely to survive in anything but calm conditions. This had already been demonstrated in the early seventies by damage stability model experiments, and was later confirmed in several extensive series of similar tests after the HERALD OF FREE ENTERPRISE accident. The new tests also indicated that even the residual stability criteria in SOLAS 90 would give sufficient protection against capsizing for a typical damaged ro-ro passenger vessel only in waves with a significant height of less than about 1.5 m. The chances of survival improved, in general, significantly with increasing residual freeboard and metacentric height.

Since a characteristic ro-ro passenger vessel sinking involves rapid heeling, the evacuation of large numbers of passengers from a high-sided jumbo ferry, perhaps in rough weather or at night, was considered a major problem. It was pointed out that "ro-ro ferries have no transition between survivable accidents and complete disaster". The minimum requirement should be that a ferry during the flooding stage should stay sufficiently upright for sufficient time to give the passengers and crew a fair chance to evacuate.

Many devices including different sponsons and movable, partial bulkheads on the vehicle deck were developed and tested in model experiments to improve the damage survivability of existing ro-ro passenger vessels, but none of these devices obtained general acceptance.

CHAPTER 10

HISTORY OF RO-RO FERRY TRAFFIC IN THE BALTIC SEA

10.1 Introduction

From about 1960 the ro-ro ferry traffic between south-west Finland and the Stockholm region in Sweden developed extraordinarily fast regarding number of ships built for the trade, their increase in size, capacity and comfort and the number of passengers and vehicles carried. The development was spurred by the competition between the two major shipping company groups engaged in the trade, Viking Line and Silja Line, both under mixed Finnish and Swedish ownership. In several respects it probably progressed faster than international regulations and the classification societies could accommodate. The rate of development during the 1970s and 1980s has generally been considered to lack equivalence in any comparable trade.

Understanding of this development has been considered important for appreciation of the overall circumstances of the ESTONIA accident. A separate study of the history of this ferry traffic was therefore commissioned from a consultant company, ADC Support AB. The study is included in the Supplement.

10.2 Development of the traffic

Scheduled steamer traffic has long existed between Helsinki and Stockholm. Passenger and cargo services were generally separate. A small number of cars could be carried on the steamers, being lifted on board in the traditional manner.

On 1 June 1959 the shipping company SF Line, Mariehamn, Åland, introduced a ro-ro passenger service between Åland and the Swedish mainland, north of Stockholm. At about the same time the project was joined by another Mariehamn-based shipping company, Rederi AB Sally.

Only four days after the first ro-ro line opened, a competing service on the same route was started by the Swedish Rederi AB Slite.

One of the vessels used for these first ro-ro-lines was a converted railway ferry and the other one was a coaster, rebuilt to allow ro-ro handling of cargo and the carriage of passengers. Passenger comfort was not considered important since the voyages lasted only a few hours. The traffic was greatly dependent on tourism and during the first few years it was suspended during the winter.

The three shipping companies involved in the first ro-ro traffic between Åland and the Swedish mainland later formed the joint marketing company Viking Line, one of the leading companies in the development of the traffic between south-west Finland and the Stockholm region.

The concept proved successful, and purpose-built ro-ro ferries were ordered. The first one, SKANDIA, was delivered in May 1961 to the competitor Silja Rederi AB, a company jointly owned by Bore Line AB, Finska Ångfartygs AB and Rederi AB Svea.

SKANDIA could carry 1000 passengers and was built with a full-size car deck, served by bow and stern ramps. The ship was put in service between Helsinki and Stockholm. In May the following year a sister ship, the NORDIA was delivered.

New ships were added every year to meet the increasing demand for transport between the different ports in south-west Finland and the Stockholm region. The standard of the vessels improved. Size and engine power increased, and from 1965/1966 the traffic could be maintained regularly also in winter.

The ro-ro service quickly became an indispensable transport element, primarily for the Finnish export industry, which could now provide deliveries to Sweden and onwards to western Europe in a safe, convenient and reliable manner.

Various factors contributed to make the ferry traffic viable. The lower demand for trucking transport during the general summer vacation period was compensated for by tourist travel during that season. Taking the car on a trip to one's neighbouring country became a convenient, economical and practical arrangement. The large number of Finnish people working in Sweden and the many family relationships between people living on both sides of the Baltic added to the need for passenger transport. Differences between prices in the two countries of daily commodities made "shopping trips" economical, as did the opportunities to buy tax-free goods on board.

In the 1970s the demand for conference facilities increased rapidly amongst Swedish companies. The ferry companies responded, and with a combination of lower prices than shore-based facilities and the adventure of a sea voyage, the ferries soon became a popular alternative. Existing ferries were rebuilt and extensive conference areas were incorporated in the design for newbuildings.

The ferries built from the mid-1980s had conference facilities and restaurants, bars, shopping arcades and entertainment areas with few equivalents ashore in the two countries.

The basis for the ro-ro ferry traffic between the two countries thus steadily increased as the table below shows.

Table 10.1 Annual traffic volume.

	1960	1975	1994
Passengers	500,000	2,800,000	6,000,000
Cars	30,000	300,000	400,000
Trucks	900	100,000	140,000

The competition demanded a steady increase of comfort and ship size. The ferries were very attractive on the second-hand market and the financial risk involved in ordering more newbuildings with more attractive features was low. Nearly fifty ferries were built for the trade between 1960 and 1990 and the general period in service was only about seven years. Considerable development took place rapidly as experience accumulated and opportunities to introduce improved concepts were frequent.

Figure 10.1 Bow door arrangements.

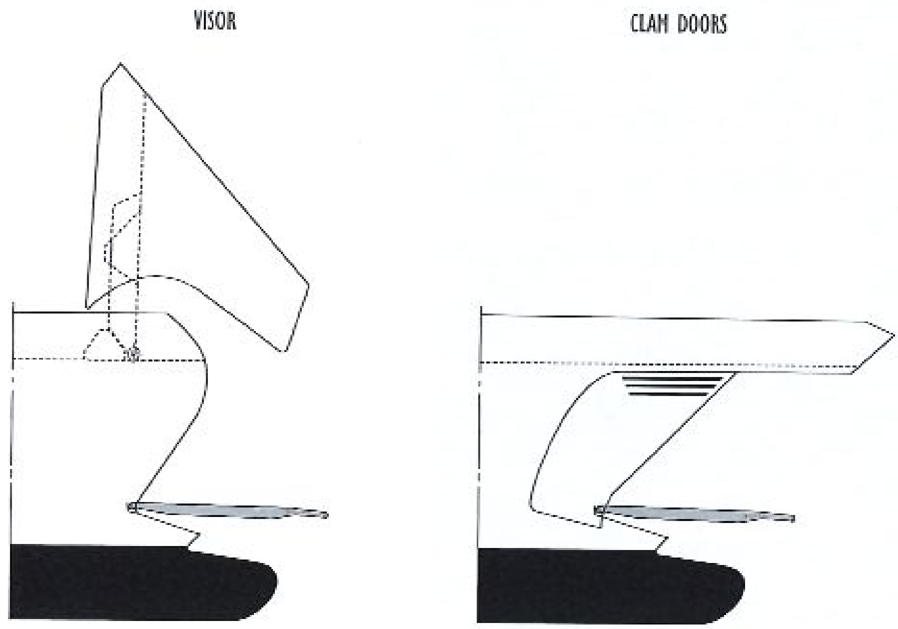
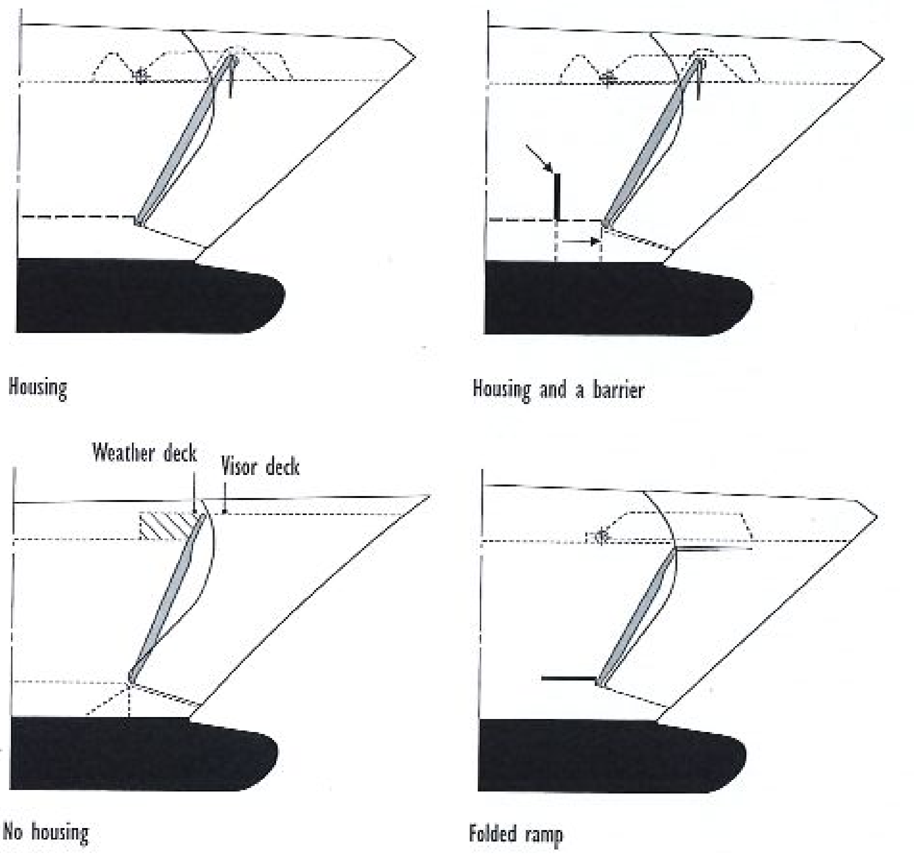


Figure 10.2 Ramps in stowed position.



10.3 Cargo deck arrangement

The cargo deck arrangement has remained generally unchanged since the building of SKANDIA. Improvements have been introduced regarding access and safety arrangements. Hoistable car decks, covering part of the cargo deck, were generally included so to increase the capacity during runs when passenger cars dominated.

Stern ramps and stern openings have increased in size but the design has remained the same, i.e. in lowered position the ramp gives vehicles access to and when raised seals the car deck.

Access to the car deck via a forward ramp became desirable to eliminate the need for turning long vehicles on the car deck and thus to reduce the time required for cargo handling. The concept was known from railway ferries and some cargo vessels.

The outer enclosure of a bow opening – the bow door – can be arranged either as a pair of clam doors, hinged at the sides and opened sideways, or as a visor, hinged at the upper deck and opened upwards. Figures 10.1 and 10.2 show various bow door and ramp arrangements.

The visor concept became quite common from the 1960s. Clam doors were initially considered more complicated and before 1985 were incorporated only in a small number of ferries. Most larger ferries built since then, however, have clam doors.

The length of the ramp was determined by the distance to the landing on the jetty and the position of the hinges. The position of the hinge point was in turn determined by the desire to have the ramp serve as an upper collision bulkhead. The SOLAS requirement on ramp position with regard to the rules for an upper extension of the collision bulkhead was, however, often disregarded. The history of compliance with this requirement is covered in Chapter 18.

The available deck height was often too low to allow the ramp to be raised to a closed position. The solutions developed were then either to let the ramp protrude above weather deck level and be enclosed in a housing, or to divide the ramp into two sections with a hinge arrangement in between. The visor housing arrangement was less complicated and was generally selected. It had, however, the disadvantage that the visor and the ramp were then mechanically interconnected, a major disadvantage that was only fully realised as a consequence of the ESTONIA accident.

Clam doors, serving as the outer enclosure, have the advantage that sea loads are absorbed into the ship's structure. Although damage to clam doors has been recorded it has therefore very seldom been of a critical nature.

Visors on the other hand may under unfavourable sea conditions be exposed to sea loads in the opening direction. This has resulted in several cases in the visor moving to more or less open position (see Chapter 11). Where the visor accommodates the top of the ramp, the risk is imminent that the ramp will be forced open, if the visor attachments fail totally and the visor falls off. In such a case, if the vessel has no watertight doors aft of the ramp, water will be free to enter the car deck as was the case in the ESTONIA accident.

Table 10.2 gives an overview of the ferries placed into service on the route by Silja Line and Viking Line between 1959 and 1993 with the type of original bow enclosure and ramp stowage solution selected in each case. Side doors and stern ramps are not mentioned.

10.4 The Tallinn–Stockholm ro-ro ferry operations

Ferry operation between Tallinn and Stockholm was initiated in 1989 while Estonia was still an incorporated region within the Soviet Union. The endeavour to re-establish regular vessel traffic between Estonia and Sweden resulted in signing a General Agreement between the Estonian Transport Committee and Nordström & Thulin AB on 28 August 1989.

The Agreement provided the basis for starting joint ferry operations, including the principles for the necessary investment in related infrastructure. It was stipulated that the Estonian side would undertake the reconstruction of the terminal in Tallinn and Nordström & Thulin would undertake to provide a terminal in Stockholm. The agreement provided that the Estline Marine Company Limited would be granted the concession for operating the ferry line for the first ten years.

For the joint undertaking on the Estonian side, Estline Eesti was established in November 1989 by the transport enterprises which were under Estonian jurisdiction. In October 1992, under the conditions of regained independence, the Government of Estonia re-formed the enterprise into the company E-Line Limited and appointed the Estonian Shipping Company (ESCO) to represent the state in operating the Tallinn–Stockholm services. The decision was made with reference to the General Agreement mentioned above.

Regular ferry service on the route started on 17 June 1990 and was carried out by N&T EstLine AB, a fully-owned subsidiary of Nordström & Thulin AB, in co-operation with a consortium of smaller tourist-related Estonian-government-owned companies. The traffic was carried in the NORD ESTONIA, a ro-ro passenger ferry with capacity for 1060 passengers, owned by Nordström & Thulin and registered in Sweden. The vessel was operated and manned by N&T EstLine AB. The NORD ESTONIA departed every second day from Tallinn and Stockholm respectively.

The ferry line was considered to be of the greatest importance to Estonia. Its establishment was opening the country westwards and giving opportunities to establish commercial as well as other relations with other countries, an essential factor in creating new prospects for the country.

Traffic was maintained by the NORD ESTONIA for about two and a half years,

Table 10.2 Original bow arrangements.

Silja Line	Year	Viking Line
Birger Jarl	1959	(Viking, Slite)
Bore	1960	–
Skandia VI	1961	(Boge)
Nordia VI, Svea Jarl	1962	–
Floria	1963	(Ålandsfärjan, Panny R)
Ilmatar	1964	Apollo VI, (Drotten)
(Holmia VI)	1965	–
Fennia VI	1966	–
Botnia VI	1967	Kapella VI, (Visby VI)
–	1968	(Viking 2 VI)
–	1969	–
Floria VI	1970	Apollo VR, Viking 1 VR, Marella VI
–	1971	–
Aallotar CD, Svea Regina CD	1972	Viking 3 VR, Diana VR
Bore I VR	1973	Viking 4 VR, Aurella VR
–	1974	Viking 5 VR, (Viking 6 VI)
Svea Corona VI, Wellamo VI Bore Star VI	1975	–
–	1976	(Apollo III)
–	1977	(Ålandsfärjan VI)
–	1978	–
–	1979	Diana II VR, Turella VRB
–	1980	Rosella VRB, Viking Song VI, *Viking Sally* VR, Viking Saga VI
Finlandia VRB Silvia Regina VRB	1981	–
–	1982	(Aurella VI, Ålandsfärjan VR)
–	1983	(Ålandsfärjan VR)
–	1984	(Ålandsfärjan VR)
Svea CD	1985	Mariella VRB, (Ålandsfärjan VI)
Wellamo CD	1986	Olympia VRB
–	1987	(Ålandsfärjan VI)
–	1988	Amorella CD
–	1989	Athena CD, Cinderella CD, Isabella CD
Silja Serenade CD	1990	Kalypso CD
Silja Symphony CD	1991	–
–	1992	–
Silja Europa CD Silja Scandinavia CD	1993	–

Notes: Ships in brackets ( ) not purpose-built for the service.

R = Ramp as outer bow enclosure.

CD = Clam Doors.

VI = Independent Visor. No housing for accommodating top of ramp.

VR = Visor and box-like housing for stowing ramp.

VRB = Visor and box-like housing for stowing ramp and a separate barrier.

until she was replaced by the ESTONIA on 1 February 1993.

On 22 September 1994 the passenger ferry DIANA II (see 3.1.1.) was bare-boat-chartered by ESCO. The purpose was to expand the ferry service between Tallinn and Stockholm with one daily departure in each direction. This did not come about, however, due to the ESTONIA accident.

The DIANA II, after considerable upgrading including permanent closure of the bow visor and forward ramp, was put into service in November 1994 under the name of MARE BALTICUM. In August 1996 she was replaced by the REGINA BALTICA.

CHAPTER 11

BOW DOOR FAILURES AND INCIDENTS

11.1 General

A number of incidents involving failure or part-failure of bow visor attachment devices have occurred in the Baltic Sea and the North Sea during the history of the ro-ro ferries. The ships involved have all been under the survey of one of four major classification societies. The following list of some of these incidents includes two involving vessels equipped with clam doors. It is especially noted that many of the incidents occurred during the first year of the vessel's operation.

With two exceptions, the list contains only Swedish and Finnish vessels and is not complete. It may be concluded that similar incidents have occurred in other areas of the world. It is, however, worth noting that the extensive flare in the bow profile of the vessels has in several instances been blamed as a contributing factor. Ferries built for Baltic Sea operators had at the time a more pronounced bow flare profile than ferries built for other services.

After the ESTONIA accident administrations and classification societies performed extensive surveys of the condition of locking devices and hinges on all ro-ro ferries within their territory. The results showed a rather high frequency of defects of varying degrees of severity, needing corrective work. One of the classification societies reported that some kind of defect, e.g. cracks or deformation of locking devices, was found in about 30 per cent of the ferries inspected. Most of the defects were, however, relatively small.

11.2 A brief history of incidents

VISBY, a passenger ferry built in 1972 – whilst proceeding from Nynäshamn to Visby in December 1973 – hit a couple of heavy waves which caused the visor to open. The ship was turned and returned safely to Nynäshamn. It was concluded that the locking devices were too weak, and heavier devices were installed. The matter was dealt with in correspondence between the Swedish Maritime Administration and the classification society involved and information was received that the society had substantially increased the strength requirements. The effect of extensive flare in the bow contour was also discussed.

STENA SAILER, a cargo ferry built in 1973, experienced heavy weather and head sea in January 1974. Speed was reduced but the visor locking devices failed. The ramp remained intact and the ship turned and headed for shelter. It was noted in the investigation that a similar incident had happened earlier and that a sister vessel under another flag had also had a similar incident.

An administration report concluded inter alia that "nearly all locking devices of bow doors on existing vessels are too weak" and recommended that the administration should first investigate how such should be designed and built, and thereafter inspect existing vessels (see 15.13).

SVEA STAR, a passenger ferry built in 1968, experienced heavy weather in May 1974. A heavy wave lifted the visor. Water collected in the visor but the ramp remained closed. The ship turned and regained port.

WELLAMO, a passenger ferry built in 1975, encountered a south-westerly storm on a scheduled voyage from Helsinki to Stockholm on a December night in 1975. About 10 nautical miles south of the Bengtskär lighthouse the officer of the watch noted that the bow visor lifted. He woke up the master. The visor was illuminated with an Aldis lamp and about five minutes later the visor lifted again. Speed was immediately reduced from about eight knots to three knots. The master and the chief engineer inspected the visor and due to the damage and the storm the master decided to turn back to Helsinki.

Next morning in Helsinki it was observed that the locking cleats were torn away and the arms of the visor were partly broken. Side plating on both sides of the visor was dented, as was a light bulkhead inside the visor. There was a small hole on the tanktop, caused by pounding of the visor. The local structure at the locking devices was reinforced, the arms were repaired and reinforced, side plating was renewed and the bow visor hull was repaired on both sides. The bulkhead was reinforced with stiffeners. Two sister vessels were similarly reinforced.

FINLANDIA, a passenger ferry built in 1981 on a scheduled voyage from Helsinki to Stockholm in the autumn of 1981 encountered heavy south-westerly seas south of Hanko. Next morning in Stockholm, the visor did not open and severe damage was found including dented structure on the port side and two broken locking bars on the centre line.

The visor had lifted a few centimetres and moved to starboard. Thus, additional locating horns were fitted on both sides and the structure on the back was reinforced. Locking devices were also reinforced. A sister vessel was similarly reinforced.

SAGA STAR, a cargo and passenger ferry built in 1981, was about to depart from port in May 1982. When the visor was being lowered the port side hinge failed, resulting in failure also of the starboard side hinge, and the visor fell down. The ship was allowed to sail a couple of voyages without visor until repairs had been performed.

VIKING SAGA, a passenger ferry built in 1980, was extensively damaged on the fore part and on the lower port side of the bow visor south of Hanko in October 1984, on a scheduled voyage from Helsinki to Stockholm. The incident took place when the vessel was running at 16 knots in heavy bow seas with a wind speed of about 14 m/s. Next morning in Stockholm it was observed that a large part of the port visor shell construction together with a horizontal platform had been dented. A locating horn on the port side was bent towards the centre line and side lockings were damaged. Several stiffeners, beams, large areas of shell plating and part of the platform were renewed. The visor construction was not reinforced, since the incident was considered typical heavy weather damage.

STENA JUTLANDICA, a passenger ferry built in 1983, experienced in October 1984 failure of the visor hinges during normal opening. The main reason for failure of the hinges was cracks in the welds. The hinges were reinforced, also on a sister vessel.

ILYICH, a passenger ferry built in 1973, encountered heavy seas with a wind speed of about 18 m/s on a scheduled voyage from Leningrad to Stockholm in December 1984. At a speed of about 17 knots, one of the visor deck hinges failed fully, the other partly and all visor locking devices broke. The visor hung on the hinge and moved up, down and sideways every time the seas lifted the visor. The incident was quickly observed from the bridge, speed was significantly reduced and the vessel run to more sheltered waters. The vessel was also involved in an incident in September 1986 at a speed of about seven knots. In this case, three visor locking bolts broke and other damage occurred. The structure of the bow visor and hinges was reinforced, locking devices were replaced by significantly stronger ones and side locating horns were fitted in 1989.

MARIELLA, a passenger ferry built in 1985, experienced heavy seas on a scheduled voyage from Helsinki to Stockholm in November 1985. The starboard hinge brackets sheared. Both starboard and port hinge beams were almost fully cut. Locking devices and the hydraulic actuators failed and the visor was forced open. Indications of brittle fracture were subsequently noted in shorn-off locking bars. The incident occurred at about 13 knots. Speed was significantly reduced when the incident was visually observed from the bridge, whilst the vessel continued her voyage in more sheltered waters.

The visor was temporarily repaired immediately after the incident. Permanent repairs, including heavy reinforcements of the locking devices and appropriate structures, were carried out later. Reinforcements were made for instance at the lower locks of the visor and below the upper locking devices. Additional locating horns were fitted on each side and the structure on the backs of these was reinforced with stiffeners. A sister vessel was similary reinforced.

TOR HOLLANDIA, a passenger ferry built in 1973, in heavy weather during the winter of 1986/87, experienced failure of the visor bottom attachments and one deck hinge. The condition was observed visually from the bridge and rapid evasive action prevented an accident. Extensive reinforcements were made in conjunction with the repair.

FINNHANSA, a passenger ferry built in 1966, lost her clam doors in January 1977 in heavy weather close to the Helsinki lighthouse. The doors were not properly secured. When it was noted that the clam doors were about 0.5 m open, the vessel was stopped in order to get the doors closed. Heavy seas had, however, already torn off the doors. The vessel returned to Helsinki.

SILJA EUROPA, a passenger ferry built in 1993, damaged her port clam door during the same night or morning as the ESTONIA sank. The damage was noted after arrival in Stockholm on 29 September 1994, when efforts were made to open the bow doors. The starboard bow door opened as normal, while the port side door could be opened only about 0.4 m. Among the damage were dented plates in the hinge arm and in a support frame. The exact time of the damage is not known. The shipowner claims that the damage occurred during the ESTONIA rescue operation.

Table 11.1 shows a summary of known bow visor incidents which occurred before the ESTONIA accident and involved passenger ferries built from 1975 to 1986 for the Finland–Sweden traffic. The list includes all passenger ferries built between 1975–1986 originally for the traffic even if they had not been involved in such incidents. The table indicates whether the bow visor has been reinforced since the incident. The information for sister vessels is given in the same box. After 1986, all passenger

Table 11.1 Damage to and reinforcement of bow visors of passenger ferries originally built for the Finland–Sweden traffic 1975–1986.

Vessel	Built	Bow door[2]	Incident	Visor reinforced
Svea Corona	1975	VI		After Wellamo incident
Wellamo	1975	VI	31.12.1975	After incident
Bore Star	1975	VI		After Wellamo incident
Viking 5	1975	VR		
Diana II	1979	VR	January 1993	
Viking Sally[1]	1980	VR		
Turella	1979	VRB		
Rosella	1980	VRB		
Viking Song	1980	VI		
Viking Saga	1980	VI	20.10.1984	
Finlandia	1981	VRB	Autumn 1981	After incident
Silvia Regina	1981	VRB		After Finlandia incident
Mariella	1985	VRB	7.11.1985	After incident
Olympia	1986	VRB		After Mariella incident
Svea	1985	CD		
Wellamo	1986	CD		

[1]Foundered as ESTONIA. [2]See Table 10.2.

ferries built for the Finland to Sweden traffic have had clam doors (Table 10.2).

11.3 The DIANA II incident

In January 1993 there was a period of heavy weather in the southern Baltic Sea. During this period the Polish ro-ro ferry JAN HEWELIUSZ capsized in the early morning of 14 January. DIANA II, a Swedish-flagged near-sister vessel to ESTONIA, operated under charter on the route between Trelleborg in southern Sweden and Rostock in Germany. She normally made two double day trips at full speed and one double night trip with reduced speed each day. According to available information, on the night of the foundering of JAN HEWELIUSZ no abnormalities were noticed as the DIANA II made the trip from Rostock to Trelleborg at low speed. She made the scheduled day and night trips on 14 and 15 January in bad but improving weather conditions. During the morning of 16 January, whilst the vessel was enroute to Trelleborg, the chief officer to be relieved and the one starting his tour of duty made a joint inspection round throughout the vessel, whereupon they noticed damage to the visor locking arrangements.

Since the visor design of DIANA II was the same as that of ESTONIA, the Commission has further investigated this damage and the repair work (Supplement).

Bureau Veritas was called upon when the vessel arrived in Trelleborg. The survey report in the Supplement shows that the starboard locking device lug was lost, the bottom lock was bent and its welds cracked and the port side locking device lug was bent and its weld cracked. Figure 11.1 shows the damage at the site of the starboard visor lug. The damage was repaired by normal procedures, to what was estimated to be equivalent to the original standard.

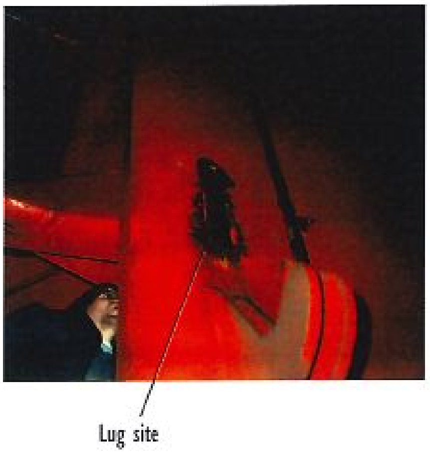
The survey report, when read at the Bureau Veritas regional office in Gothenburg, was not considered to indicate a serious incident. No initiative was therefore taken to investigate the matter further, nor was any general action taken.

The repaired side locking lug mounting site was surveyed after the ESTONIA accident. The survey showed repair by multiple welding of the cracked lug weld sites, and local backing plates had been added. Some old cracks were also detected.

The visor mating lug to the bottom lock of DIANA II was also recovered with the bottom locking bolt. The locking bolt had extensive wear on its upper forward sector in a location mating with the eye of the lug that had also worn. The visor mating lug also showed marks from overloading in tension, as its eye had been extended by stretching at the aft tip of the lug. Strengthening plates had been added to the mating lug both to strengthen its tip and to add vertical rigidity to its attachment to the visor structure. It is not known when these reinforcements were installed. The bolt of the bottom lock was made of high-strength steel grade approximately 700 MPa ultimate strength, and the visor mating lug was of mild steel.

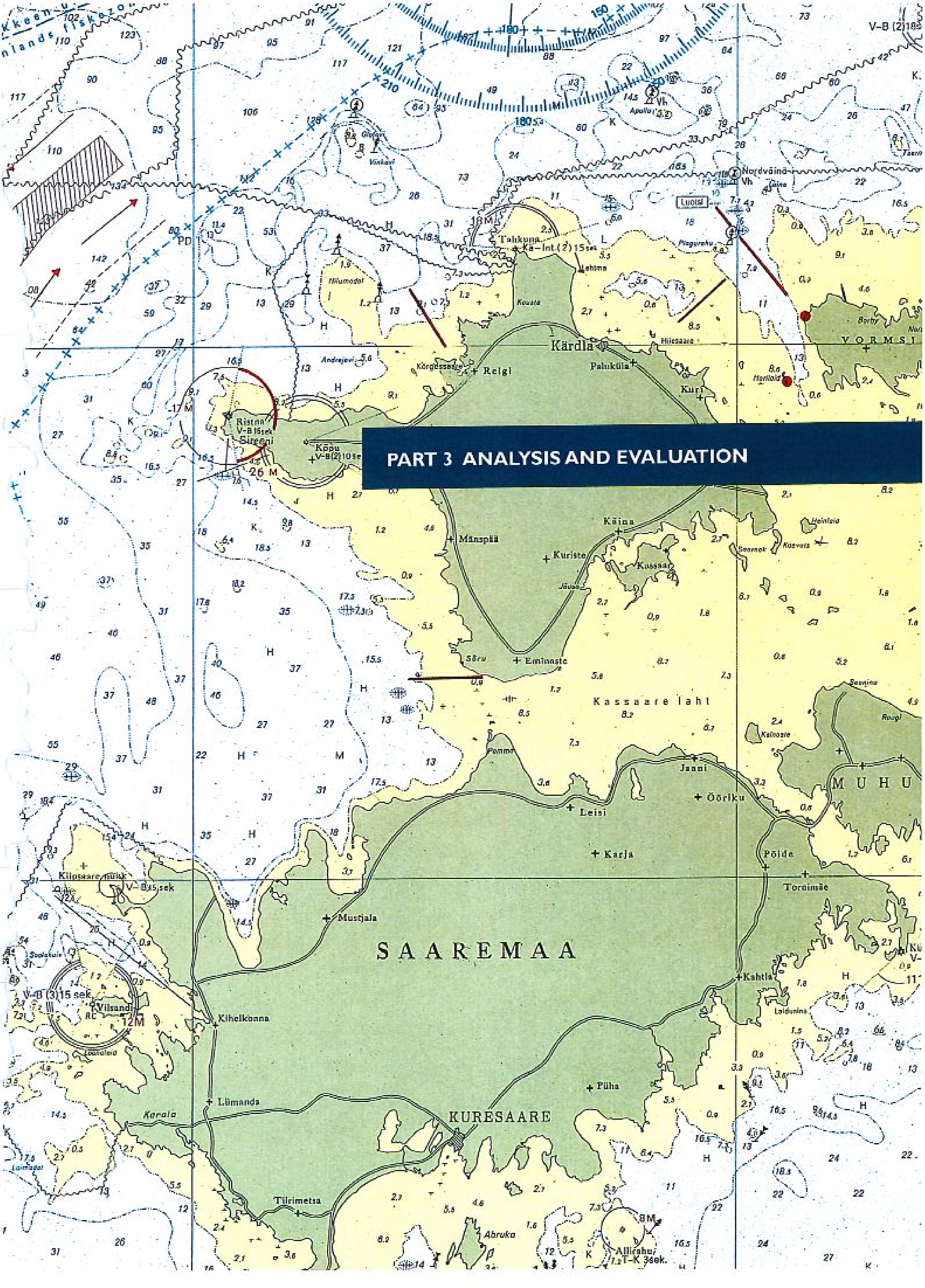
The Commission has not been able to verify whether the local office of the Swedish Maritime Administration was informed of the DIANA II incident. From the vessel it is claimed that information

Figure 11.1 Loss of the starboard visor locking lug of DIANA II in January 1993.



was given to the Administration by way of a telephone call one of the first days after the incident, and that the inspector answering the call was satisfied with the way the repairs had been carried out. The Administration on the other hand claims that no information on the incident was received until after the ESTONIA accident. An inspector from the Administration visited the DIANA II about one month after the visor incident. He was called to survey a gangway and claims that at the time of the visit, he had no information on any damage to or repair of the bow visor or its attachments.

PART 3 ANALYSIS AND EVALUATION



CHAPTER 12

OVERVIEW OF SEPARATE INVESTIGATIONS

12.1 Determination of sea loads on the visor by model tests

12.1.1 Test program

Extensive model tests ordered by the Commission have been performed at the maritime research centre, SSPA laboratories. The main purpose of the test programme was to determine the wave impact loads on the visor at the speed, on the heading and under the wave conditions in which the ESTONIA was likely to have been operating at the time of the visor failure. In addition, the influence of variations in some of these parameters was tested. The model test results have further been compared to computer simulations of wave loads as summarised in 12.2. SSPA's complete test report is appended in the Supplement.

A 1:35 scale model of the ESTONIA was built and equipped with propulsion units and controllable rudders. The bow visor was made separate from the hull and attached with a six-component balance to measure integrated forces and moments on the visor in all six degrees of freedom. The static weight of the visor was excluded from the measurements and the moments were transferred to the centre position of the visor hinge axis.

Sea load tests were carried out both in the towing tank (TT), for head sea conditions, and in the Maritime Dynamics Laboratory (MDL) for oblique sea conditions. The model was in both cases self-propelled. Long-crested irregular waves were generated according to the JONSWAP wave spectrum.

The model tests emphasised the determination of extreme values and the statistical distribution of loads. Two of the conditions were therefore tested in a large number of repeated runs with slightly modified wave amplitudes and phase lags.

The test programme in irregular seas consisted of the conditions given in Table 12.1.

A peak period of 8.0 s for the wave spectrum was used for all conditions except for the last one which used a period of 8.3 s. This last condition was at the time assumed to be the most probable condition in which the bow visor of the ESTONIA failed.

Table 12.1 Test programme at the SSPA laboratories.

	Heading	Speed, V	Significant Wave Height, H_s Nominal	Measured at bow	Measured time
Towing Tank:					
Head sea:	180°	10 knots	4.0 m	3.9 m	30 min
	180°	15 knots	4.0 m	3.9 m	320 min
	180°	19 knots	4.0 m	3.9 m	20 min
	180°	10 knots	5.5 m	5.1 m	60 min
	180°	15 knots	5.5 m	5.2 m	40 min
	180°	19 knots	5.5 m	5.2 m	30 min
MDL:					
Head sea:	180°	15 knots	4.0 m	4.1 m	30 min
Bow sea:	150°	10 knots	4.0 m	4.2 m	30 min
	150°	10 knots	5.5 m	5.3 m	30 min
	150°	15 knots	5.5 m	5.3 m	30 min
	150°	14.5 knots	4.3 m	4.5 m	180 min

12.1.2 Summary of results

Due to the non-linear and random nature of the bow impact loads, the absolute quantitative measured loads must be judged with care. Small changes in the relative motion between the ship bow and the waves, as well as in the wave profile, resulted in large differences in load values. The maximum loads were not generally measured in the highest individual waves but rather in the worst combinations of waves and ship motions.

The most critical wave-induced load component, the opening moment around the deck hinges, the Y moment, measured in the different tests is plotted in Figures 12.1–12.2 on the basis of mean exceedance period. The vertical force, the Z force, is shown in a similar way in Figures 12.7–12.8. Mean exceedance period means here the average time between individual load peaks equal to or higher than the corresponding value. The graphs were produced by taking the total full-scale time of each test series and dividing it by the number of load peaks exceeding a certain level as given by the Weibull plot in SSPA Report 7524.

The wave-induced forces and moments shown do not include the static weight of the visor itself. This will decrease the vertical force by about 0.6 MN and the opening moment by about 2.9 MNm. (1 MN equals the force of 102 metric tons).

12.1.3 Long test series in oblique bow seas

The long series of tests at MDL in port bow sea with a nominal significant wave height, H_s, of 4.3 m and a ship speed of 14.5 knots were, at the time the tests were performed, believed to represent the prevailing condition when the attachments of the visor of the ESTONIA failed. In this series, during three full-scale hours of measurements, the individual maximum components of wave loads on the bow visor were recorded as given in Table 12.2.

All the maximum values except for Y force and Z moment were measured at the same incident (Y force was measured to 2.2 MN and Z moment to 3.8 MNm simultaneously). When these highest loads were measured, wave crest amplitude was 3.7 m, relative motion between bow and wave was 6.3 m and relative velocity 6.2 m/s.

The longitudinal and vertical force peaks always appeared in phase and with approximately the same magnitude. Only a few of these load peaks, however, resulted in a positive opening moment about the hinge axis that would have been large enough to exceed the closing moment from the static weight of the visor, and only two opening moments were above 20 MNm. Most of the load cycles caused closing moments with peak levels up to about 5 MNm.

Figure 12.1 Measured wave-induced vertical opening moment on the visor in bow sea.

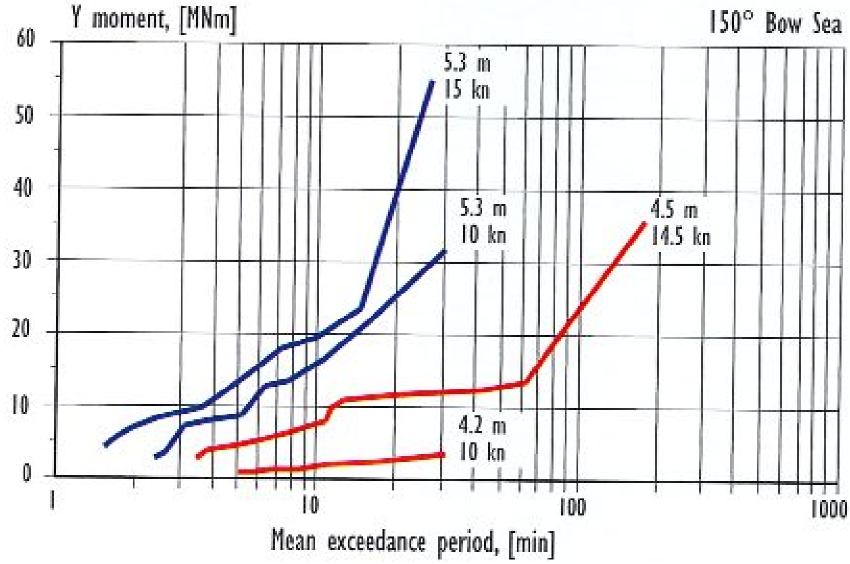


Figure 12.2 Measured wave-induced vertical opening moment on the visor in head sea.

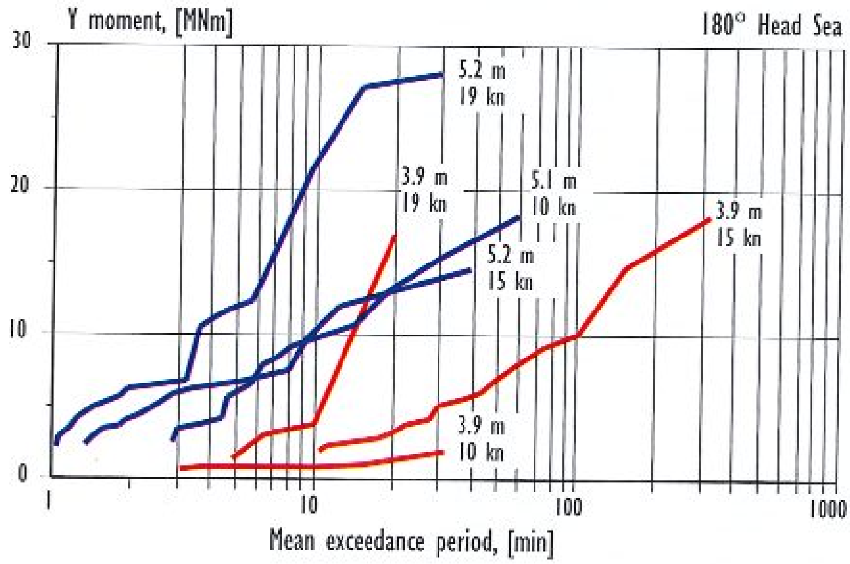


Figure 12.3 Example of time series from model tests.

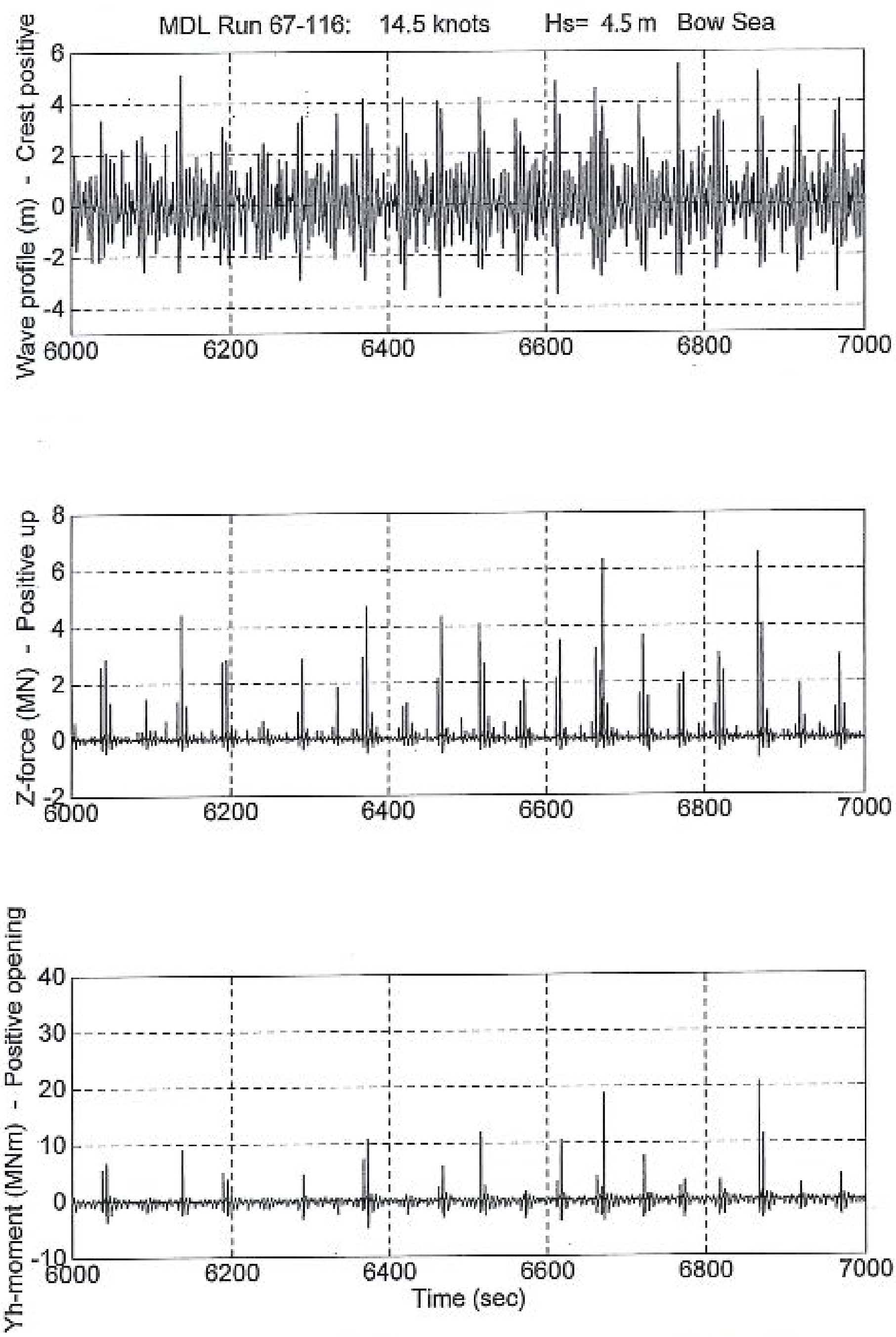


Table 12.2 Maximum wave load components in bow sea with H_s = 4.5 m.

Forces:			
Longitudinal force	X force	7.7 MN	(directed aft)
Side force	Y force	2.7 MN	(directed to starboard)
Vertical force	Z force	7.4 MN	(directed upwards)
Moments at the visor deck hinge position:			
Moment about longitudinal axis,	X moment	10.2 MNm	(upward on port side)
Moment about transverse axis,	Y moment	35.4 MNm	(upward opening)
Moment about vertical axis,	Z moment	4.1 MNm	(forward on port side)

Figure 12.3 shows an example of a time series of measured wave profile, vertical force on the visor and opening moment about the hinge axis. The figure covers about 17 minutes of full-scale time.

12.1.4 Wave load components – influence of wave height, heading and speed

The influence of significant wave height, heading and speed on the wave-induced loads on the visor is summarised in Figures 12.4-12.6 and 12.9. In the comparison, the most probable maximum values over 30 min. of exposure are used. For most of the test series this means that the given value corresponds to the single highest measured, and hence the uncertainty in these levels is large. In the figures, the test results are connected with straight lines to show the same condition. However, the sea loads are a function of H_s raised to a higher power, and the straight lines should not be used for inter- or extrapolation.

It is apparent that the wave height influence is much larger in bow sea than in head sea. The results indicate that there is a 'threshold' sea condition in bow sea below which the wave-induced loads on the visor are very low. When this condition is exceeded, the risk of high forces and moments rapidly increases even though the general condition with regard to motions and accelerations on board is not changed significantly. In the conditions tested, the threshold is apparently found at about 4 m significant wave height.

The wave forces show an approximately linear relation to the speed in bow sea for both wave heights studied. A decrease of speed from 15 kn to 10 kn thus reduces the forces by about one third. In head sea, at higher wave heights, the speed influence seems to diminish.

Figure 12.4 Longitudinal and transverse wave force on the visor. Model test results in head and bow sea at 10 and 15 kn speeds.

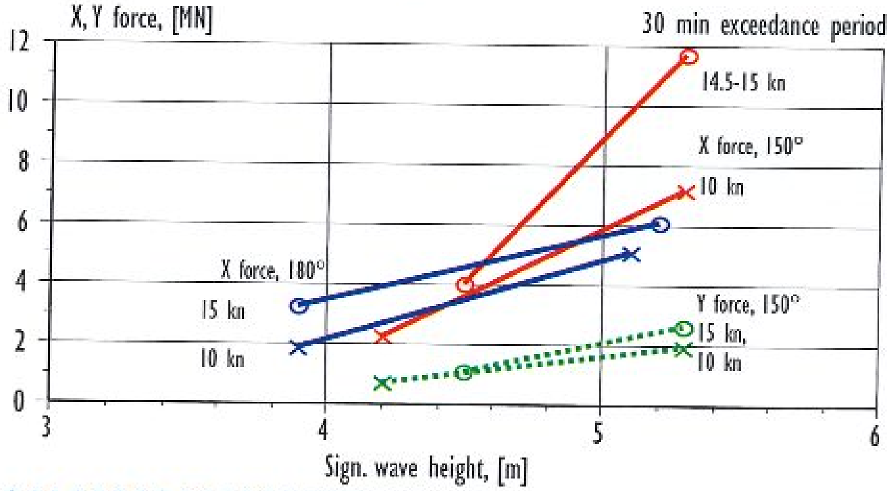


Figure 12.5 Wave-induced moment about visor longitudinal and vertical axis. Model test results in bow sea at 10 and 15 kn speeds.

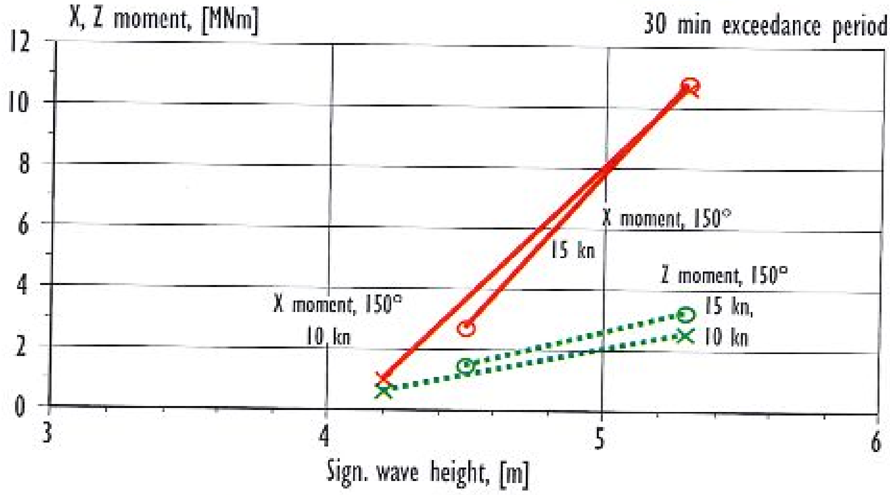
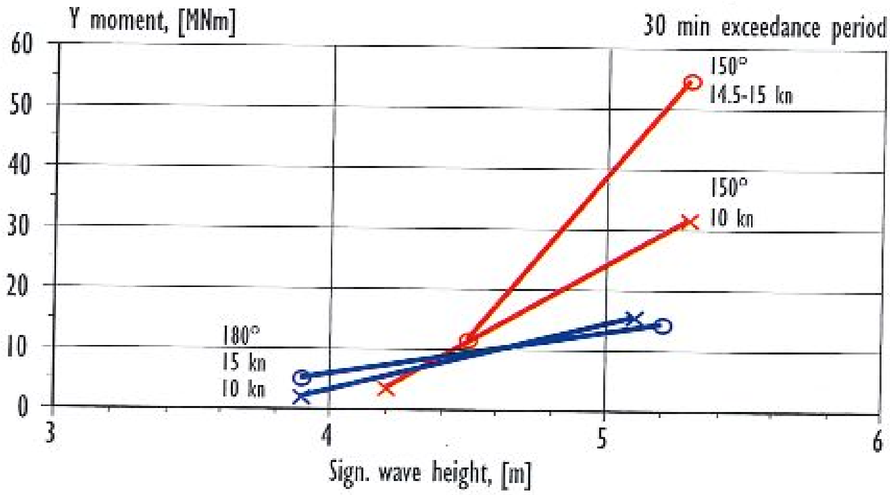


Figure 12.6 Wave-induced opening moment about visor deck hinge axis. Model test results in head and bow sea at 10 and 15 kn speeds.



12.2 Numerical simulation of vertical wave loads on the bow visor

12.2.1 Introduction

Vertical wave loads on the ESTONIA bow visor have also been simulated using a non-linear numerical method to estimate the loads during the accident voyage and to investigate the effects of the most important load parameters. The numerical predictions supplement the SSPA model experiments since it has been possible to simulate much longer time sequences than could be tested in a model basin.

Due to the very complicated flow phenomena around a body entering water, no exact numerical methods exist for analysing the flow, and the simulation method used is based on an engineering approach with which the vertical component of the wave load could be calculated. It has thus not been possible to simulate the other load components or compute the pressure distribution on the visor surface.

The numerical method is discussed in more detail in the complete report in the Supplement. To evaluate the accuracy of the method, the simulated vertical wave loads have been compared with the experimental results.

The simulations have been carried out for long-crested, irregular wave time histories generated according to the JONSWAP wave spectrum formula. In each case, the simulated time sequence was 36 hours long, consisting of six 6-hour simulations. The full simulation programme is shown in Table 12.3.

12.2.2 Simulation method

The simulation method is based on the non-linear strip theory, which is a practical method for simulating ship motions and hull loads in waves. In the method

Table 12.3 Simulated wave-induced vertical loads on the bow visor. Simulation programme and example of results (weight of visor excluded).

Heading [deg.]	Speed [kn]	Bow wave [m]	H_s [m]	T_p [s]	Z force [MN] Mean exceedance period 30 minutes	Z force [MN] Mean exceedance period 10 hours
Head seas, 180	15	1.0	4.0	8.0	2.50	3.60
180	15	1.0	4.0	8.5	2.55	3.95
180	12	0.65	4.0	8.0	2.05	3.10
180	10	0.4	4.0	8.0	1.70	2.70
180	10	0.4	5.5	8.0	4.35	7.15
180	12	0.65	5.5	8.0	4.80	7.50
180	15	1.0	5.5	8.0	5.35	8.10
180	15	1.5	5.5	8.0	6.30	9.60
Bow seas, 150	15	1.0	4.0	8.0	2.95	4.20
150	15	1.0	4.5	8.0	4.00	5.60
150	15	1.5	4.0	8.0	3.45	4.80

applied, the time histories of irregular, long-crested waves and ship motions are generated by employing the linear superposition principle. The bow visor was considered as a small body entering water. Thus, in determining the vertical force on the visor it has been assumed that the dynamic wave pressure and the wave motion, velocity and acceleration are constant within the volume occupied by the visor. The assumption is valid when the wave length is significantly longer than the dimensions of the bow visor.

The numerical model includes the hydrostatic and hydrodynamic forces incorporated in the strip method and the non-linear hydrodynamic forces according to the momentum consideration. The non-linearities of the hydrodynamic forces arising from the variation of the submerged portion of the visor are taken into account by considering at each time step the instantaneous waterplane. The following force components are incorporated in the numerical model:

- Weight of visor, assumed to be 0.6 MN (60 t).
- Inertia force based on rigid-body vertical acceleration of ship at centre of visor.
- Hydrodynamic force due to added mass and damping of visor assumed to be proportional to vertical relative acceleration and velocity, respectively. Heave added mass and damping coefficients were computed beforehand at different waterlines with a three-dimensional sink-source method and curve-fitted. At each time step, values corresponding to instantaneous draught were used.
- Hydrostatic buoyancy force due to instantaneous submerged volume of visor.
- Froude-Krylov force defined as the integral of the linear hydrodynamic pressure in the undisturbed, incident, wave over submerged surface of visor.
- Non-linear, vertical impact force in which the important term is rate of change of the heave-added mass times vertical relative velocity squared.
- Force due to the stationary flow around the submerged visor was computed beforehand by the SHIPFLOW program in calm water at different fore draughts. At each time step, curve-fitted values were used.

The effect of the stationary bow wave was considered as a constant offset increasing the submergence of the visor. Thus, the height of the bow wave estimated by the SHIPFLOW program for different forward speeds was added to the vertical relative motion on the centre line of the visor.

12.2.3 Results

The main results of the simulations are graphs presenting probabilities at which the vertical component of the wave force on the visor exceeds different levels. If exceedance probabilities referring to the number of wave encounters are plotted on a logarithmic scale, and the vertical force on a linear scale, straight lines seem to fit the data quite well. There is no theoretical basis for the linear relationship between the logarithm of the exceedance probability and the vertical visor load. The Weibull distribution has often been applied in fitting long-term wave height and wave load data, but in this case it is unknown how well it would represent the extreme end of the distribution. For this reason, long simulations have been carried out to avoid extrapolation of the data.

The wave load on the bow visor is highly non-linear with regard to wave amplitude. Low waves do not even reach the visor. While the simulated waves have approximately equal wave crest and trough amplitude distributions, a simulated visor load record shows high peaks only when the bow is submerging to the incident wave. When the bow emerges from the water, the force on the visor is close to its weight.

The highest simulated load values have an exceedance probability of about 1/30 000, corresponding to the approximately 30 000 waves encountered during the 36-hour total simulation time. Thus the exceedance probabilities may be changed to mean exceedance periods by using the number of waves encountered during the period in question. In head seas at 10 kn speed the vessel encountered about 780 waves per hour and at 15 kn speed 970 waves per hour. In bow seas at 15 kn, the number of wave encounters was 860 per hour.

Table 12.3 summarises the simulation programme and the results in terms of visor loads with mean exceedance times of 30 min. and 10 hours respectively. There is a chance of about 1/20 that during 30 min. of exposure the extreme load was larger than the value corresponding to 10 hours mean exceedance period. The results are given in the same way as for the model tests with the static weight of the visor excluded.

Table 12.3 and Figure 12.9 show the large effect of wave height on the vertical visor loads. When the significant wave height increases in head seas from 4 to 5.5 m, the load increases by 160 % for 10 kn and 120 % for 15 kn. In bow seas, an increase in wave height from 4.0 to 4.5 m causes an increase of about 35 % in the visor load.

The effect of forward speed on the vertical component of the visor load is approximately linear in the lower sea state. Thus, at 15 kn speed the visor load is about 50 % higher than at 10 kn speed in head seas with H_s = 4.0 m. In the higher sea state, the visor load increases more gradually with speed than in the lower sea state. The visor loads increase when the heading changes from head to bow seas by 15 to 20 % in waves of 4 m significant height.

The effect of stationary bow wave height on the visor load is much smaller than the effect of significant wave height. However, the bow wave is taken into account in a rough way in the numerical method and may in reality have a larger effect on the loads.

Figure 12.7 Comparison of vertical visor loads in oblique bow seas from model tests (red) and from simulations (blue).

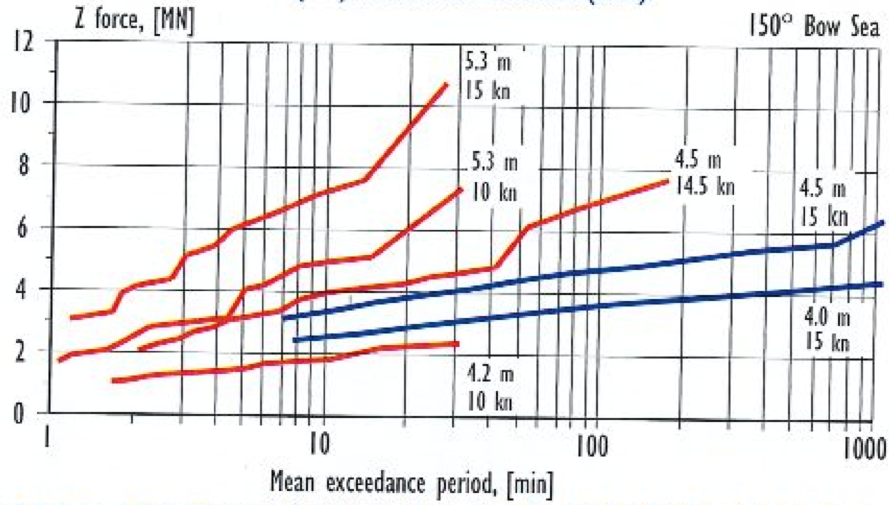


Figure 12.8 Comparison of vertical visor loads in head seas from model tests (red) and from simulations (blue).

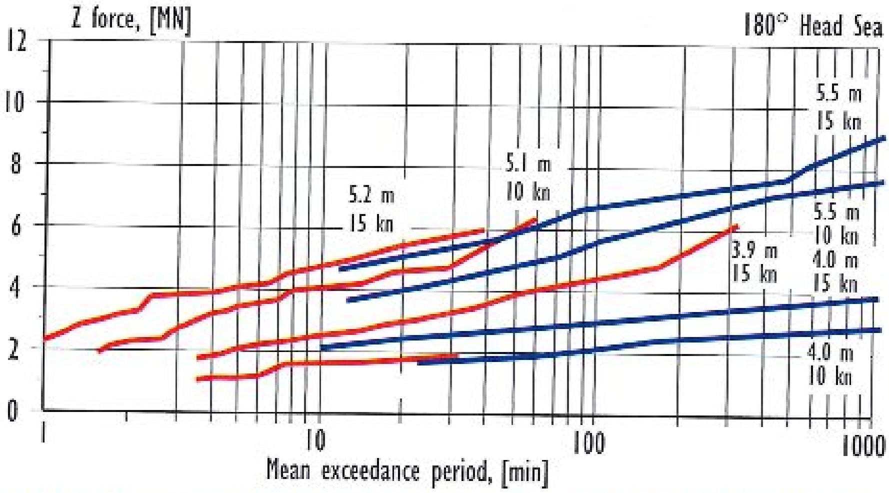
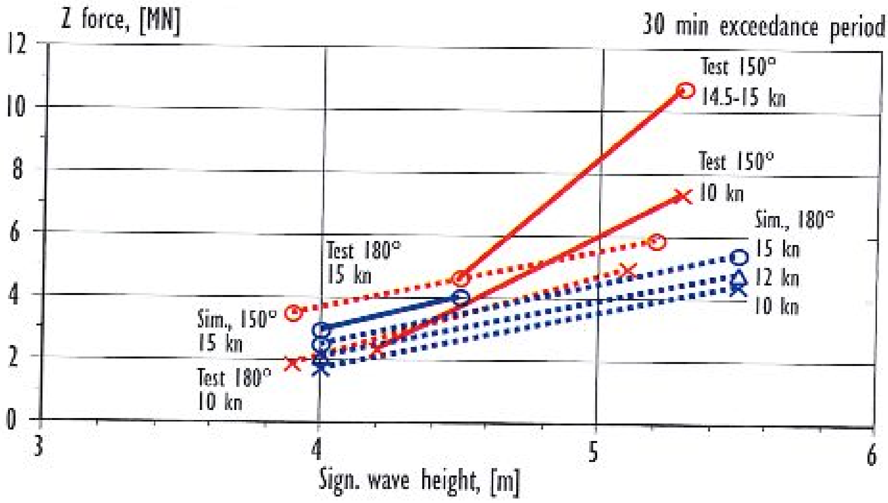


Figure 12.9 Comparison of vertical visor loads from model tests (red) and from simulations (blue). Influence from wave height and speed.



12.2.4 Comparison with experimental results

Qualitatively the simulated results agree well with the experimental data. The experimental time histories of the vertical load on the visor have high upward peaks similar to those of the simulated records and in the downward direction the loads are negligible. The model tests confirm the very strong effect of wave height on the loads and the approximately linear relationship between visor loads and forward speed. Also in the experiments the visor loads were larger in bow seas than in head seas.

Quantitatively the simulations are

compared to the model experiments in Figures 12.7 and 12.8 showing vertical visor load plotted against mean exceedance period, and in Figure 12.9 showing the influence from wave height and speed for 30 minutes mean exceedance period.

In all cases, the simulated loads were smaller than the measured loads. In general, the correlation was better in the higher sea state than in the lower. The correlation was very good in the lower sea state at 10 kn speed in head seas. In 4.5 m bow sea at 15 kn speed, the simulated results agreed quite well with the experimental data up to a mean exceedance period of about 40 minutes, after which the test results increased at a much higher rate than the simulated visor loads.

In addition to the general approximate nature of the numerical simulation method and the several simplifying assumptions involved, there may also be other reasons for the growing divergence of the numerical and the experimental results for mean exceedance periods longer than about 30 minutes. Statistics may have contributed to the divergence at the extreme end of the experimental load values since naturally the model tests were not very long.

A second possible reason for the divergence is a difference in the characteristics of the waves. The simulated wave crests and troughs followed the symmetrical Rayleigh distribution while the higher waves of the experimental wave record were unsymmetrical with higher crests than troughs. Some of the wave crest amplitudes in the tests were rather extreme compared to the significant wave height.

Both the model experiments and the simulations indicate, however, that it is not the highest wave crests which exert the largest loads on the visor. It is not clear what kind of individual wave characteristic are mandatory for high loads, but it seems that the wave crest must be relatively high and steep. Often the trough preceding a high visor load has been quite flat. Though the highest wave crests did not cause the highest loads, the experimental results indicate that there may be some correlation between the highest wave crest in the wave record and the highest vertical load on the visor. It may be anticipated that if the wave crest heights are extreme, those wave characteristics which are significant for high loads on the visor may also be extreme.

Waves measured in the open sea in deep water in general follow the Rayleigh distribution quite well. During heavy storms, however, wave crests start to become steeper and troughs become flatter so that their distributions deviate from that in milder conditions. Also, short wave records may include one or a few very high individual waves.

12.3 Estimate of maximum wave loads on the visor for the conditions at the accident

After the ESTONIA had changed course at the waypoint she sailed for about half an hour at about 14 knots in bow seas before the failure of the visor attachments. The significant wave height has been estimated by different meteorological institutes to 4.0–4.1 m at 0100 hrs at the accident site. Based on the results from model tests and numerical simulations, the Commission has evaluated a probable range of maximum wave loads on the visor during this last period.

The long model test series in bow seas with a significant wave height of 4.5 m is used as the prime basis for the evaluation. Weibull probability distributions have been fitted to the different load components measured at the test. As shown by the long numerical simulations, this type of distribution seems to be valid even down to very low levels of probability. From the basic distributions, extreme value distributions for 30 minutes of exposure time have been calculated, and from these the most probable maximum loads and the range of maximum loads for a 90 % confidence interval. The analysed model test is summarised in Table 12.4. Since the number of recorded load peaks per 30 minutes was low, the range of evaluated probable maximum values becomes wide. Especially the X and Y moments, which have a significantly lower shape parameter, k, than the forces, show a large spread in the distribution of maximum values. The Z moment distribution was not analysed in detail.

Finally, the loads for the accident condition were roughly estimated by reducing the model test loads with respect to the differences in significant wave height, 4.5 m and 4.0–4.1 m respectively. The forces were reduced by 30 % and the moments by 50 %. The level of reduction in forces is taken from the numerical

Table 12.4 Summary of wave load probability distributions for the model test: H_s = 4.5 m, 150° bow sea, 14.5 knots speed.

Load type	Cumulative probability distribution			Maximum value during 30 min.		
[MN] [MNm]	Weibull: $F(x) = 1-\exp(-(x/b)^k)$ parameters: b	k	No. of load peaks per 30 min n	Exceed. probability 0.95	Most probable maximum	Exceed. probability 0.05
X force	1.41	1.04	50	3.85	5.23	9.01
Y force	0.58	0.93	11	0.85	1.49	3.53
Z force	1.40	1.05	53	3.86	5.20	8.86
X moment	1.00	0.60	8	1.28	3.39	14.88
Y moment	5.11	0.81	11	7.97	15.04	40.71

simulations, see Table 12.3 and Figure 12.9, while the reduction in moments is based on an analysis of the correlation between forces and moments, Figure 12.10.

The Commission's estimate of maximum wave loads on the bow visor for the accident conditions is summarised in Table 12.5. Since the waves in the model tests had rather high crests compared to their troughs, this estimate may be on the high side. On the other hand, the uncertainty in sea state is, according to the meteorological institutes, about 0.5 m in significant wave height. Were this uncertainty also accounted for, the maximum values in the given range would increase significantly.

Figure 12.10 Correlation between vertical forces and opening moments from model tests. Rings show the single highest measured value in the different series, black dots show the 13 highest values in the test with bow sea and H_s=4.5 m. The line shows the estimated range of maximum loads for the accident condition.

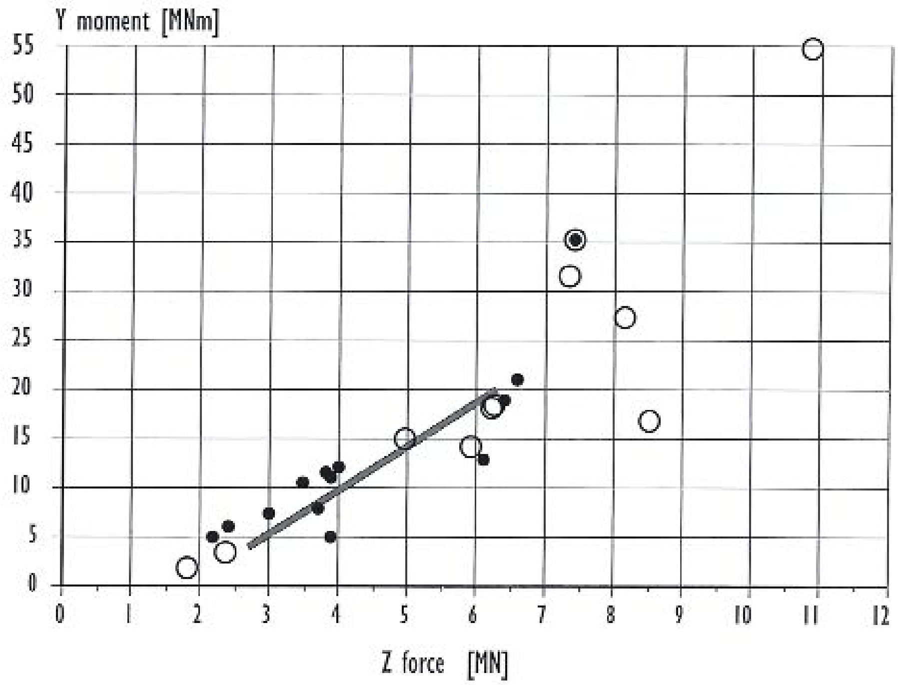


Table 12.5 Summary of estimated maximum wave loads for the accident conditions. Oblique bow sea, H_s 4.0–4.1 m.

Load type	Load direction	Maximum value during 30 min. Range of 90% confidence	Most probable
Visor forces:			
X force (longitudinal)	aft	2.7 – 6.3 MN	3.6 MN
Y force (side)	starboard	0.6 – 2.5 MN	1.0 MN
Z force (vertical)	upward	2.7 – 6.2 MN	3.6 MN
Deck hinge moments:			
X moment	upward on port side	0.6 – 7.4 MNm	1.7 MNm
Y moment	opening around hinges	4.0 – 20.0 MNm	7.5 MNm
Z moment	fwd. on port side	0.5 – 2.5 MNm	1.0 MNm

12.4 Predictions of wave-induced motion

12.4.1 Computation method

To analyse the general situation on board the ESTONIA with regard to wave-induced motions, numerical predictions have been made by applying the linear strip theory and the linear superposition principle. The strip theory underlies a very well known numerical method which has been validated in many comparisons with model and full-scale experimental results. In the present case also the theoretical results show good correlation with experiments.

Main attention has been paid to passenger comfort as dictated by vertical accelerations, to green water on deck and to bottom slamming. The full report on wave-induced motions is included in the Supplement.

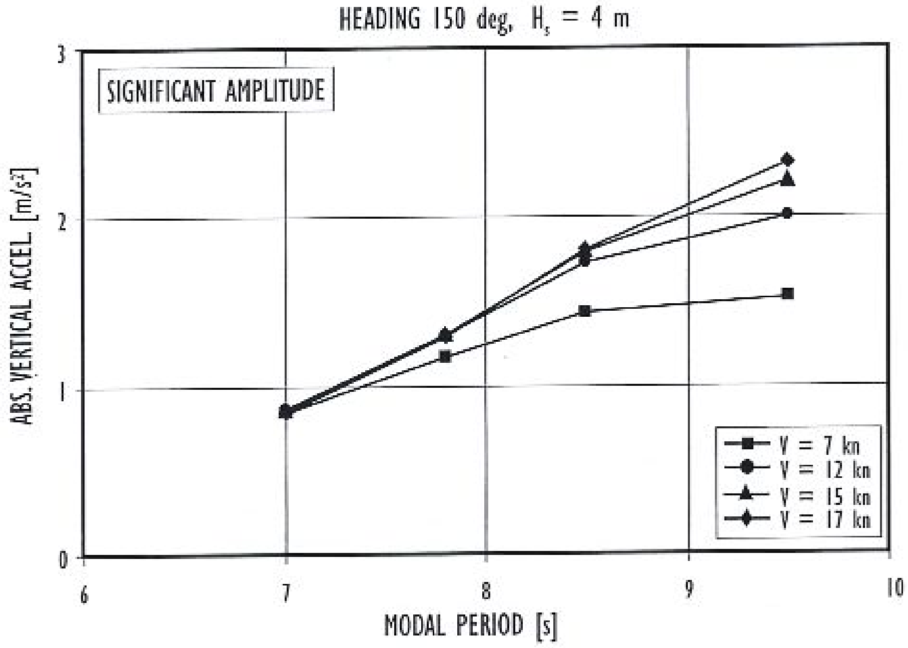
The numerical predictions were made for long-crested irregular seas defined by JONSWAP and ISSC wave spectra. The wave periods corresponding to the spectrum peaks, the modal periods, were 7.0, 7.8, 8.5 and 9.5 s. In the case of 7.8 s, which is close to the wave period at the time of the accident, wave-induced motions were also computed in short-crested seas. The significant wave height used was always 4 m, i.e. the estimate of the conditions prevailing at the time of the accident.

The effect of ship speed on the wave-induced motions was examined assuming speeds of 7, 12, 15 and 17 knots. The headings to waves were 180° i.e. head seas, and 150° and 120° representing bow oblique seas. The ESTONIA encountered the waves slightly on her port bow.

12.4.2 Results

The numerical results show in general that modal wave period and heading to waves have a greater effect on wave-induced motions than does forward speed

Figure 12.11 Vertical acceleration at the station of the bridge in bow sea with H_s=4 m.



within the wave periods and headings considered here. Significant motion amplitudes increase with increasing wave period and when the heading to waves changes from direct head seas towards beam seas. The motions were larger in short-crested seas than in long-crested with the exception of the heading 120°. The results indicate that the waves during the accident night were relatively short compared to the length of the ship and she was more or less running through the waves, in particular before midnight.

Just before the accident the significant amplitude of vertical acceleration at the bow visor was 2–2.5 m/s² and the largest amplitudes may have been about 0.4g. This acceleration level is roughly half of the level at which cargo vessels change heading or slow down to decrease the accelerations, and about two thirds of the corresponding level for ro-ro cargo vessels.

In the fore part of the passenger compartment shortly before the accident, the vertical accelerations significantly exceeded the severe discomfort boundary of the Motion Sickness Standard ISO 2631/3. The corresponding ISO boundary value is 1.0 m/s² in terms of a significant amplitude corresponding to a motion sickness incidence (vomiting) of 10 %. About 20 % of the passengers in the ESTONIA's fore cabins may have been seasick. Amidships the vertical accelerations were significantly below the ISO boundary value and aft they were approximately at that value. Before midnight, when the wave height was smaller, the vertical accelerations were at least 25 % less than just before the accident.

A reduction in speed from 15 knots to 7 knots would have decreased the significant vertical acceleration from about 1.5 m/s² to 1.3 m/s² in the fore part of the passenger compartment, or at the station of the bridge (Figure 12.11). By changing the heading to waves, the acceleration level would have started significantly decreasing in stern-quartering waves. Considerably higher vertical accelerations than these predicted for the ESTONIA have been measured on board passenger vessels in severe storms in many sea areas including the Baltic.

The water level at the bow rose above the level of the car deck at nearly every wave encounter due to the combined vertical motion of bow and wave surface. On average, one wave in a hundred, i.e. one every five minutes, reached the level of the upper edge of the ramp opening. From here, there was still 2.5 m freeboard to the stemhead. On these occasions, spray and water reached the foredeck. Survivors have stated generally that there was quite a lot of spray and water flying in the air with occasional submergence of the bow. However, serious amounts of green water on the foredeck were rare as were real bottom slams. Flare impacts probably occurred much more frequently than bottom slams.

12.5 Determination of hydrodynamic characteristics in heeled condition using model tests

It has been discovered both from the sonar investigations of fragments on the seabed and from manoeuvring simulations that the ESTONIA made a port turn at an early stage of the accident. To determine whether the port turn could possibly have been initiated spontaneously by the ship's changed hydrodynamic characteristics when she started to heel in forward speed, a series of model tests was carried out at SSPA Maritime Dynamics Laboratory in conjunction with the wave load tests. A full report of the test results is given in the Supplement.

The self-propelled model of the ESTONIA was run in calm water and in bow seas respectively at a forward speed of 14.5 knots. During running, different weights were placed on the ship side, causing static heel angles from 9° to 27°. With the autopilot working there were no problems to maintain a straight course using only moderate rudder angles. With the rudders locked, the ship had a tendency to turn in the same direction as the heel angle i.e. a starboard list would cause a starboard turn. There were no significant differences in behaviour when the weights were placed at different longitudinal positions.

From the model tests it can be concluded that the possible port turn at an early stage of the capsize was not initiated by the changed hydrodynamic characteristics of the ship in heeled condition. However, the tests were carried out without any wind. From manoeuvring simulations, it has been shown that with locked rudders and decreasing speed a bow wind would cause the ship to turn towards the wind, but not fully through the wind over to the other side.

12.6 Simulation of flooding and sinking of the vessel

Theoretical studies were ordered by the Commission to clarify and simulate the rapid flooding, capsize and sinking of the ESTONIA. These studies include analysis of hydrostatic floating conditions and stability, wave-induced motions in heeled condition and water inflow rate on the car deck in the initial phase of the capsize. The full reports are included in the Supplement. Below is given only a brief summary of the major results.

12.6.1 Floating conditions and stability during flooding

New stability calculations were carried out for the Commission, based on the latest valid inclination test. The calculations confirm that for the loading condition of the accident voyage the ESTONIA satisfied the two-compartment damage stability requirements specified in the SOLAS 1974 Convention. The damage stability requirements concern only the watertight part of the vessel below the bulkhead deck, i.e. below the car deck in this case.

The initial stability of a ro-ro ferry with a large open car deck is extremely sensitive to water ingress to the car deck. Small amounts of water will impair upright stability and cause extensive heel in equilibrium condition.

The ESTONIA's static stability with various amounts of water on the car deck has also been analysed. Figure 12.12 shows static stability curves for increasing amounts of water on the car deck, from 0 to 4,000 t. These curves apply when ship side is intact. The analysis shows that 400 t of water on the car deck will give a static list angle of just over 10° and 1,000 t just over 20° (Figure 12.13). The additional heel from a sharp turn at 15 knots would be about 3°.

Even though the list developed rapidly, the water on the car deck would not alone be sufficient to make the ship capsize and lose its survivability. As long as the hull was intact and watertight below and above the car deck, the residual stability with water on the car deck would not have been significantly changed at large heel angles (Figure 12.12). The capsize could only have been completed through water entering other areas of the vessel.

According to the hydrostatic calculations, a continuously increasing amount of water on the car deck would make the aft windows of deck 4 the first possible flooding point to other areas (Figure 12.14). Soon thereafter the windows and the aft entrance doors of deck 5 would

Figure 12.12 ESTONIA's static stability curves for different amounts of water on the car deck, ship side assumed intact.

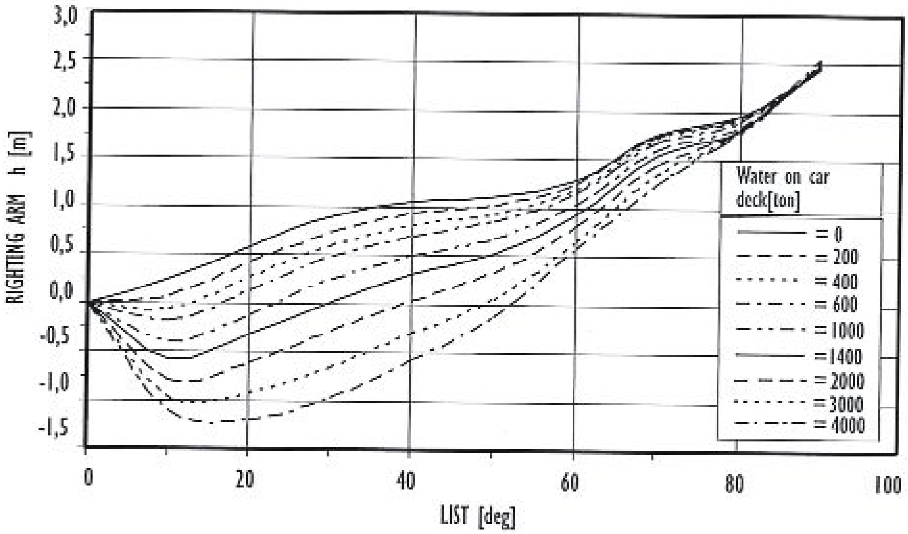


Figure 12.13 ESTONIA's list against the amount of water on the car deck.

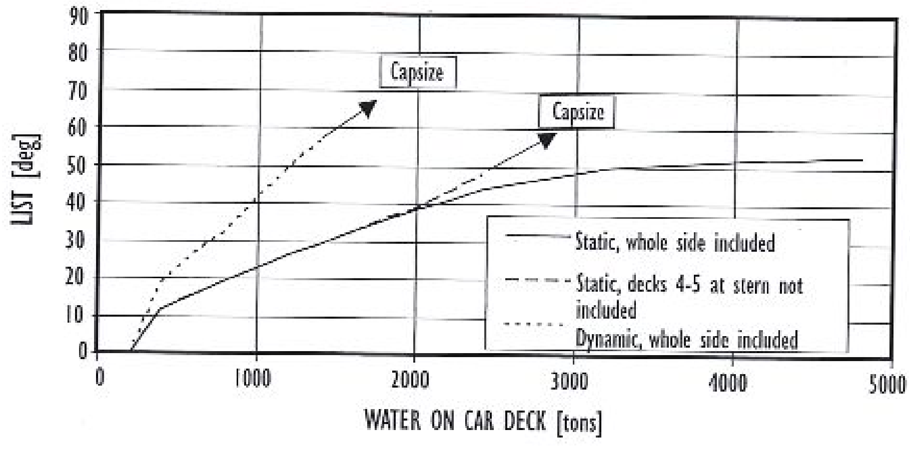
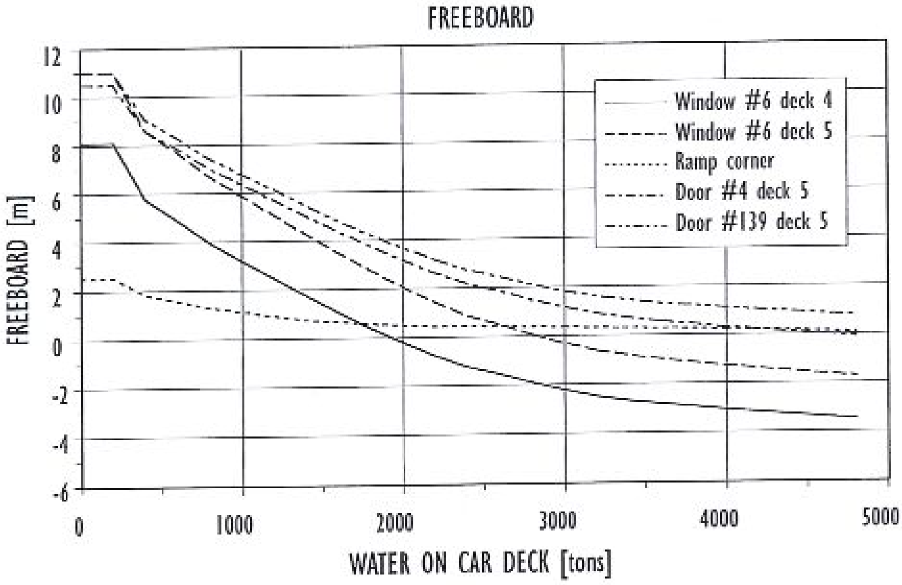


Figure 12.14 Freeboard to first possible flooding points plotted against amount of water on car deck. The openings are aft side windows on decks 4 and 5 at frame #6, bow ramp starboard corner, aft door on deck 5 and fore door on deck 5.



also be submerged. A little less than 2,000 t of water on the car deck would be sufficient to bring the first flooding points down to the mean water surface. In this condition the list would be about 35°. The lowest corner of the ramp opening would here be still a little above the mean water surface.

As soon as water was free to enter the accommodation decks all residual stability would be impaired and the ship in practice lost. Without an intact superstructure above deck 4, the largest possible equilibrium heel angle before a complete capsize would be 40°. This condition would be exceeded with about 2,000 t of water on the car deck.

Stability calculations show that the ESTONIA would have had a small positive initial stability if the two sauna compartments and the next compartment aft on deck 0 had been flooded. The stability would have been worst at the initial phases of flooding and would have improved when more water flowed to these three compartments.

The influence of cargo shifting was also investigated in separate studies. Due to the distribution of vehicles on deck, the maximum transverse shifting of cargo centre of gravity could have been of the order of just a few metres. Two metres of cargo shift would have the effect that the progressive flooding of deck 4 started with about 10 % less water on the car deck.

12.6.2 Water inflow simulations

The water inflow through the ramp opening after the visor had failed and was lost was simulated with two different numerical methods. One is similar to the numerical wave impact load simulation, i.e. an approach where the relative motions between bow and waves are described in the time domain. The other approach uses the frequency distribution of relative motions.

The common input to the simulations is:

- A description of relative motion in a random sea condition,
- a description of the relative velocity of water particles in the ship's longitudinal direction as a function of vertical position, wave profile and the ship's heading and speed,
- a description of the changing floating condition during water ingress.

Results obtained from the simulations are very sensitive to small changes in the initial parameters, and the inherent uncertainty in the random nature of waves and ship motions during short periods of time is very large. Therefore, the results cannot be used to independently prove a certain time sequence of water inflow. The value of the simulations is primarily to verify whether the assumed capsizing scenario is possible with regard to the water inflow rate.

During the first phase of the accident, the ESTONIA is assumed to have been sailing at a speed of about 14 knots into bow-incoming waves with a significant wave height of about 4 m. The average water inflow at the instant when the ramp was torn fully open has been calculated to be in the range of 300–600 t/min depending on what assumption is made regarding forward freeboard in running condition (Figures 12.15 and 12.16). This means that within just one or a few minutes a heel angle of about 20° could possibly have developed.

The successive phases of the capsize are dealt with in more detail further on in this report, where the time sequence and the full capsize scenario are analysed based on witnesses' statements and an interpretation of the results obtained from these simulations. Here the general influence of changing conditions is briefly summarised.

The speed of the vessel greatly influences the inflow rate. If the speed is reduced from 15 to 10 knots, the inflow rate in head and bow seas decreases by about 50 %. This effect is due partly to reduced inflow velocity and partly to reduced bow wave height.

The amount of water on the car deck also affects the inflow rate. When the ship heels over, the freeboard to the ramp opening decreases and the inflow accelerates. To some extent this effect is contradicted by changed motion characteristics in heeled condition. The separate

Figure 12.15 Probability of exceedance for different amounts of water inflow to car deck through bow ramp opening in bow and head seas at 15 knots speed with list angle as a parameter. C = Freeboard to the starboard corner of ramp, BW = bow wave height.

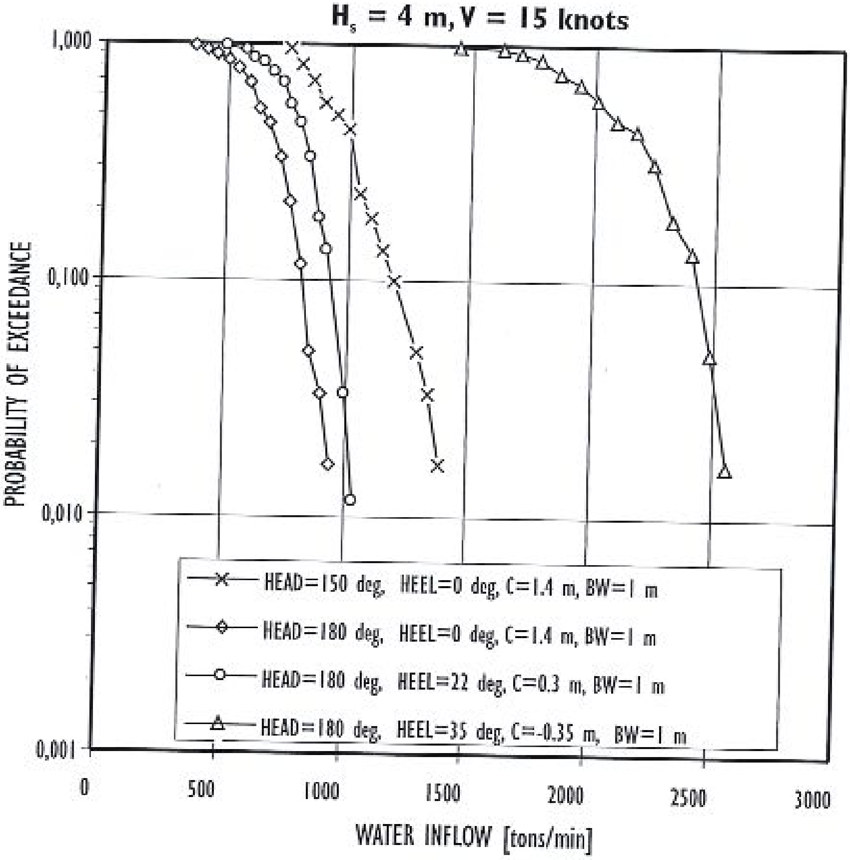
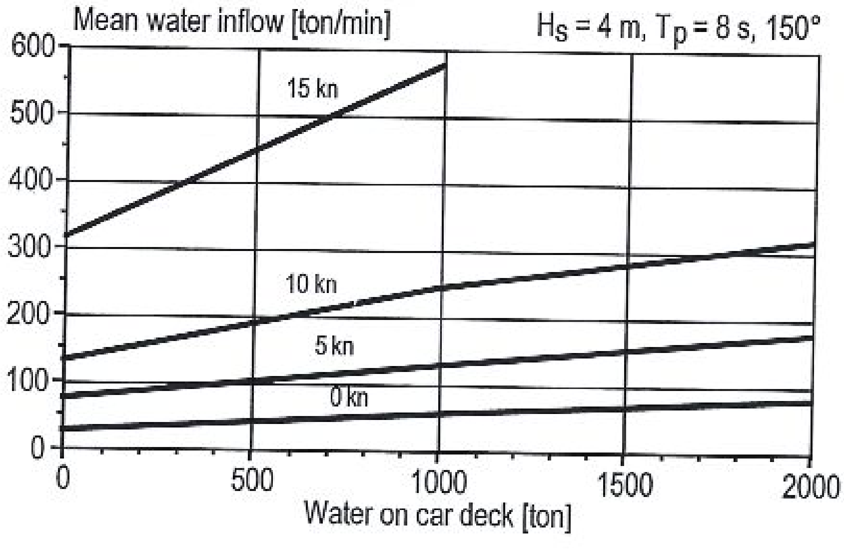


Figure 12.16 Mean water inflow as function of ship speed and amount of water on car deck in bow sea.



studies produced some differences regarding the motion characteristics and the results diverged with respect to heel angles; however, the inflow rate is generally 2–3 times larger than the initial upright condition when 1,800 t has entered the car deck and the heel is around 35°.

Wave direction also affects water inflow. The highest rate of inflow is found in bow sea due to large relative motion amplitudes. In beam sea the inflow rate is very low as long as the speed and heel angle are not excessive.

The simulations indicate that the time from the first inflow through the ramp opening until progressive flooding of accommodation deck 4 started was about of 5–15 min. However the time estimates depend greatly on what action is assumed to have been taken during the first critical minutes.

12.7 Investigation of visor attachment

12.7.1 General

Different investigations of the failed visor attachments and closely related items were performed. They include detailed studies of recovered parts from the actual installation, strength analysis and laboratory tests. Components retrieved from the near-sister ship DIANA II were investigated for comparison. This section contains a brief summary of the reports included in the Supplement. A conclusive analysis of the visor attachments' strength is given in Chapter 15.

Materials of recovered parts were identified by analysing their constituent chemical elements and with mechanical, hardness, tensile and impact testing as appropriate to establish strength and basic standard cold brittleness. The deformed visor lug of the bottom lock was measured for estimating the type of overload and the load level to which it would have been subjected comparing it with deformation-load interdependencies obtained through full-size model testing. The stiffness of the whole visor was measured to assess its effects on the wave load distribution to the various attachment points.

Analytical and finite element calculations were used for estimating the strength of the different attachments taking account of their actual geometry and material. The welds as well as any deficiencies found were assessed where pertinent.

The combined strength of the visor attachment system was estimated with balanced reaction load calculations using variation of external loads. In the calculations, either parameters describing load sharing and/or attachment site stiffness were used, or attachment loads were assigned by using parametric variation of the wave load centre of action in relation to the positions of the attachments.

The paint layers on the surface of the bottom lock were investigated in some detail to estimate approximately the age of the attachment.

12.7.2 Material identifications and microscopical observations

Materials used for the various attachments were identified as given in Table 12.6. The table also defines the tests applied and includes remarks on main observations.

Optical and electron microscopy were used to find signs of cracking and to identify the character of various fractures. Particularly the visor actuator mounting platforms had fatigue cracks of marked significance for ultimate strength. On the port side about half of the perimeter cross-section through deck 3 had developed fatigue cracks before the accident. Some repair welding had been undertaken.

Table 12.6 Summary of materials used for the attachments and tests applied.

	Main investigation	Additional tests	Other	Probable Material ID & other remarks
Bottom lock				
Visor lug	Dimensions	Hardness HBS 10/3000		Mild steel. Stretched about 6 mm by load exceeding limit for general yield.
Broken lugs and weld joint of forepeak structure.	Tensile test	Hardness HV 10	Microscopy	Lugs: mild steel. Weld: high-strength steel. Some cracking in welds.
Locking bolt from DIANA II.	Hardness and dimensional measurement.	HBS 5/250 and HRB		230 – 235 HBS 5/250 96 – 98 HRB (UTS = 760–785 MPa)
Visor lug from DIANA II.	Hardness and dimensional measurements.	Hardness HBS 10/3000		Mild steel. Stretched similar to the ESTONIA lug.
Side locks				
Visor aft plating	Tensile test. Through thickness tensile test. Test section 12x12 mm², length 8 mm.	Thickness 8 mm		Mild steel. No detrimental effect of delamination on strength – material of high quality.
Horizontal stringer	Tensile test	Thickness 10 mm	Chemical analysis	Mild steel
Vertical stiffener		Thickn. 20 mm Weld a ≈ 5 mm	Chemical analysis	Mild steel
Hinges				
Lug plates	Tensile test Impact test			Mild steel Grade E (TKV28<-40°C)
Bearing bushing	Chemical analysis			
Bushing weld joint	Tensile test of 14 mm slice including bushing, weld joint and lug plate.			Fracture dominantly by 6.4 mm wide shear at weld joint, UFL 0.12 MN, USS = 717 MPa
Lifting cylinder attachments				
Hinge arm lug	Hardness testing			Mild steel
Deck 3 plate	Impact testing		Fracture microscopy	Grade C (TKV28<0°C) Fatigue and cold brittleness cracking.

Hardness measurements: HBS 10/3000 is Brinell hardness measured using steel ball of 10 mm diameter and 3000 kg mass, HRB is Rockwell B-hardness and HV is Vickers pyramid hardness. Strength values: UTS=ultimate tensile strength, USS=ultimate shear strength and UFL=ultimate fracture load. Cold brittleness characteristic TKV28=temperature for reaching 28 J impact toughness using the Charpy-V method.

12.7.3 Investigations of the attachments

Bottom lock attachment and visor lug

Specimens of the actual bottom lock attachment lugs recovered from the wreck were tested with regard to material properties. The material was regular mild steel with a yield strength of about 240 MPa and an ultimate tensile strength of about 410 MPa. The lug fractures showed patterns typical of good-quality ductile plate that failed due to local overload. Some branched cracks that were small compared to the size of the lugs were detected close to the primary fracture surfaces of the welds between the plates and the locking bolt housing. These cracks may have developed under normal operation due to the cyclic nature of operating loads or e.g. during the sequence leading to failure of the bottom lock. The separate effect of these small cracks has been impossible to quantify but their combined effect on the load-carrying capacity of the lock was apparently small due to the ductility of the plate material.

The fracture surfaces of all three bottom lock attachment lugs were examined by optical stereo microscope and by scanning electron microscope. It was concluded that all the fracture surfaces had a ductile character and that the failure types were the result of overload. It was also noted that the fillet welds attaching the housing and the lock bushing showed signs of poor fusion and lack of penetration.

Hardness was measured on welds and base plate of the lug assembly on the forepeak deck to estimate the strength of the weld. The hardness of the bushing-lug weld material was HV10 = 270–275, which translates to an ultimate tensile strength of 865 MPa (DIN 50150) for the weld material. The hardness of the lug plates was HV10 = 128–150, which correlates well with the ultimate strength of 417 MPa measured. The weld material and the adjacent heat-affected zone were thus significantly stronger than the material of the plates that had been joined together.

The failure strength of each attachment lug was calculated based on the material properties found in the testing and the actual cross-section of each fracture surface.

The welds contribute significantly to the strength of the lug assembly. A large variation in the path of the weld fracture made measurements of the weld size contributing to strength very tedious. The most unambiguous value for the strength of the bottom lock was obtained by analysing the deformations of the mating lug. A transfer calculation developed as part of the investigation served to estimate the contribution from the welds. The calculation indicates that the effective size of the weld joint could have been around 3 mm. This was also observed, although the actual weld joint was quite irregular.

The mating visor lug was bent and elongated (Figures 12.17 and 12.18). Hardness testing showed the plate material to be most probably mild steel and

Figure 12.17 The visor lug for the bottom lock with a disc of the same diameter as the bolt inserted.

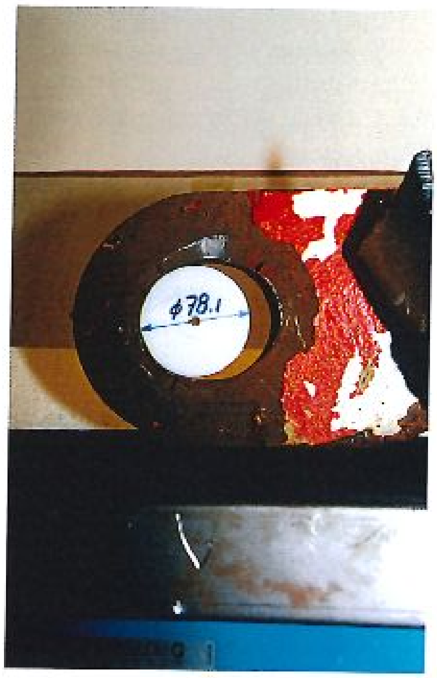
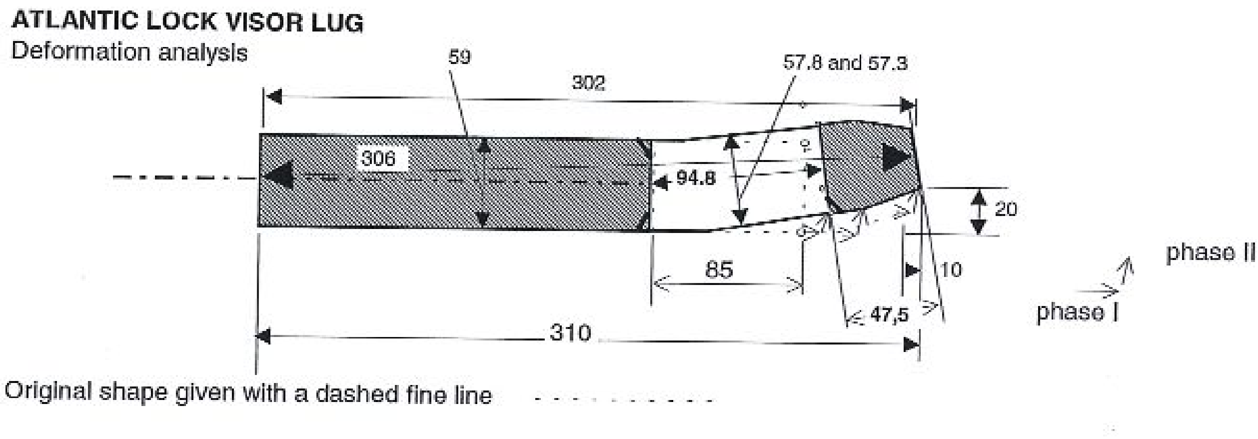


Figure 12.18 Dimensions of the visor lug after the accident.



similar to the material of the hinge plate. The aft or eye end of the mating lug had been elongated and bent to starboard. By analysing the shape of the hole and lug rim it was concluded that the original dimensions of the lug aft end had conformed to drawing. In its retrieved condition the aft end eye ligament had the designed dimension of 47.5 mm suggesting no damage by wear to this side of the eye.

Comparison with tests with several mock-ups of full or subsize scale showed that the lug had been stretched, most probably prior to the bending. The tests indicate that permanent yielding in the authentic lug started at a tensile load of about 0.5 MN. The measured net stretching of around 6 mm may have occurred under a load of about 1.5 MN. In addition wear of up to 2 mm was observed on the stem (forward) side of the eye suggesting leaning of the visor against the locking bolt. The dimensional analysis indicated that the initial length of the lug stem was 3 mm less than the drawing dimension.

Load capacity of the forepeak deck lug assembly was estimated by calculations based on two different methods. One used the deformation energy principle employing the assumption of a perfectly stiff locking bolt. The other was a simplistic strength estimate based on the assumption of the weld carrying its ultimate strength in shear of the simply sheared part of the failure path cross-section and the projection of the weld cross-section actually subjected to mixed shear and tension. Both methods included parameters that needed quantification by test results.

It was impossible to determine whether usage-related damage – e.g. fatigue cracks – had reduced the strength of the bottom lock. No fatigue cracks were found in the forepeak deck lugs, but cracks could have existed in the welds prior to failure. Recognising this it was estimated that if half or more of the weld joint related load-carrying capacity had been lost, the strength of the bottom lock would have been about 0.8 MN at its lowest as demonstrated by testing at the Technical University of Hamburg (see 15.3). In this case, logically the 1.5 MN load that had sometimes acted to stretch the visor lug must have actually occurred earlier. This load must then have initiated the damage to the welds, and the original strength of the bottom lock would have been more than about 1.5 MN. It has also been calculated that the strength of the bottom lock could theoretically not have exceeded 1.8 MN, the estimated load needed to break the visor lug by shearing the lug tip, as indicated by testing at the Technical University of Hamburg.

Bottom lock details from the DIANA II with a similar visor locking installation as in the ESTONIA were also investigated. They included the visor lug and the bolt. The bolt material was identified to be of a higher strength grade than the lug plate. The visor lug material was identified as mild steel. The aft or eye end had stretched apparently by overloading up to several millimetres in similitude with the visor lug of the ESTONIA. The lug eye and the bolt had several millimetres more wear on their stem sides due to leaning of the visor onto the locking bolt and the rubbing that had occurred.

Paint layer analysis

Samples of paint coatings were analysed from the forepeak deck starboard lug (Figure 12.19) and from the visor lug for the bottom lock (Figure 12.20). The paint system consisted of several paint layers, from 4 to 7 in the samples from the forepeak deck lug and 8 layers in the sample from the visor lug. Many of the layers were discontinuous. The chemical compositions of the paint layers indicate that both lugs had similar light brown "varnish" and grey primer. The yellowish primer closest to the steel in the visor lug was not detected in the paint samples from the forepeak deck lug. White and red paint stains found between the topmost layers and on the surface of the forepeak deck lug had similar chemical composition as the red and white paint layers in the sample from the visor lug. It thus seems evident that the whole bottom lock was old and dated at least to the early history of the ship. The detailed reports of the paint systems investigations are included in the Supplement.

Side locks

The side locking lugs with part of the visor plating remain on the wreck, still attached to the locking bolts. Thus the only parts possible to investigate from the actual installation were from the visor structure at the original position of the side locking lugs.

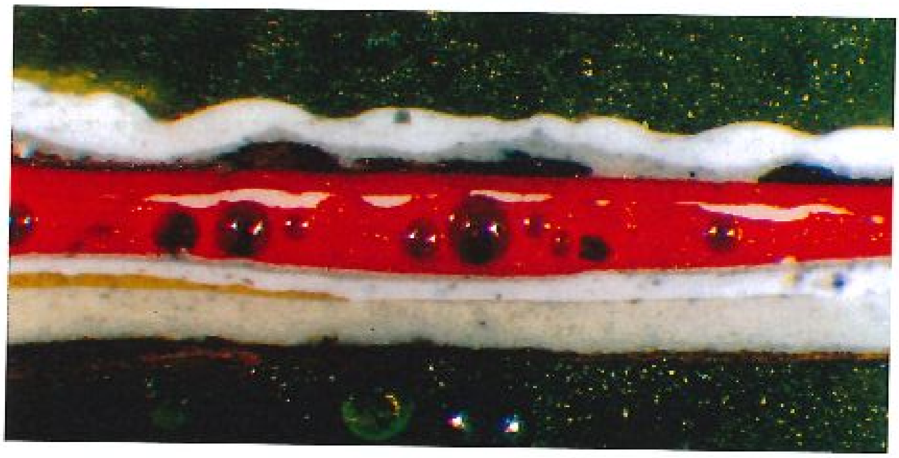
The bulkhead plating in the areas where the lugs for the side locks had been mounted were investigated. It was concluded that the lugs had separated by shearing of the horizontal stringer plate, the vertical stiffener at the related weld and through the visor aft plating. Some delamination of the aft plating material was observed. The shear surface in the aft or bulkhead plating had marks of heavy rubbing.

The attachment arrangement for the side locking lugs was investigated in detail and their strength was evaluated with both full scale mock-up tests and computer modelling and calculations. A loading direction commensurate with visor release by rotation either about the hinge axis or the stem post without twisting or yawing was primarily considered. Thus only tension at 38° to the visor aft plating was considered in the tests, but other directions were assessed by calculation.

Four full-scale mock-up tests were made with various degrees of rigidity in the plate membrane and stiffener plates onto which the lock lug had been welded (Figure 12.21). In the relevant test cases the failures were very similar to the authentic failures, i.e. tearing of the aft plating. Membrane and stiffener stiffness had a significant effect on the strength of the lug attachment model. The test which was deemed to be most representative gave a failure load of the lug attachment of about 1.8 MN. Tensile tests of authentic plates were made. A welding defect was noted on the authentic port side installation of the horizontal stringer (Figures 12.22 and 12.23). This defect was estimated to reduce the strength to 1.2 MN,

Figure 12.19 Cross-section of a paint sample from the forepeak deck starboard lug.

Figure 12.20 Cross-section of the paint sample from the visor lug for the bottom lock.



account also taken of the differences between the test mock-up materials and the authentic plates. Similarly, the strength of the starboard locking site was estimated to be 1.6 MN. The failures took place by shear of the stringer plate first and then in the plating around the fillet weld of the lug, leaving similar fractures to that noted in the actual failure.

Calculations made parallel to the testing confirmed the test results. A numerical estimation by the finite element method, using the actual material stress strain curve data and partial visor structure, gave an ultimate collapse load level of 1.6 MN. The failure load of the lug attachment would have been lower if the acting force had been parallel to the bulkhead plating, e.g. if the visor had been lifted vertically instead of rotated around its end points.

Hinges

Fracture surfaces of the hinge beams were partially investigated in the same way as the bottom locking lugs. The studied failures were of ductile character and signs of fatigue were not seen. A fracture was observed in one sample, penetrating through the weld. The gap inside the weld was filled with magnetite, indicating slow corrosion in an atmos-

Figure 12.21 Full-scale mock-up test of the side locking lug structure.

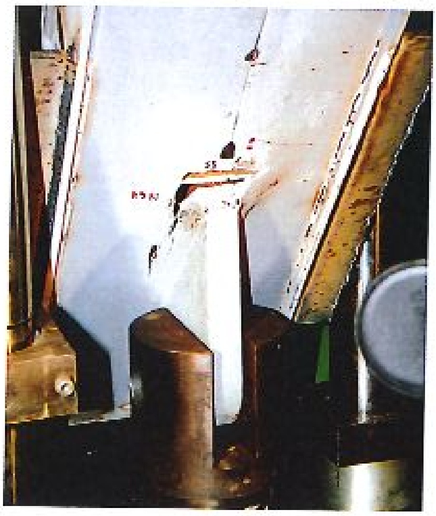


Figure 12.22 Failure at port side lug location at horizontal stringer.

Figure 12.23 Failure at starboard side lug location at horizontal stringer.

phere with low oxygen content. This was taken as indication that the crack had existed for a long time before the accident, allowing some moisture to penetrate.

In subsequent studies it was also confirmed that the welds at the hinge bushings had extensive cracking in the roots and that these cracks had to some extent progressed under fatigue conditions. It was concluded that the failure of the rims of the hinge beam side plates started with ductile failure of the lower part of the periphery as a result of overload, followed by failure of the upper part due to bending as evidenced by lateral contraction of the tensile or inner side and lateral expansion of the outer or compression side. Microscopic features displayed ductile character.

The parts of the hinge lug plate rim fractures that were flat fractures called for evaluation of their character also with respect to material toughness or cold brittleness. For this reason impact toughness specimens from the hinge beam side plate were tested. The values indicate high toughness and thus no tendency to reduced strength by brittleness.

The ultimate failure strength of the plate material was found by standard tensile testing to be 450–460 MPa, i.e. mild steel.

Two tensile tests were also carried out on the weld joints using a slice of the bearing support bushing-hinge plate rim. Test specimens were prepared from segments of one recovered hinge bushing with parts of the outer rim of the visor hinge beam side plate attached to it. These gave a failure load of 0.12 MN for the tested length (14 mm) of actual fillet welds. The failure occurred dominantly in shear with an ultimate shear stress of about 700 MPa. Thus, the weld material had a very high strength.

The strength of a complete hinge was calculated on the basis of the test results for the strong tensile aftward direction of 21° down from horizontal and aft, and the weak shearing direction of 21° forward from down. The strong direction is assumed to coincide with the line bisecting the angle of the hinge beam in its aft part and the weak direction is normal to this.

The strength for one hinge was estimated to be 4.6 MN for the weld joint shear fracture of bushing to lug weld and an additional 2.3 MN for the lug rim at yielding load if this addition applied in case of close clearance between the lug and the bushing.

A previously observed crack in the downward segment of the hinge bushing weld joints that was reported to the Commission was taken into account in the strength estimates. Root cracking detected in the forward segments was not accounted for separately and may have lowered the actual strength from the values given.

Actuator attachments

The attachments of opening actuators had secondary influence on the release of the visor. Material identification and fractography was undertaken for completeness of the investigation. It was found that the mounting platform at the bottom of the port actuator on deck 3 had cracking significant for the strength of the platform. Deck 3 plate had finally fractured by the cold brittleness mechanism – cleavage. One lug of four on the hinge beams –providing for the upper attachment of the actuators – was identified by hardness testing to be mild steel.

Attachment system

The combined strength of the visor attachment system was estimated by calculations covering strength estimates for the individual attachment components and studies of the load distribution within the system.

A system of five attachments is statically indeterminate and reaction forces will depend on the stiffness both globally and locally at the attachments. Also misalignment and play between bolts and lugs at the locks may influence the load distribution. It was thus considered to be of little value to make a complete numerical analysis of the whole visor. Instead the failure load levels for different assumed load or stiffness distributions were assessed. The results of the analyses are therefore indicative rather than conclusive.

The global stiffness of the visor was measured in its upside-down, stored position as supported at the hinge beams. By adding a weight at one hinge beam and lifting at the other, a vertical displacement compliance of approximately 25 mm/1 MN lifting load was obtained. The visor was thus moderately flexible across its centre line in relation to the expected loads of several MN. Each side of the visor is a box structure and is estimated to be fairly stiff compared to the visor's side-to-side distortion flexibility. The lower part of the structure holding the bottom locking lug is also flexible compared to the sides.

Three different calculation schemes using principles of statics including assumed load sharing by the locking sites were formulated for estimating the load levels and directions at the attachments from an applied bow load level and direction. One of the methods varied load sharing systematically between the attachments, another varied the relative stiffness of the attachment points and the third varied the location of the wave load centre of action. Load component ratios obtained from SSPA's model tests were used in estimating the total load needed to break the visor attachments. The results indicate that the port side lock appears to have broken in bow sea at a lower level than the load required to break the next attachment. It could not be determined which of the remaining attachments, the bottom lock or the port hinge, would break second as the uncertainty in finding the strength level of the hinge was quite large. Estimated failure load levels in bow sea were significantly lower than those in head sea.

Observed damage to the visor indicates that the hinge may have broken second, allowing subsequent rising of the visor with damage caused to the port locating horn recess as well as a marked downward bending of the mating bottom lock lug on the visor.

CHAPTER 13

DEVELOPMENT OF THE ACCIDENT

13.1 Meteorological conditions

The weather at the accident site at about 0100 hrs was rough but not extreme. The wind was south-westerly, mean velocity 18–20 m/s. Statistically, winds of such force occur five to ten times annually during the autumn and the winter in the northern Baltic Sea. The significant wave height was about 4 m. Generating a wave pattern with a significant wave height of this magnitude requires wind of 15–20 m/s from S–SW for at least ten hours.

Numerous studies of wave statistics show that, if the significant wave height is 4 m, one wave in a hundred will be higher than 6 m. A maximum wave height is estimated as twice the significant height.

The weather forecast for the midnight hours predicted a significant wave height of only 2.5 to 3.5 m whereas the actual height was about one metre more. Even if the predictions had been correct, this would most likely not have changed the way the passage was conducted.

The weather forecast was not regarded as severe on board the two passenger ferries leaving Helsinki for Stockholm the same day. They both selected the coastal route in shallow waters instead of the deep-sea route followed in heavy weather.

The direction of the waves is difficult to determine as indicated by the different meteorological institutes (see 5.4.2). The Commission is of the opinion that before reaching the waypoint the ESTONIA encountered waves close to head sea. Thus after the turn of about 25 degrees to starboard she had the waves coming at about 30 degrees on the port bow.

As shown in 2.3 the general wave statistics of the different routes where the ESTONIA had been operating indicate that significant wave heights above four metres on the bow should have occurred for a total of less than about twenty hours during the full operating history of the vessel. Most of this time refers to the 20 months on the Tallinn–Stockholm route.

A review of the weather reports for the entire time while the vessel operated on the Tallinn–Stockholm route shows that wind and wave conditions similar to those during the accident voyage only occurred once or twice.

Thus it can be concluded that the vessel had generally been protected from heavy sea conditions during her lifetime.

A probable development of the directions and forces of the wind, and of wave heights hour-by-hour along the route, is shown in Figure 13.1.

13.2 Course of events

13.2.1 Introduction

The general course of events described in this section has been plotted from observations on the wreck, analysis of statements by witnesses, analysis of the damage and evaluation of the strength of the visor and ramp attachments. Calculations and model tests of the vessel's behaviour in waves have also been used. Specific parts of the sequence of events are detailed in 13.3 to 13.6. In Figure 13.2, the course of events is illustrated.

The Commission has analysed 258 statements from 134 survivors. The Commission is aware that none of the survivors is a witness proper, in the sense of an observer. All the witnesses are victims of the accident, involved in it and a part of the chain of events. Their observations and recollections are thus influenced by prolonged anxiety, exhaustion and stress. All statements are furthermore restricted to individual experience on board and outside the vessel only, and no witnesses have had any possibility of gaining an overall view.

When analysing the chain of events the Commission has usually put somewhat more emphasis on earlier statements than on later ones. The reason for this is that earlier statements were made at a time when witnesses' recollections were presumably less influenced by information from other witnesses and the media.

Figure 13.1 Development of weather conditions along the ESTONIA's route.

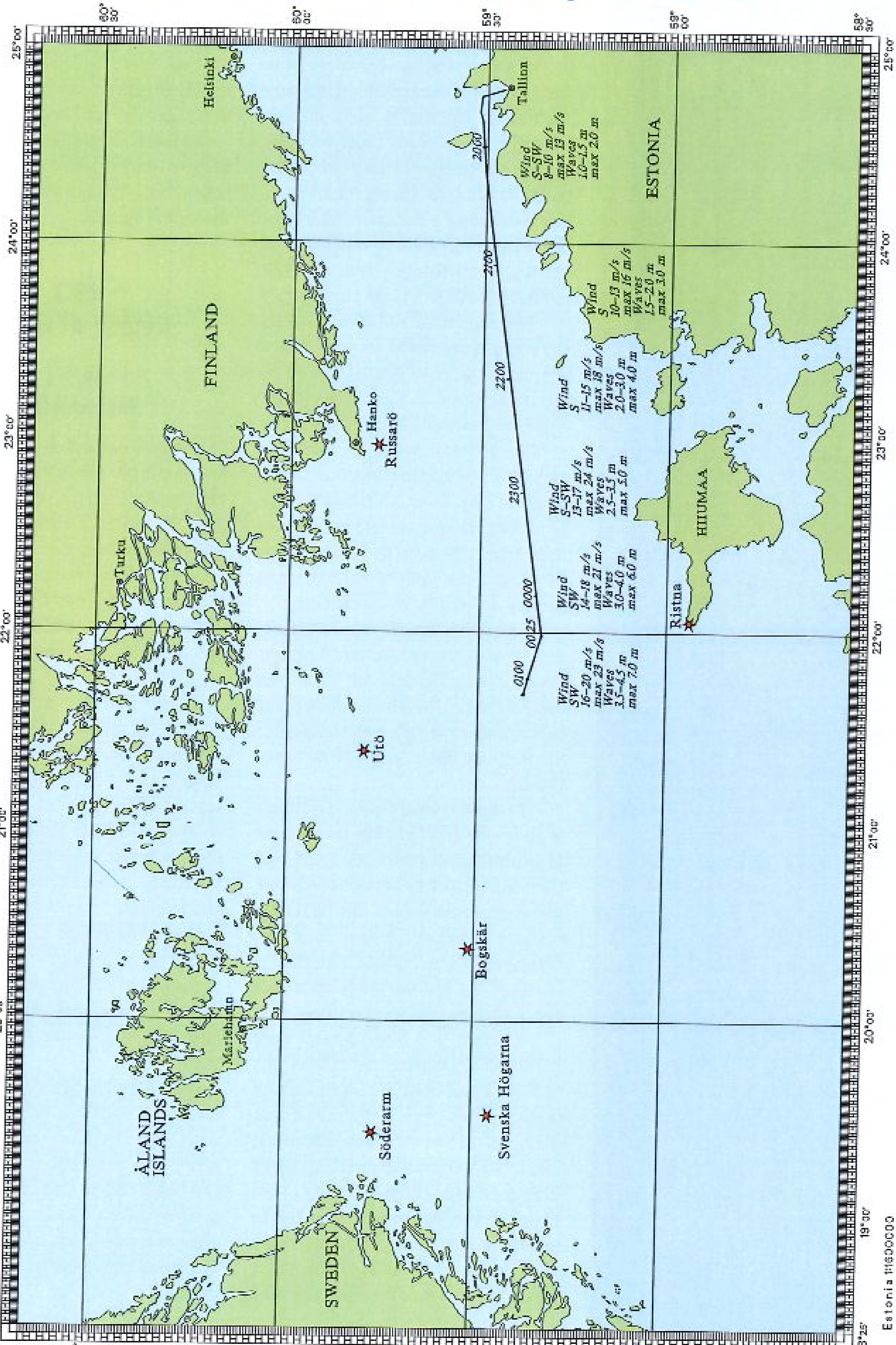
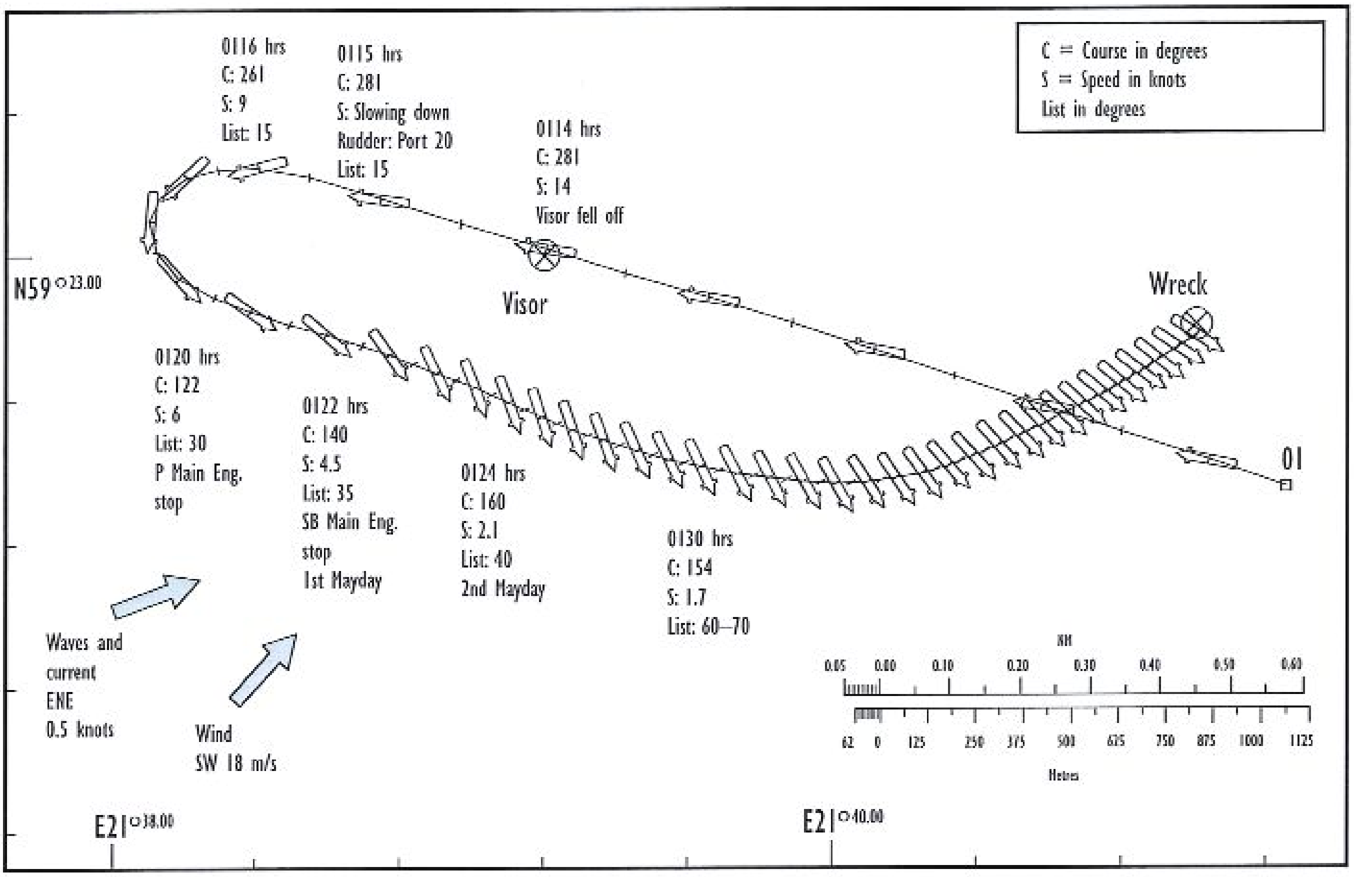


Figure 13.2 Course of events as composed by the Navigation Simulator at the Maritime Academy in Kalmar, Sweden.



The Commission has also given more weight to witnesses' recollections of objective and perceived events than to statements concerning time or time spans. This is because most objective events were experienced by many in different locations whereas statements concerning points of time vary radically and are judged to have been more subjectively influenced. Also statements concerning degree of list are judged to be considerably subjective. Somewhat more credibility is, however, given to such estimations by crew members and to their judgements of sounds, because of their experience.

A few crew members when interrogated, however, were more inclined directly to give exact and precise information about actions and points of time rather than to reveal any uncertainty. In such cases they often stated that they had acted in accordance with their instructions.

One of the key witnesses, the AB seaman of the watch, was interrogated several times and some details are not consistent throughout his statements. His latest statement seems, however, to be more reliable concerning specific parts and supplementary details because he then revealed new information that was partly to his discredit, and also commented upon his earlier statements.

13.2.2 Preparations for the voyage

The route-specific weather and wave height forecast was received from the Swedish Meteorological and Hydrological Institute (SMHI) in accordance with the existing subscription arrangement as well as other weather forecasts. The master was informed prior to departure that a low pressure with increasing winds would be encountered during the night.

No route plan has been available to the Commission, as planning was done on board only. It is deemed likely, however, that the plan was to proceed along the normal route with full service speed as long as the vessel was in sheltered waters in the Gulf of Finland, and thereby gain some time margin for crossing the Baltic Sea.

Loading began at 1620 hrs via the forward ramp and was completed shortly before departure. The loading was supervised by second officer A. According to witnesses large trucks were loaded almost bumper to bumper on the aft and mid parts of the car deck. Smaller trucks and cars were loaded on the forward part.

Heavy vehicles seem to have been loaded on the car deck without sufficient account of the athwartships weight disposition, resulting in the ship leaving port with the port side heeling tank almost full and the starboard one empty. Due to this cargo disposition and the wind pressure on the port side the ESTONIA, gaining the open sea, had a starboard list of about one degree according to the third engineer.

In compliance with the loading practice for ro-ro ferries on short routes, when strong winds are expected the major part of the weight should be located on the windward side in order to maximise possibilities to compensate for wind-induced heel. Hence, the ESTONIA should have been loaded differently.

The deck crew had been instructed to secure the heavy cargo with extra care due to the weather expected. Surviving crew members have testified that the trucks were properly secured with lashings, generally four per vehicle. It is claimed to be common practice that securing of vehicles is not finished when the vessel leaves port but is completed during an early stage of the voyage. All indications are that the cargo was secured to normal standard.

In this context the Commission has noted that the number of cargo damage claims was low while the vessel was operating on the Tallinn-to-Stockholm route and that no damage has been related to inadequate lashing of trucks, containers or other cargo.

13.2.3 Condition of visor and ramp closure

The Commission has noted from observations on the wreck that one of the locking bolts for the forward ramp was most probably not in its properly extended position at the time of the accident, and the related indicator lamp on the bridge was then not lit. The deficiency did not prevent closing of the visor.

It is possible that the locking bolt had been in its proper position and had backed out prior to the accident due to movement between the ramp and the ramp coaming in combination with hydraulic leakage, e.g. past the operating piston seals. Such movement of locking bolts at sea has been noted in other ro-ro ferries.

Even if this defect had existed at the time of departure it has not been possible to find out whether any action was called for. This potential deficiency would have had no effect on the development of the accident, as the ramp would have been forced open by the visor even if all the locking bolts had been in their proper positions.

Some rags can be seen on pictures filmed from a remotely operated vehicle (ROV) in the area of the half-extended locking bolt on the lower port side of the ramp. This may indicate that a sealing problem in the ramp, mentioned by the second engineer in his testimony, had been temporarily cured by packing rags into the gap. However, the Commission considers it likely that the mattresses and rags were washed into the area from nearby storage spaces during the final flooding of the car deck. They were observed at a point which was the highest on the car deck and still over the water surface when the stern reached the sea bed. Other floating objects and debris were also observed in the bow area, all probably trapped by the partly closed ramp when the bow started sinking.

If rags had been tucked along the sides of the ramp it is most likely that they would have been washed away when the ramp was forced open. The rags were partly in a position between the failed hinge lugs and the lug in the hull, where they could not have penetrated when the hinge was intact. The plastic covers of the mattresses appear intact, which indicates that they had not been subjected to heavy rubbing. It would hardly have been possible to close five ramp locks with rags packed in the positions observed.

Truck drivers have stated that sometimes there were problems in opening the ramp locks, and tools had to be used. Such problems have also been encountered on other vessels.

The magnet of the visor bottom lock position indicator was on the bracket in the locking bolt but the sensors could not be found during the ROV and diving investigations. The empty ends of the sensor cables were near the mounting bracket of the sensors. The mounting bracket appeared to be undamaged like remains of the broken port lug and the deck plating near the bottom lock. This indicates that the sensors were not in their place during the accident voyage. However, since the distance from the magnet to the nearest sensor was a few centimetres, a small chance remains that the pounding visor detached the sensors. According to crew members and the technical superintendent the bottom lock position indicator had been in working order. The most likely absence of the sensors would not have had any effect on the accident since there was no indicator lamp on the bridge showing the position of this locking bolt.

According to statements by members of the alternate crew, a strict routine was followed in the closing and securing of the ramp and visor, and technical assistance was called upon if any malfunction developed. No problems were evident at the time of the last crew change, nor had any reports about deficiencies in the ramp or visor locking system been made to the technical superintendent of the vessel.

The Commission's conclusion, which is supported by the failure pattern, is that the visor had been properly closed and secured at departure and that there were no deficiencies in the ramp affecting the development of the accident.

13.2.4 The voyage up to the accident

The ESTONIA departed from Tallinn at 1915 hrs. The crew was into the 13th day of its current 14-day duty period.

The speed was around 19 knots at the beginning of the voyage and when passing Osmussaar lighthouse at about 2200 hrs the ESTONIA was approximately on her normal schedule in spite of leaving

Tallinn 15 minutes late. Weather conditions deteriorated during the night. Because of this the resistance of the vessel increased and the speed gradually decreased. After the course change at the waypoint at about 0025 hrs, the ESTONIA encountered waves on the port bow and conditions became more unfavourable, with increased rolling and pitching and more severe wave impacts on the bow. The stabilising fins had been extended just after the waypoint. Shortly before the accident the speed had dropped to about 14 knots.

It may be of interest to compare the ESTONIA's speed with those of the MARIELLA and the SILJA EUROPA, two other passenger ferries en route to Stockholm on the same heading and encountering the same sea state as the ESTONIA. On the MARIELLA, speed was reduced at about 2300 hrs to 12 knots by order of the master. The SILJA EUROPA was running at approximately the same speed as the ESTONIA, i.e. 14.5 knots at about 0055 hrs. Just afterwards the SILJA EUROPA's officer of the watch reduced the speed due to the weather.

13.2.5 Separation of the visor

The first indication that something was wrong in the bow area was noted and reported to the bridge about five minutes before one o'clock by the AB seaman of the watch when he, at the forward ramp on his routine watch round, noted a sharp metallic bang from the bow area. This coincided with a heavy upward acceleration that nearly made him fall. He reported this bang to the bridge. Remaining about five minutes near the ramp he then continued on his round to decks 1 and 0 and finally to the bridge. He heard no more unusual sounds, nor made any unusual observations.

Shortly after one o'clock a few wave impacts on the visor caused the visor attachments to fail completely. The visor started cutting openings in the weather deck plating and associated structures. Soon the back wall of the visor housing came into contact with the ramp, hitting its upper edge and thus breaking its locks. The ramp fell forwards and remained resting inside the visor. In a few minutes the visor started falling forwards.

The ramp then followed the visor in a forward, tumbling motion. The starboard side actuator was extended to its full length and was torn out of the hull during the final stage of the sequence. The visor subsequently tilted over the stem, left the ramp fully open allowing large amounts of water to enter the car deck, and as it fell collided with the bulbous bow of the vessel. The failure sequence of the visor and the ramp is described in further detail in 13.5.

This sequence of events is supported by witnesses from several areas on board who heard a repeated metallic noise from the bow area during a period of about ten minutes, starting shortly after one o'clock. The detailed timing is, however, uncertain. The witnesses have given several good descriptions of these sounds and it is beyond doubt that the sounds were caused by the visor moving and pounding on the forepeak deck. Some of the metallic blows were associated with hull vibrations. The sounds from the bow area ended in a few loud, metallic crashes, caused by the final separation of the visor and its colliding with the bulbous bow of the vessel. This occurred at about 0115 hrs. The collision is documented by clear impact marks on the visor. The observations by the witnesses are described in detail in Chapter 6.

13.2.6 Development of the list and sinking of the vessel

On deck 1 the first passengers left their cabins already when they began hearing metallic blows from the bow area. A few have reported seeing small amounts of water in corridors on deck 1 and feeling that the vessel already at this stage had a slight list.

While the ramp was partly open inside the visor, water entered the car deck along the sides of the ramp, as observed first by the third engineer at 0110–0115 hrs on the TV monitor showing the forward part of the car deck. The water noted by the first passengers fleeing from their cabins on deck 1 could at this stage have poured down to the accommodation on deck 1. Later, during the evacuation, several passengers observed on deck 2 that water entered the staircases through the slots around the fire doors to the car deck.

After the ramp had been forced open by the visor, waves may have caused the ramp to move between fully open and partly closed position but generally a significant opening was available for waves to enter the car deck as further described in 13.5 below. The large amounts of water flooding onto the car deck caused the vessel to heel over and after a few rolling movements a significant list developed to starboard. This happened within the first minutes after the visor had separated from the ship. According to witnesses the ship steadied temporarily at a list angle of about 15 degrees.

Just before the moment when the list developed many crew members and passengers noticed a change in the vessel's motion. This coincides with the time when the visor separated from the vessel and may have been the effect of the first larger volume of water to enter the car deck.

At about the time when the list developed, the engines were throttled back close to idling speed and the vessel was turned to port into the wind as dealt with further in section 13.3. She passed through the wind's eye and continued to port with decreasing speed. Information from some survivors indicates a reduction of engine speed just before the accident but the timing is uncertain. It is, however, the opinion of the Commission that full service speed setting was maintained right up to the time when the list developed.

During the port turn water continued to enter the car deck and the list increased to 20–30 degrees where the vessel for some minutes stabilised as the water inflow decreased. By about 0120 hrs all four main engines had stopped, at intervals of a few minutes, starting with the port side engines, due to lack of lubricating oil pressure. The main generators stopped about five minutes later.

After the main engines stopped, the ESTONIA drifted with a list of about 40 degrees and the starboard side towards the waves. Water continued to enter the car deck through the bow but at a significantly lower rate. Waves were pounding against the windows on deck 4. Window panels and aft doors broke, allowing flooding of the accommodation to start. As the flooding progressed, the list and the trim by the stern increased and the vessel started to sink. At a list of about 80 degrees the bridge was partly flooded. This happened shortly after 0130 hrs as indicated by a clock in the chartroom whose hands had stopped at 2335 hrs UTC. The emergency generator stopped at about the same time but the accumulators supplied power for limited lighting. The sinking continued, stern first, and the vessel disappeared from the surface of the sea at about 0150 hrs. This phase of the accident is covered further in 13.6. Figure 13.3 illustrates the development of the list and sinking of the vessel.

13.2.7
The evacuation

Shortly before the start of the accident, most passengers were in their cabins. The major part of the crew were off duty, some in bed and others together in the messrooms or in cabins on decks 7 and 8.

Passengers were moving about in the foyer areas, passageways, corridors and staircases. A few remaining passengers and some crew members were in the Night Club, and in the Pub Admiral there were 30 to 60 people. Some passengers were resting or sleeping in the lounges and in the café. A limited number were resting in other public areas, passageways and staircases.

Some passengers had left their cabins at an early stage due to the motion of the ship and the noise. As the list developed, passengers had difficulties in getting out from their cabins due to the furniture and luggage which had slid against the doors. The list made it increasingly difficult to move inside the vessel and to reach open decks. First people tried to help each other, for instance by forming human chains, but soon it became impossible due to the increasing list.

At about 0120 hrs, i.e. five minutes after the list developed, a weak female voice was heard over the public address system calling in Estonian "Häire, häire, laeval on häire" (Estonian for: "Alarm, alarm, there is alarm on the ship"). Shortly thereafter the second officer A called the alarm *Mr Skylight to number one and two*. About two minutes later the general international life boat alarm was initiated.

Many of those who succeeded in reaching open decks had difficulties in putting on lifejackets properly. People hung on to the railings and climbed onto the side of the vessel when she was lying nearly on her side. Waves washed some people into the sea and others started jumping into the sea at about half past one o'clock. Most had difficulties in gaining the rafts, tens of which were floating around the vessel. Few people were able to board a raft on the side of the vessel. Figure 13.4 illustrates the development of the list as experienced on the open deck near the funnel.

The time available for evacuation to open deck was between 10 and 20 minutes. During this period at least 237 people escaped from the vessel. The evacuation is further analysed in Chapter 16.

13.3
Action on the bridge

When the ESTONIA was at sea the bridge-watch always consisted of two officers and one AB seaman. The duties of the AB seaman were to make inspection rounds in the vessel and to serve as an additional look-out. For further details of the working routines see 4.3.

When the officers on the bridge received the AB seaman's report of the metallic bang shortly before one o'clock, second officer B ordered him to stay in the area and investigate the origin of the sound. After about five minutes he reported back that he had found nothing abnormal and the sound was not repeated. The AB seaman was ordered to continue his watch round.

There was a watch change on the bridge at one o'clock when the second officer A and the fourth officer relieved second officer B and the third officer. Normally the ongoing watch arrived at the bridge not later than five minutes prior to the start of its watch, and there are no reasons to believe that the routines were deviated from during this night.

It is considered confirmed that the reported sound from the car deck was known to the officers commencing their watch at one o'clock. The Commission concludes that the information received was not considered alarming since the relieved watch left the bridge as normal.

When the AB seaman of the watch returned to the bridge from his round about five minutes after one o'clock, he saw the master arrive just ahead of him. The master made general comments on the speed and their probable late arrival in Stockholm. Nothing has been reported to indicate that his visit was other than routine and thus not caused by any concern about the prevailing situation.

Shortly after his arrival at the bridge, the AB seaman was ordered to call the boatswain and accompany him to the car deck to check the bow area and the general situation. Second officer A who gave the order had received a telephone-call, most likely from a crew member, reporting loud noises, believed to be originating from the forward part of the car deck. The boatswain was responsible for operating the ramp and the visor, and the fact that he was called out on his free watch indicates that the situation was considered serious by the officers of the watch. There are no indications that any other action was taken at this stage.

By this time the bridge had received

Figure 13.3 Computer-generated pictures illustrating the development of the list and sinking of the vessel. Approximate times, and list in degrees, are shown at bottom right of each picture.

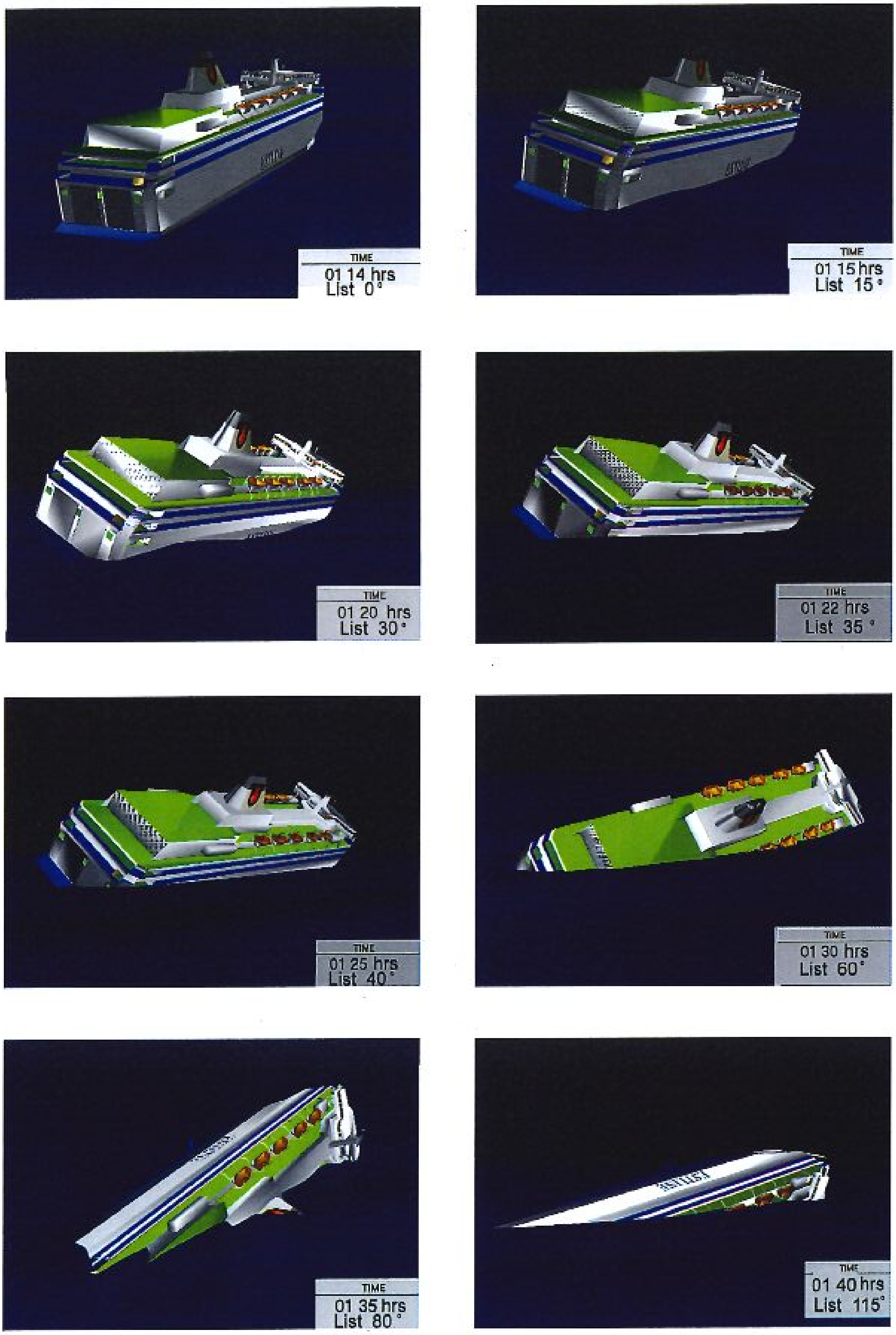
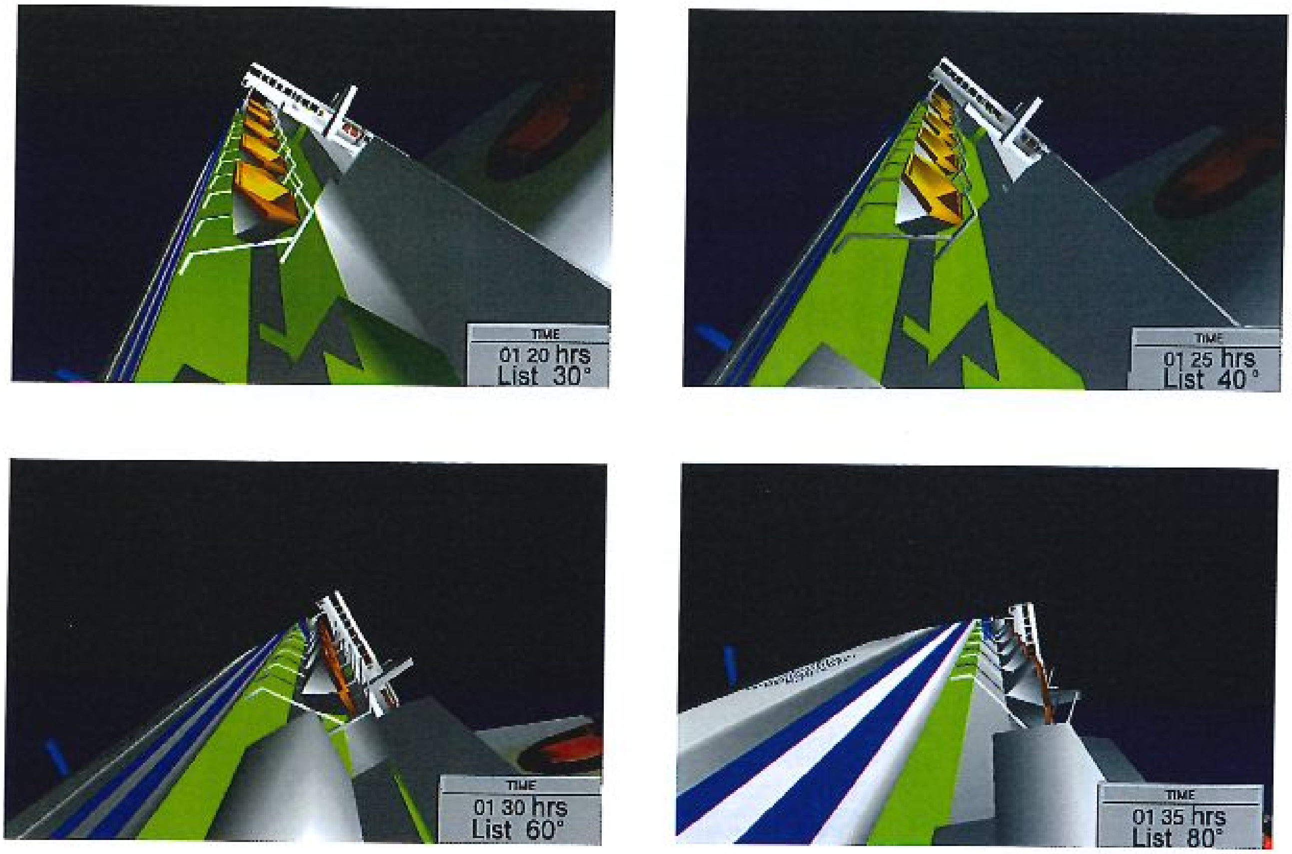


Figure 13.4 Development of the list as experienced on the open deck.



two reports of sounds. The Commission considers these reports so alarming, that the officers should at least have reduced speed at this stage.

The AB seaman has testified that the master was on the bridge when he was sent to the car deck. It is therefore considered most likely that the master was informed of the situation and agreed to the action taken, and that he remained on the bridge during the development of the accident.

The AB seaman never managed to reach the car deck. He waited at the information desk on deck 5 to have the car deck doors unlocked, and at about this time or possibly some minutes earlier, the visor was lost and the ramp pulled open. While he was waiting at the information desk the vessel heeled over and remained with a list of about 15 degrees to starboard. The AB seaman immediately proceeded downwards but was kept back by a stream of passengers escaping from the lower decks, some of them screaming that there was water on deck 1. He turned around and ran towards the boat deck. The whereabouts of the boatswain during this period is not known.

It is not known what additional information the officers on the bridge received after the AB seaman left the bridge, but it is obvious to the Commission that at least the sound from the visor's collision with the bulbous bow must have been noticed.

It is evident to the Commission that, because of the list and the sound from the collision the officers on the bridge initiated a reduction of speed and a turn to port. Some minutes later they also closed all watertight doors.

Three to five minutes after the list had developed, the bridge was informed by the AB seaman of the watch, who now was on the boat deck, that passengers were escaping in great numbers from the lower decks screaming that there was water on deck 1. He was again ordered to go down and find out more about the situation. At about the same time the third engineer was ordered by telephone to compensate for the list by pumping ballast. He tried to pump sea-water to the almost full heeling tank but the pump sucked air. The starboard list was at this time about 30 degrees and the officers on the bridge were obviously still seeking more information to understand what was going on. They evidently thought that the adverse conditions could be rectified.

In view of what is known about the rapid course of events and the consequent short time for evacuation, the Commission finds it most unfortunate that the lifeboat alarm was not given until about five minutes after the list developed and when the list was around 35 degrees. Nor was any information given to the passengers over the public address system.

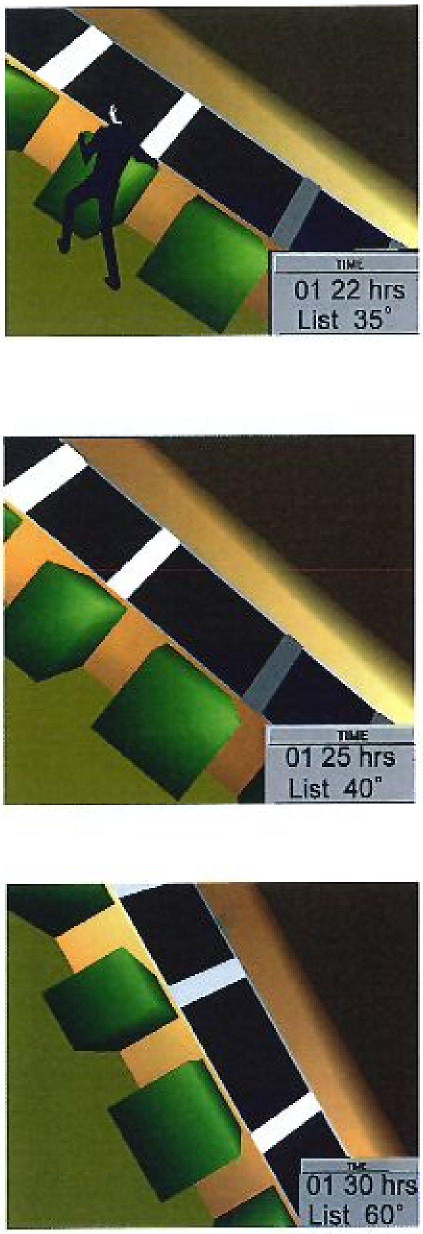
The first Mayday call was received from the ESTONIA at about 0122 hrs, i.e. at about the same time as the lifeboat alarm was given and just after the main engines had stopped. It was a very brief message, containing no other information than the word "Mayday" and the name ESTONIA. The operator has been identified by voice as second officer A on duty. In later radio traffic the operator has been identified as the third officer. A voice heard in the background has been identified as the chief officer's. He and the third officer had come to the bridge obviously alarmed.

The time for the distress traffic, from the first call to the last, was eight minutes. Nothing is mentioned to indicate that the officers had any appreciation of what had caused the vessel to develop a list and take in water. The information given was[1]: "Yes, we have a problem here now, a bad list to starboard. I believe that it was twenty, thirty degrees" followed later on by "We have black out" and, at the end of the distress traffic, "Really bad, it looks really bad here now". It was about seven minutes before the ESTONIA gave her position. Due to the very fast development of the accident the late start of the distress traffic did not, however, have much effect on the final outcome of the rescue operation. The distress traffic is reproduced in full in 7.3.3. Figure 13.5 illustrates the development of the list during the distress traffic as experienced on the bridge.

Of the five officers known to have been on the bridge, second officer A and the third officer were seen leaving the bridge in the final stage of the accident. It is believed that the master, the chief officer and the fourth officer remained on the bridge throughout the accident. This assumption is also supported by the fact that three bodies were seen inside the bridge during the diving investigation.

The two officers that left the bridge were later seen distributing lifejackets and trying to launch lifeboats and rafts. Also the boatswain, who just before the

Figure 13.5 Development of the list as observed on the bridge.



start of the accident was called out to help investigate the sounds on the car deck, was seen on deck 7 taking part in this.

It is noteworthy that so little exchange of information seems to have taken place between the bridge and the engine control room during the development of the accident. The third engineer did not inform the bridge about the inflow of water he observed (see 6.2.3). Nor did the officers of the watch call him for an assessment of the situation. If the observation on the monitor had been discussed and evaluated immediately, there could still have been a possibility to influence the development of the accident.

Nothing indicates that the officers realised that the bow was fully open, although it must have been obvious that the situation was very serious, and that the survival of the vessel was threatened.

Simulations carried out by the Commission show that a quick reduction of speed and change of heading would have significantly reduced the rate of water ingress. The safest condition for the vessel with the bow open would have been lying beam on to the waves at zero speed. It has also been established that turning the vessel to starboard would not have endangered her stability. The wind pressure would have increased the list by only a few degrees. Thus turning the vessel, with the bow fully open, towards the wind and the high waves was not the best action. On the other hand it must be kept in mind that from the officers' point of view turning the vessel to starboard away from the wind would have exposed the port side to the full force of wind and waves and would have further increased the list and the roll. In this light the decision to turn the vessel to port and into the wind is understandable.

The question of whether a lower speed would possibly have prevented the accident has been reviewed by the Commission. Extensive model tests and numerical simulations have been carried out as summarised in 12.1 and 12.2. The result confirms that a lower speed would have reduced the general loads on the visor and hence the probability of failure. However even at a speed of 10 knots, the loads would still have been close to the strength limits of the visor attachments.

The Commission has also considered

[1] The quotations are translated from Finnish.

whether the officers of the watch had reasons for reducing the speed prior to the start of the accident.

As is the case for many ships, there were no strict procedures or company policy for heavy weather routines on the ESTONIA. The Commission has noted that passengers' comfort, which can easily be observed by the crew, normally seems to be the prime reason for speed reduction for this type of large ferry. In the Commission's experience most masters consider that speed must be reduced for comfort reasons long before it reaches the vessel's strength and safety limits.

Although some survivors have described the voyage as being rough before the accident, the officers did not apparently find comfort-related reasons for reducing speed.

For comparison, numerical analyses and model tests show that in the foremost part of the ESTONIA vertical accelerations after midnight exceeded by 50 per cent the severe discomfort boundary of International Organisation for Standardisation motion sickness standard. In the restaurant and entertainment areas amidships and in the aft part of the vessel the vertical accelerations were on the other hand significantly below and close to the severe-discomfort boundary, respectively. Considerably higher accelerations than predicted for the ESTONIA have been measured on board passenger vessels in rough weather in many sea areas including the Baltic. Calculations also show that the general condition on board with regard to vertical accelerations and sea-sickness would not have improved much even if speed had been reduced considerably (see 12.4.2).

Thus it is concluded that the voyage was uncomfortable for many passengers but not exceptional. The vessel was run above or close to the boundaries for comfort criteria. Referring to the above, the officers obviously believed that there was still a good margin to the limits of the bow strength.

The accident points out the need for crews on large ro-ro ferries to have operating instructions and training in manoeuvring vessels in heavy weather. It is a serious shortcoming for the whole shipping industry that there is in general no information on the limits of operability with regard to the ship's strength available on the bridge of large vessels with powerful engines, specially as the size of the vessels makes their motion less perceptible. In the case of the ESTONIA accident, the operating limit with regard to the strength of the visor attachments was significantly lower than the crew had reason to believe.

13.4 Advance indications and alarms from the bow area

As described in 3.3.5 indicator lamps on the navigation bridge showed locked or unlocked visor and ramp, respectively. The indicator lamps for the ramp were controlled from the locking devices in such a way that all devices had to be in the position ordered for the lamps to go on, green for locked ramp and red for unlocked. Since one of the locking bolts was most likely not fully extended already at departure, there was no indication on the bridge that the ramp was locked.

The indicator lamps for the locking of the visor were, as far as the Commission has been able to verify, connected in the original way, controlled via the position sensors for the side locking devices only. The lamps thus did not directly indicate the position of the visor. The side locks were in locked position during the last voyage and the visor position lamp was thus green. The green light remained also after the separation of the visor as the side locking devices remained in locked position. Hence no light indication was given on the bridge when the visor started to become detached.

The first audible indication may have coincided with a partial failure at one of the visor attachment devices. Loud metallic sounds could hardly be generated before that point in time.

Four TV cameras surveyed the car deck with monitors on the bridge and in the engine control room. The monitors sampled the four cameras manually or automatically. One camera showed the area inside of the forward ramp. The bridge monitor was mounted at the entrance to the chartroom, facing starboard. It could not be kept under observation from the conning station. The inflow of water along the sides of the ramp was first noted on the monitor in the engine control room. It has not been possible to establish whether the officers on the bridge made the same observation.

In many other reported incidents of equivalent severity as far as the failure of the various attachment devices is concerned, the opening of the visor was observed visually from the bridge and the officers of the watch were able to take appropriate action. On the ESTONIA, however, the visor was not visible from the conning position.

The circumstances and arrangements did thus not give the officers on the bridge any direct information or warning about events in the visor area as the accident developed.

13.5 Failure sequence of bow visor and ramp

This section describes what the Commission considers to be the most likely sequence of events leading to the loss of the visor and opening of the ramp.

The loads to which the visor was exposed in the seaway were simulated theoretically and examined in model tests in conditions similar to those deemed to have prevailed at the time of the accident. Experimental and theoretical results are presented in 12.1–12.3 and summarised in 15.2.

The maximum opening moment to which the visor was exposed after the ship had turned at the last waypoint is estimated to have been between 4 and 20 MNm and the maximum resultant force between 4 and 9 MN. Such high loads and opening moments occurred randomly. The resultant load and the opening moment may have exceeded the lower limit of the range a number of times within half an hour under the prevailing conditions. Levels above the upper limit of the range have a low probability of occurring but cannot be excluded. The vast majority of wave impacts created no opening moment at all.

As described in 15.10 it is concluded that the strength of the visor attachments was insufficient to withstand a resultant wave load of 7–9 MN, corresponding to opening moments in the range of 13–20 MNm. There is a theoretical probability higher than 1 in 20 that a single wave load would exceed the largest estimated combined strength of the attachments within 30 minutes in the conditions after the last waypoint. The port side lock may have failed at a lower load level than the maximum given above.

All the attachments of the visor, the locking devices, the deck hinges and the lifting cylinder mountings failed under local overload tension. The attachments may have failed in one or, possibly, a few steps. The partial initial failure may have coincided with a single metallic bang, observed by the AB seaman.

The main failure is believed to have happened in a subsequent wave impact, shortly after the metallic bang. In this main failure the remaining locking devices failed completely, allowing the visor to open partly. Once the visor had lifted off its locating horns, the port side hinge failed under the overload generated by the high twisting and yawing moments and the vertical force. The starboard side hinge failed as a result of twisting when the visor was rotating clockwise. Hydrodynamic loads pressed the visor against the front bulkhead along which it slid upwards. The hydraulic lifting cylinders may have failed at the same moment or may have remained connected for some further time. The port side actuator, which at some stage was pulled out of the hull by failure of the already weakened bottom mounting platform, had extended by about 0.4 m at least. The starboard side actuator failed hydraulically but remained connected and was ripped out of the hull, fully extended, as the last physical connection between the visor and the hull.

After the locking devices and hinges had failed and the actuators had lost their restraining effect, the visor had a natural tendency to tumble forward due to its forward-located centre of gravity relative to the new centre of rotation, i.e. the stem post area. The visor's position was at this stage governed by the actuators and the actuator attachment lugs on the hinge beams, protruding into openings in the forecastle deck. The visor was thereby constrained in the longitudinal direction.

Subsequent wave impacts caused the visor to move backwards and forwards in combination with some vertical movements, resulting in various impact damage to the bulkhead and the hinge beams. Impact marks indicate violent transverse movements, and upward movements of about 1.4 m. The damage is described in detail in Chapter 8. As estimated from impact marks on the aft edges of the visor hinge beams, the number of heavy aftward blows was at least two and probably less than five. The vertical wave force exceeded the weight of the visor on average once a minute under the prevailing conditions. The dynamics of this aft-forward movement of the visor generated sufficient impact forces to enable the hinge beam lugs to cut through the transverse deck beam, which was the heaviest structural element preventing the visor from moving forward.

It was when the deck beam, and thereafter about 360 mm of the deck plating, had been cut through that the visor housing came in contact with the top of the ramp, primarily on the port side as the sea loads had caused the visor to twist somewhat to starboard. Probably in one single movement, the visor pulled the ramp forward so that its locking devices and hydraulic actuators failed. The ramp was then free to fall forward towards the uppermost cross-bar of the visor. Subsequently the visor actuator lugs cut the rest of the deck and the front bulkhead plating until the visor was free to tumble forwards and overboard.

The exact timing of this development cannot be determined as it was affected by the irregular occurrence of wave loads sufficiently high to move the visor. Several visor movements were needed to cut through the deck and beam. Only during the final phase, when the ramp had been forced partly open could water, collected in the visor, flow onto the car deck through the openings along the sides of the ramp. The time from the initial water ingress on the car deck until the visor separated from the vessel and the starboard list started to develop is thus likely to have been short, of the order of five minutes.

Great force was needed only twice during this final part of the failure sequence, when the deck beam was cut through and when the ramp was forced open.

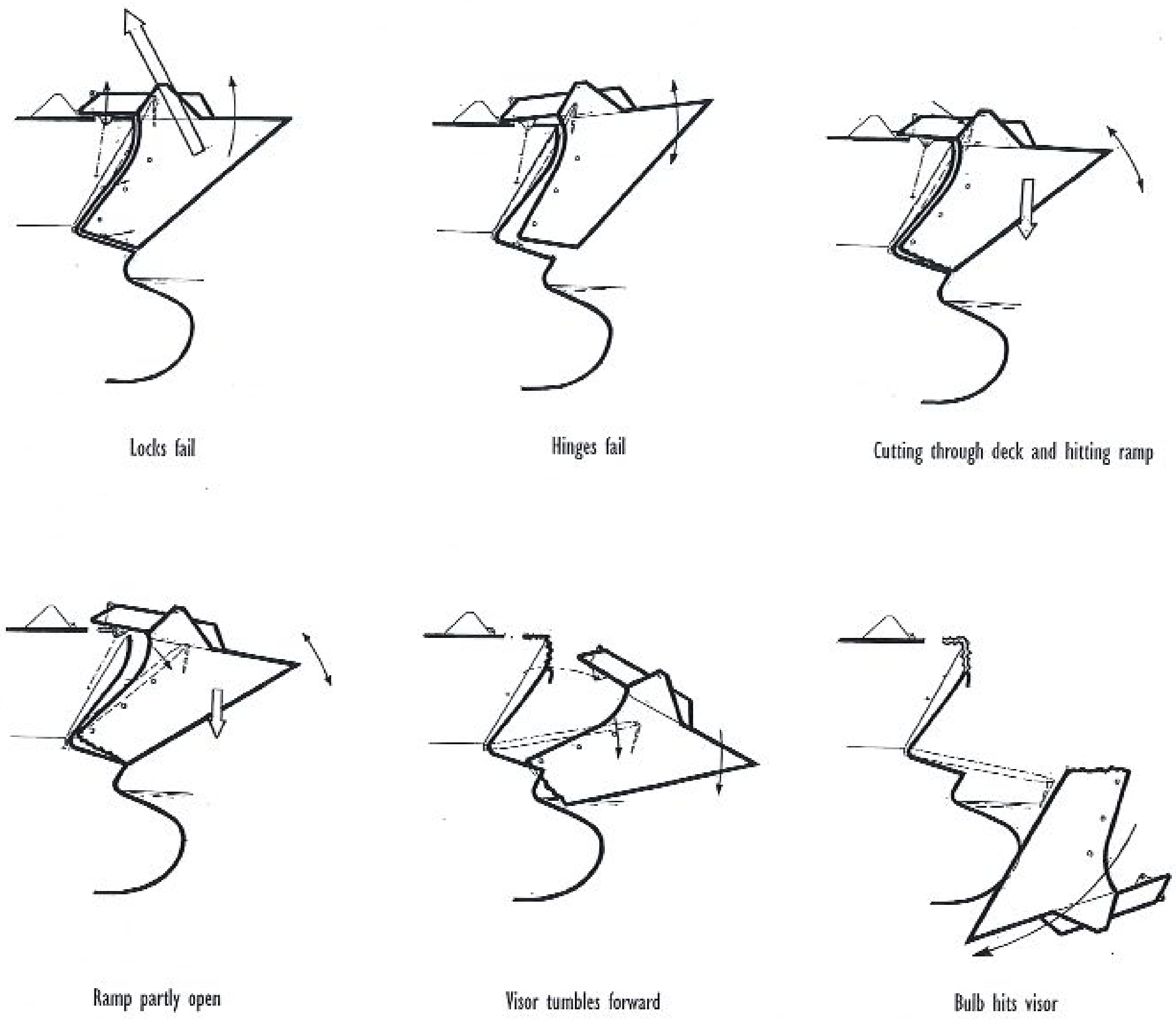
The many uncertainties involved make detailed calculations of this development meaningless. However, calculations under simplified assumptions verify that the course of events described is fully possible. The time for the full failure sequence which is illustrated in Figure 13.6 may have been 10–20 minutes.

13.6 Flooding of the accommodation and sinking of the vessel

Although damage stability requirements concern only the watertight part of a vessel below the bulkhead deck, a large stability reserve remains in the superstructure as long as it remains intact. The stability manual for the ESTONIA included the hull up to deck 4 as contributing to the stability range.

Because of the list, waves reached up to the accommodation decks, breaking doors and windows. The interior started to flood and the stability reserve disappeared. Critical openings were (see 12.6.1) large aft-located windows on decks 4 and 5, the cafeteria doors on deck 5, a weathertight door to the forecastle deck, and the ramp opening. Ventilation ducts to

Figure 13.6 Probable failure sequence of the bow visor.



the car deck were installed at deck 4 level. According to testimony from a member of the alternate crew the ducts were normally closed. The ducts may, however, have opened during flooding.

The first potential openings to be submerged were the aft windows on deck 4. In calm water this would have happened when about 2,000 tons of water, or about 70 cm evenly distributed had entered the car deck and caused a heel angle of about 40 degrees. Waves with considerable impact energy would have pounded against these windows earlier. It is unlikely that the windows, although of heavy construction, withstood such impact forces. The first windows broke probably a little after the main engines had stopped and when the vessel was drifting with her starboard side to the waves. Quickly submerged were also the aft windows and the aft door on deck 5. This happened at a list of about 50 degrees, which is supported by an observation from a witness in the Cafeteria on deck 5.

When some of the large windows on decks 4 and 5 broke, these decks became subject to progressive flooding and no buoyancy or stability contribution was available from this part of the superstructure. List and trim to stern increased and the flow rate through the openings accelerated. As soon as the accommodation spaces started flooding, the flooding could not stop before the vessel sank, or the condition could no longer remain stable as there were connections between different decks via staircases and other openings. The watertight compartments below the car deck were thus flooded from above.

The speed of flooding, however, depended on the size of the openings to the sea and on the escape of air from inside the hull regarding which there are several witness observations. Calculations indicate – as an example – that 18,000 tons of water on board, distributed between the car deck and decks 4 and 5, would have given a heel angle of about 75 degrees. This amount of water had entered the vessel in about 15 minutes, indicating an average flow rate of 20 tons per second. This is feasible through openings which have a total area of 5–10 m^2. Progressive flooding was under way to several decks and compartments at the same time as the upper decks gradually sank under the mean water level.

If the windows and doors had remained unbroken the vessel may have remained in a stable heel condition for some time. It is, however, less likely that any reasonable strength of the large windows would have been adequate to withstand the wave impact forces.

It can be concluded that, although the vessel fulfilled the SOLAS damage stability requirements valid for its building period, she had no possibilities to withstand progressive flooding through the superstructure openings once the heel angle approached 40°. When windows on the accommodation decks were broken by wave forces, subsequent sinking was inevitable.

CHAPTER 14

OWNERSHIP AND OPERATING ARRANGEMENTS

The initial ferry operation between Tallinn and Stockholm started on 17 June 1990 and was carried out by N&T EstLine AB, a fully-owned subsidiary of Nordström & Thulin AB, in co-operation with a consortium of smaller tourist-related companies owned by the Estonian government. The initial positive development in traffic volume was drastically reversed in 1991 due to the political unrest in Estonia, resulting in large economic losses for N&T EstLine AB, which firm in practice carried the total financial burden of the traffic. Attempts to lower operating costs by employing senior officers from Sweden and the rest of the crew from Estonia failed due to objections from the Swedish trade unions. The traffic was, however, maintained and in 1992 a positive development of passengers and cargo volumes started, indicating a future need for a bigger ferry. Due to the accumulated losses, however, it was not deemed feasible for Nordström & Thulin AB alone to finance a further large investment in N&T EstLine AB. To ensure continued traffic it was therefore agreed with the Estonian government that the N&T EstLine operation should be discontinued and the traffic should be taken over by a new joint venture company.

For this reason the Estline Marine Company Limited was established in Cyprus. The company was owned equally by the Estonian Shipping Company Limited (ESCO) and Nordthulin Luxembourg S.A., (for further details, see Chapter 2). The ESTONIA was acquired by the Estline Marine Company. These complex ownership arrangements were necessary to allow the vessel to be financed on a mortgage basis and seem to have had no other function.

The Estonian partner in the joint venture, ESCO, assumed the responsibility for operating the vessel. Technical management and the responsibility for insurance matters were subcontracted to Nordström & Thulin AB in a standard ship management contract. Commercial operations, including catering, were handled by the Swedish company Estline AB. This company was owned equally by ESCO and Nordström & Thulin AB and had a subsidiary company in Estonia to provide the corresponding services in Tallinn.

Complex arrangements between the true owner and the actual performers of the various operational functions are common in the shipping industry and have become increasingly so as competitiveness has demanded a high level of performance at the lowest possible cost.

The Commission has not found any evidence that the ownership and operating arrangement for the ESTONIA could in any way have influenced the development of the accident, or that any matters of importance for the safety of the vessel had been neglected because of these arrangements.

It appears that Nordström & Thulin AB kept a closer eye on the operation of the vessel than called for by the technical management agreement. This seems to have benefited the operation as Nordström & Thulin AB had previous experience of the traffic. The areas of responsibility, however, seem to have been clear and respected by all parties and as far as the Commission has been able to verify co-operation between the parties has been at an acceptable level.

ESCO was responsible for the overall operation of the vessel including the manning, the qualifications of the crew and increasing crew members' proficiency. However, Nordström & Thulin AB had the right – under the technical management agreement – to refuse the appointment of masters and chief engineers, in order to ensure that good communication could be maintained in English. A number of candidates were rejected by Nordström & Thulin AB as being under-qualified in this respect.

ESCO was also responsible for providing qualified catering personnel. The exception was that Estline AB, via the Swedish shipping company Rederi AB Hornet, provided advisors for the top positions in the catering organisation.

The ESCO land organisation was rigid and of traditional, strict hierarchical structure. This condition possibly supported a mentality whereby individuals carefully performed their explicit duties but were not encouraged to show initiative. The operating arrangements relied totally on the ship's master, who had to determine the operational limits for the vessel, operational practice for nautical instruments, the use of automation and the remote control system and the implementation and updating of the on-board safety system. The Commission has not found any documented procedures or instructions about these elements. However, the Commission has noted that the radio officer, according to the Safety Manual, was not responsible for radio traffic in emergency situations.

The operative controls carried out in connection with port state controls, as well as a major fire exercise carried out under the supervision of the Swedish Maritime Administration, elicited good remarks, with active and ambitious participation by crew members.

The Nordström & Thulin AB organisation responsible for technical management consisted only of one full time technical superintendent, reporting directly to the chief superintendent, who in turn reported to the fleet manager. The technical superintendent met the master and the chief engineer regularly during the vessel's calls in Stockholm and discussed maintenance and any other technical items that may have come up. He sailed frequently with the ship. One purchaser was also involved. This arrangement seems to have been fully satisfactory for the function intended.

The pilot regulations for the Stockholm archipelago require that to operate a passenger vessel of the size of the ESTONIA in the Stockholm fairways under the pilot exemption rules, the master and one more officer of equal qualification must have pilot exemption certificates for the fairway and the vessel. Up to the time of the accident, only the masters of the ESTONIA had acquired such exemption certificates and only for the fairway via Sandhamn (4.2.2). To avoid the inconvenience and the costs incurred in taking a pilot on board every voyage, it was arranged with Rederi AB Hornet that they should provide two alternating Swedish officers with the required qualifications. The officers appointed were former employees of Nordström & Thulin AB and had been sailing in senior positions on the previous ferry on the same route. The Commission has noted that these Swedish pilot officers were not part of the crew and had no other formal function on board than participating in the navigation in the Stockholm archipelago.

One of these officers was occasionally consulted by the masters of the ESTONIA regarding improvements to the safety organisation and related documentation. The two may also have served partly as Nordström & Thulin's observers of the operations on board.

The fact that the vessel was manned and operated by an Estonian company and flew the Estonian flag initially spurred an intense debate in Sweden regarding "flag-of-convenience" arrangements and substandard operations. The Commission has found no basis for this debate.

It is the opinion of the Commission that the operating arrangements in general worked satisfactorily and that traditions and experience from the established ro-ro ferry traffic in the northern Baltic area were incorporated in the operations by way of the influence of Nordström & Thulin AB and through the personnel provided by Rederi AB Hornet.

CHAPTER 15

STRENGTH EVALUATION OF THE VISOR AND THE RAMP ATTACHMENTS

15.1 Design basis and requirements for the bow visor

15.1.1 Bureau Veritas' requirements for the visor attachments

The bow visor structure was built to scantling requirements specified in the Bureau Veritas Rules of 1977. Compliance with these has not been verified in detail in this investigation.

The locking devices should, according to the Bureau Veritas rules valid at the time, cause the bow door to be "firmly secured". Structural reinforcements were specified in general wording to be required at attachment points for cleats, hinges and jacks.

Thus the Bureau Veritas rules did not specify minimum pressure heads to be applied to the horizontal and vertical areas of the visor. The yard has stated that it therefore used a Bureau Veritas "Note Documentaire", number BM2 dated 5.4.1976 for determining the design loads. This note was intended as guidance in the design of the bow of large tankers and bulk carriers. It has not been possible to fully explore how this guidance note was interpreted and used in arriving at the applied loads. The loads so derived were, however, of the same magnitude as those required by some other classification societies at the time.

The design loads to be applied to the attachments of a bow visor of a ro-ro vessel have been continuously developed incorporating new data, and were in general not well established when the ESTONIA was built. The pressure head and the calculation procedure to be applied became more clearly defined and detailed rules were given, for instance, in the 1982 Unified Requirements of IACS and later recommendations. The requirements of IACS 1982 specified equivalent design loads per locking device of about twice as high as those used in the design of the ESTONIA. However, Germanischer Lloyd already in 1978 had a specific formula for the design load of a bow visor which would have given about three times the load used for the ESTONIA.

15.1.2 Shipyard design procedures

From the external design pressure on the visor shell plating determined by the procedure indicated above, the total external load components were calculated by the yard to 536 t (5.3 MN) in upward vertical direction and 381 t (3.7 MN) in aft horizontal direction. These were assumed to act at the centres of the projected areas. The reaction force at the position of the bottom lock was determined by calculations of the momentum about the longitudinal middle point between hinges and side locks at the level of hinges, and found to be 152.5 t (1.5 MN). This horizontal force and the total vertical load reduced by the static weight were divided by 5 and a design force of 100 t (1.0 MN) was obtained as a resultant for each attachment point, hinges included.

Although there is an obvious lack of logic in the procedure used, it was to some extent supported by rules of other classification societies at that time, e.g. Lloyd's Register of Shipping. However, in these design rules, the calculated reaction forces were only to be distributed evenly to the cleats and not to the hinges. It is the opinion of the Commission that the calculations by the shipyard resulted in considerably lower design loads per attachment point than would have been the case if a more realistic design load distribution had been applied.

The design load was used by the yard for calculating a minimum load-carrying cross-section of 6100 mm^2 for an attachment device. This was obtained by applying a normal stress level of 164 N/mm^2 calculated from a permissible normal stress of 123 N/mm^2 for mild steel divided by a material factor of 0.75 due to the intended use of high-tensile strength steel, St52-2. The calculations did not take into account the reduced strength in the shear mode to which many of the attachment elements would be subjected. A copy of the calculations by the shipyard is included in the Supplement.

The hand calculations by the shipyard were not submitted to Bureau Veritas for approval. In the actual installation, the calculated effective design cross-section was not incorporated in the bottom lock, nor was high-tensile strength steel used in any of the attachment lugs investigated by the Commission.

The von Tell assembly drawings did, in accordance with the purchase order, identify the operational loads the hull would have to absorb via hinges and operating devices due to the weight and geometry of the visor and the ramp. Loads to be absorbed at the attachment devices due to wave-induced forces were not indicated on these drawings.

Bureau Veritas communicated in March 1980 with the von Tell company regarding the design loads used by von Tell in determining the strength to be built into the locking devices. The von Tell company explained in a brief telex that they had used the rules of Lloyds Register of Shipping in the absence of Bureau Veritas rules and had calculated a load of about 80 t for each device. Although no details are known, the outcome of this correspondence seems to have been satisfactory to Bureau Veritas.

Two notes made by the Bureau Veritas surveyor, one on the assembly drawing of the visor and one on the von Tell general arrangement drawing for the visor and ramp installation, stated that "Arrangement of locking devices subject to the approval of the National Authorities" and "local reinforcement of the ship's structures in way of locking devices, cylinders and hinges to Surveyor's satisfaction." On the assembly drawing was also a remark that "jack lifting eye on arms, atlantic lock eye, side lock eyes requested in steel grade St52-3" i.e. a high-tensile-strength steel. These drawings were approved by Bureau Veritas with these comments in November 1979 as regards the von Tell drawing and in June 1980 as regards the shipyard drawing.

The shipyard drawing for the visor was submitted to Bureau Veritas for approval only shortly before the vessel was delivered. The note on the von Tell drawing was, however, brought to the attention of the yard by the Bureau Veritas site inspector in March 1980 as recorded in his daily work statement. It is also worthy of note that the von Tell company communicated with the Finnish Maritime Administration in December 1979 about approval of the von Tell design in general but did not then make any reference to the note on the von Tell drawing a month earlier regarding the Bureau Veritas requirement for specific approval of the locking devices by the national administration.

The Finnish Maritime Administration was, under a national decree, exempt from carrying out a hull survey if the vessel had a valid class certificate issued by an authorised classification society. Bureau Veritas did not, on the other hand, make a detailed survey of the visor attachments, as requirements for these were not included in their rules at the time. This situation and the confusing timing of the correspondence about approval of the locking devices, seem to have led to the calculations and the design of the attachment points for the locking devices not being examined for approval either by Bureau Veritas or by the Finnish Maritime Administration.

15.2 Sea loads on the visor

A visor is subjected to hydrodynamic and hydrostatic loads when the vessel is proceeding in a heavy seaway. Due to the geometry of the visor, the wave load amplitude increases in a non-linear way with respect to the relative vertical motion between the bow and the wave surface. A small increase in the displacement and velocity of the relative motion will cause a significantly higher increase in the wave loads.

In straight head or oblique bow sea, the resultant force on the visor of the ESTONIA would be directed approximately 45 degrees from the waterline due to the shape of the visor, causing upward- and aft-directed load components of equal levels. In bow sea there would in addition be a transverse load component, but mostly smaller. The centre of action of the larger forces on the visor would be positioned high up and forward, causing opening moments, and in a bow sea also twisting and yawing moments about the longitudinal and vertical axes, respectively. The forces from lighter sea impacts would generally cause closing moments on the visor.

Due to uncertainty in the estimate of the sea state, the randomness of relative motions and the non-linearity of the forces created on the ESTONIA's visor, there is considerable uncertainty in the estimates of the maximum loads. On the basis of numerical simulations and model tests (see 12.1–12.3) the Commission has concluded that the most probable maximum resultant force on the visor, developing in a significant wave height of about 4 m and after the vessel had changed course at the waypoint, was between 4 and 9 MN. Divided into force components, this equals simultaneous upward and aft forces of 3 to 6 MN and a starboard transverse force of 0.5 to 2.5 MN. The resultant maximum moments about the hinge points were 4 to 20 MNm opening moment, 0.5 to 7.5 MNm twisting moment and 0.5 to 2.5 MNm yawing moment. Load and opening moment levels in the lower part of the range could well have been exceeded a number of times. Levels above the upper limit of the range are judged to have had a low probability of being exceeding, but cannot be excluded.

The Commission has noted that the estimated maximum sea loads at the time of the accident in terms of vertical and longitudinal forces on the visor were of magnitudes about equal to those used by the shipyard as design loads. Later during the accident night the wave height increased and the forces would have increased significantly if the ship had continued at the same speed and heading towards the waves.

The distribution of reaction forces and their directions in the visor attachments are affected by the positions of the attachment points in relation to the position of the centre of wave load action on the visor, the play in the locking devices, the overall stiffness of the visor and the local stiffness at the attachment points. In the following sections the strength of the various attachments is discussed separately based on calculations and tests as described in the Supplement. An estimate of the combined overall capacity is given in 15.10.

Figure 15.1 The failed starboard mounting lug for the bottom locking device.

15.3 Evaluation of the bottom locking device

The bottom locking device failed in its attachments to the forepeak deck (Figure 8.13). The failure took place by fracture in the three plate lugs carrying the bolt housing and the mating support bushing and in the weld around the housing and the bushing (Figure 8.14). The fracture of the parts indicates tensile failure load directed forwards.

The starboard and centre mounting lugs had essentially failed in the longitudinal plane of the vessel whereas the port lug had restrained the forward movement of the locking bolt and housing and become twisted. The locking bolt had slipped out of the mating lug on the visor at an angle of about 30 degrees.

The failed lugs were recovered from the wreck and have been subjected to metallurgical and strength examination of the fractured surfaces and of the base material (Supplement). All indications are that the lugs failed in a local overload condition with one or a few cycles. The general appearance of the failed lugs is shown in Figure 15.1. The failure in the weld joint was partly in the weld beads and partly in the surrounding material. The thickness of the weld beads was around 3 mm. Indications of pre-accident root cracking or lack of fusion can be seen in the fractured areas of the weld beads.

The load-carrying capability of the bottom lock assembly (Figure 15.2) to failure has been estimated using calculations detailed in the Supplement. Only two lugs, symmetrically located one on each side of the visor lug, effectively contributed in carrying load applied in the longitudinal direction via the visor lug. This failure pattern is also supported by the result of tests carried out in Hamburg and referred to below.

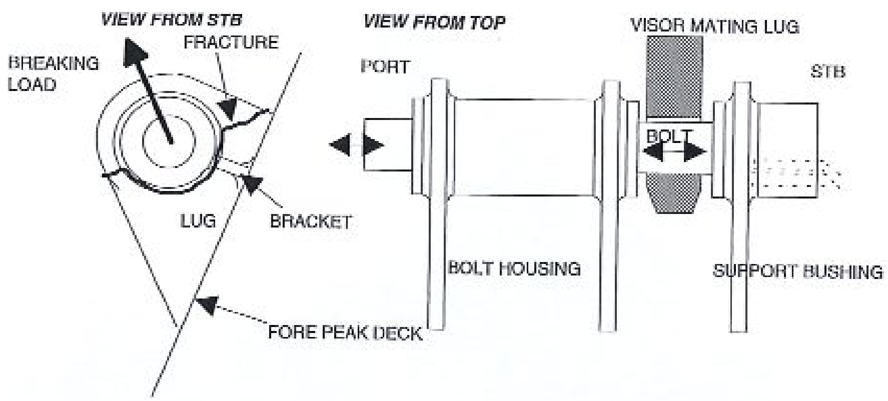
The load was carried by the rims of the lugs and by the welds between the lugs and the housing and support bushing for the locking bolt. The fracture area of each lug was about 1100 mm^2 of mild steel, contributing a load-carrying capability of about 0.3 MN to the failure load of the welded assembly. This value is based on a failure mode wherein the lugs would only have been loaded to the yield level when the welds failed due to their lower ductility. The welds had a load-carrying capability of 0.3 to 0.5 MN at each lug, the actual contribution depending upon the quality of the welding and any existence of root cracks.

The total failure strength of the assembly will have been the strength to failure of the welds plus loading of the two lugs to their yield stress, or altogether 0.6 to 0.8 MN per lug. Two contributing lugs would then have given the complete bottom lock assembly a holding capacity of about 1.5 MN including a small contribution from the starboard bracket. The Commission considers this to be a realistic maximum value.

The Commission is aware of a series of tests carried out in 1996 at the Technical University of Hamburg on behalf of the yard with full scale mock-ups of the bottom lock assembly made of high-tensile strenght steel. In these tests, characterised by different extent of welding between the attachment lugs and the locking bolt housing, failures occurred between 1.0 and 2.0 MN. A test that incorporated intermittent welds resulted in failure at 1.42 MN.

The mating lug on the visor had a tensile load-carrying capacity to failure of about 1.8 MN, taking into account the material (mild steel) and that the lug tip was loaded more critically in the shear mode than in the tensile mode assumed in design. The visor lug was therefore just a little stronger than the forepeak deck assembly. Results of analysing the deformation of the recovered lug using modelling and experiments indicate that the lug may, at some time, have been exposed

Figure 15.2 Bottom locking device.



to a tensile load of up to 1.5 MN (Supplement).

The Commission has learnt that the bottom locking device assembly was manufactured by the yard as a shop subassembly that was subsequently welded to the forepeak deck. No detailed drawing with welding data was issued specifically for this subassembly as welding data was generally contained in yard standard tables. The Commission has not found information on any modifications or repairs of the bottom lock. The paint test (see 12.7 and the Supplement) and statements by people involved in maintaining the lock indicate that it is original or dates back to a very early period of the vessel.

To satisfy the outcome of the yard design calculations, the lugs should have had a larger minimum cross-section. It appears that dimensions of the attachment lugs as indicated schematically on a von Tell assembly drawing for the bottom locking device were used in the manufacture of the attachment lugs rather than a design based on the yard calculations. It is noted that the design calculations also assumed high-tensile strength steel, whereas the actual attachment lugs were made from regular mild steel. With regular mild steel the load-carrying effective cross-section of the bottom lock attachments should, according to the shipyard's design calculations, have been about 8300 mm^2 whereas the built-in equivalent cross-section, including the small welds and the load effectively being carried by two lugs, was only about 4600 mm^2.

It is concluded that the load-carrying capacity of the installed bottom locking device was not adequate to satisfy the design load and calculated minimum cross-section requirement.

15.4 Evaluation of the side locking devices

The side locks failed at the attachment of the lugs to the aft bulkhead plating of the visor. No drawing showing details of the installation and welding of these to the visor plating has been identified. An extract from the von Tell assembly drawing for the side locking arrangement was apparently released for manufacture of the side locking lugs. This sketch shows the lugs to have a bottom length of 370 mm, compared to about 550 mm as indicated on the general assembly drawing for the visor.

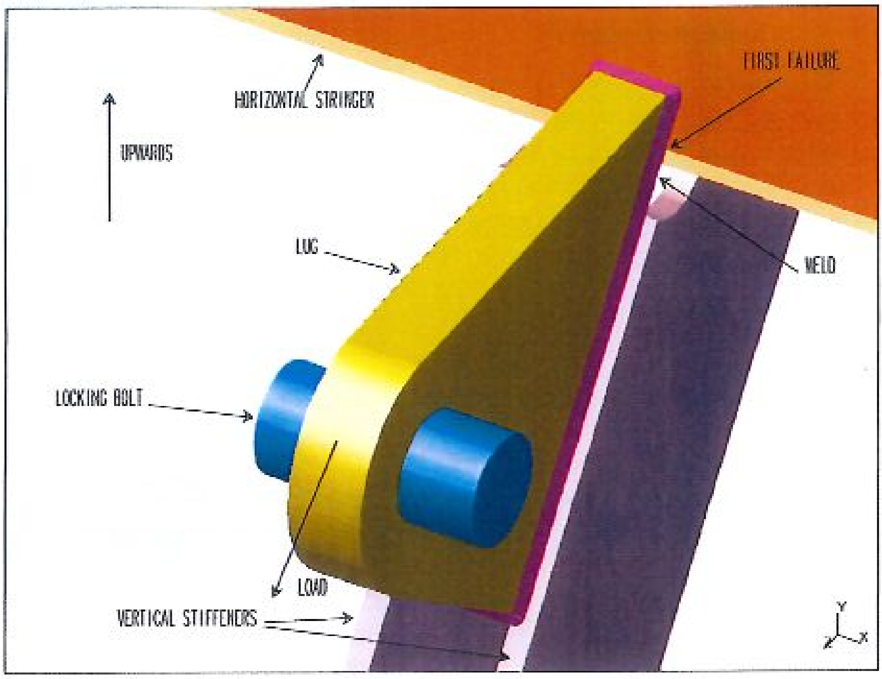
The lugs were ripped out of the visor plating together with part of the plating itself, leaving rectangular holes, about 390 by 85 mm, with fracture surfaces mainly in shear through the aft plating (Figures 8.19 and 8.20). The lugs remain on the locking bolts in the wreck. The bottom surfaces of the lugs are shown in Figures 8.17 and 8.18.

The thickness of the aft plating of the visor was 8 mm. Two vertical stiffeners were installed behind each lug at the surveyor's request for local reinforcement of the structure bearing the locking devices (Figure 15.3). One of these stiffeners was so located that there was an overlap of the fillet weld of the lug and one of the stiffener weld to the bulkhead plating. The other vertical stiffener had no overlap. The strength contribution from these stiffeners has been estimated to be small. A horizontal stringer on the visor aft bulkhead, located close to the upper corner of the lug, had failed in the plating and partly in the weld between the stringer and the bulkhead surface. No other strength continuity was incorporated behind the lugs.

The force required to pull and break the lug away from the visor in a direction tangential to the rotation about the hinge points and in the lug plane has been estimated with mock-up testing and calculations to be at most about 1.2 MN on the port side and 1.6 MN on the starboard (Supplement). These values take into account a weld defect at the stringer behind the port lug and the uneven distribution of the fillet weld between the stiffeners and the bulkhead plating. The load-carrying capacity would be lower for a load applied at a smaller angle to the bulkhead plating and higher for a load more normal to the plating.

It is especially noted that the side locks had deficient loading capacity because their geometry induced primary shear in the aft plating of the visor. Thus, although the minimum cross-section of the lugs was almost equal to that required by the design calculation, the strength was, very approximately, only half of what a similar tension-loaded cross-section could provide. However, the cross-sections of the horizontal stringer and

Figure 15.3 The visor side locking lug assembly with bulkhead plating removed.



the very modest vertical stiffener weld added some holding strength.

The ultimate load-carrying capacity of the side locking lug welds has been calculated to be less than the value above for a weld bead of 8 mm, but the thickness and strength of the weld material is uncertain. The actual failure did not, however, occur in the welds.

It is concluded that the absence of sufficiently detailed manufacturing and installation drawings for the lugs and their supporting structure resulted in an insufficient load-carrying capacity in comparison with the calculated design load requirement.

15.5 Evaluation of the hinges on deck

The hinges at the aft end of the visor deck beams were subjected to loads of about 1.2 to 1.5 MN during normal opening and closing of the visor, acting in directions between downward and aft depending on the position of the visor. The lower rims of the hinge plates had generally failed under tension and the upper ones under bending leaving stretched tongues with strongly contracted tensile, ductile shear fractures of the failed lower rims and flat fractures of the upper rims with clear signs of bending overload (Figures 8.21–8.24). The welds to the bushing failed in the forward part leaving the rim attached to the separated part.

The lugs and one recovered hinge bushing have undergone metallurgical and strength investigations as described in 12.7 and in more detail in the Supplement. The investigation of the recovered hinge bushing has revealed extensive cracking in the weld beads, primarily in the downward-facing area. This cracking was initiated by cracks in the root of the weld and progressed through the weld, generally in one of the fusion zones. At a couple of places the cracking proceeded to the outer surface of the welds, as reported after the accident by a student doing paint work on board. The loads generated during normal operation are judged to have been sufficiently high to cause fatigue cracking to progress in the welds, initiated by the original root cracks.

The lug rims ultimately failed in tension of the lower lip and bending of the upper one without previous fatigue cracking, as clearly noticeable on the recovered specimens. The fracture surfaces of the lugs indicate that the final failure took place within one or a few load cycles.

The cracks observed had only marginally influenced the strength of the hinges against wave-induced loads primarily because of the load directions generated.

The load-carrying section of the hinges consisted of the rims of the lugs of the visor hinge beams and the fillet welds around the hinge bushings. The rims of the lugs had a cross-section of 60 by 25 mm in each plate. The lugs of one hinge assembly (two plates) would then, according to simplified assumptions and calculations, have had a load-carrying capability in aft-directed tension of maximum 2.7 MN, using an ultimate tensile strength of 450 N/mm^2, verified during actual testing. With the minimum cross-sections of the rims at yield in a welded assembly their contribution to ultimate strength in aft-directed tension would be 1.5 MN. In the same loading mode the weld would contribute about 5.8 MN making the total resistance to a single load at most about 7.0 MN for aft-directed tension.

The ultimate strength of a hinge against lifting load has been estimated to about 4.6 MN assuming a clearance larger than about 1 mm between the steel bushing and the lug plate.

The surfaces of the holes in the lugs where the bushings had been inserted had, along much of their peripheries, a very rough contour as from manual flame cutting. This applied to all four lugs, but more so in the starboard hinge. The burn marks were in the lug plates only with no corresponding marks on the recovered bushing. In addition, the forward contours of the holes in the lugs in the starboard side hinge were located about 10 mm further forward relative to the outer contours of the hinge beam than those on the port side. It has not been possible to find the reason for the rough surface, whether it was an adjustment of the hinges during assembly or remains from a later repair. No documentation from any repair in this area has, however, been recorded.

It is most likely that the forces to cause the hinges to fail were generated when the visor, moving upwards around its hinges and having lost support from the locating horns, was exposed to twisting and yawing moments. Given the relatively high stiffness of the deck hinges compared with that of the attachment of the locking devices it is also possible that initial failure of the port hinge was caused by high reaction forces before all locking devices failed.

The Commission notes that the hinge strengths were in general commensurate with design intent. However, the cracks generated during normal service indicate insufficient strength of the hinge lug rims and bearing bushing welds. Also the rigidity of the lug rims to vertically-directed loading is considered poor because of the modest bearing bushing weld and the flame-cut bushing hole with its rather loose tolerance.

15.6 Manual locking devices

The manual locks at each side consisted of two plate lugs welded to the aft bulkhead of the visor and an eye bolt in a cavity in the hull, so arranged that it could be rotated to position between the lugs and tightened. The total load-carrying capacity of the manual locks has been estimated to be at most 0.7 MN each. Had they been applied they may to some extent have contributed to the overall load-carrying capability of the visor locks. The fact that there were no instructions for their use has been taken as an indication, however, that they were not regarded as part of the operational locking system.

15.7 Evaluation of the visor actuators and their attachments

The visor had two heavy-duty actuators for controlling the opening and closing of the visor. These were connected to the visor hinge beams at a distance of 1.3 m from the hinges and were mounted on reinforced horizontal platforms in the front structure of the hull. The actuators were connected hydraulically to a solenoid-type control valve, which was closed at all times except when the visor was being moved. Various restrictor valves were installed in the system to limit the speed of opening and closing. The pumps in the hydraulic power supply system had been replaced once with new ones capable of delivering a higher hydraulic pressure as the original ones had marginal capacity.

When sea loads started to open the visor, an upward load was also applied to the actuators, which resisted the opening movement. The leverage from the centre of attack of the sea loads compared to that of the actuators enabled a high pulling force to be transmitted to the actuators. The port side actuator was at this moment pulled out of the hull (Figure 8.26) while only partly extended whilst the locked-in hydraulic fluid acted to transmit the force to the lower attachment of the unit. The vertical force to shear the actuator support out of the hull has been estimated to be from 4 MN down to possibly as low as 2 MN, taking into account the unsymmetrical attachment point of the load and extensive cracking in the platform edges and welds as well as the steel grade used for deck 3. Tests revealed signs of cold brittleness in this steel even at room temperature. The actuator mounting platform has undergone a detailed investigation (Supplement).

The normal operating loads from the actuators appear to have been high enough to initiate fatigue cracking of the platform plating and the welds, in particular where some crack-promoting discontinuities may have existed. The port platform exhibited cracks around a large part of its periphery, generated by vertical loads from normal visor opening and closing.

The seals in the starboard actuator failed, preventing the hydraulic fluid from transmitting the load. The piston rod of this actuator was therefore extended and the actuator remained connected in the hull during the initial phase of the visor movement. The load initially taken is uncertain but must have been below the ultimate strength of the platform, estimated to be below 8 MN.

15.8 The ramp locking devices

The ramp was secured in the closed position by six locking devices, i.e. two pull-in hooks at the upper end and two locking cleats along each side of the ramp.

After the accident, the upper pull-in hooks were in closed position as verified by ROV video pictures of the actuator and lever mechanism. It has, however, not been possible to determine in which mode the hooks themselves failed. An upper limit of the load-carrying capability of a hook may have been the load at which the metal in the contacting area between the hook and the mating pin started to yield. This load was approximately 0.2 MN. It is assumed that the pin slipped off the hook when yielding started in the hook material, as the bend-over angle of the hook tip was small.

The side securing bolts, in locked position, extended into box-like structures welded to the side bars of the ramp. These boxes were ripped open following failures in their welds. The force required to rip any one of these boxes open has been estimated to be 0.2–0.3 MN. The lower port box, however, was not damaged and it is concluded that the locking bolt was not engaged when the ramp was forced open by the visor. A question remains about the condition of this locking device just before the accident. This did not, however, have any effect on the overall development of the accident.

The locking devices failed sequentially as a result of load applied to the port side first. A force applied to the top of the ramp from contact with the visor had larger leverage than the locking devices had, reducing the force actually required to break the devices. The contact force required to deform the stiffeners in the deck housing of the visor has been estimated at 0.3–0.4 MN, sufficient to break open the ramp locking devices.

15.9 Other damage to the visor

Other damage to the visor that is related to the accident includes extensive pounding of its bottom and indentations on its front. The bottom plating was forced upwards and had cracks in many places, primarily in welds. The stem post had separated from the side plating and been folded inwards together with the bottom plating (Figure 8.6). Damage marks indicate that this happened when the visor started to tumble forward and was rotating downwards on the ice-breaking prong of the bulbous bow. This damage caused by the ice prong continues upwards along the stem, culminating in large mid-height indentation (Figure 8.5). Further indentations, scratch marks and paint marks on the starboard side of the visor indicate its continued movement when it slid off the bulbous bow and sank underneath the vessel.

Analysis of paint marks in the main indentation shows that these came from paint of the same type as that used below the waterline of the vessel, including the bulbous bow.

It is concluded that the bottom plating of the visor became deformed when the visor was dropping back after having been lifted by waves, initially pounding on the forepeak deck and, secondly and extensively, on the stem head.

Some indications of old cracks have been found in welds, primarily in those between the stem post and the side plating and between the side plating and the bottom plating. Some of these joints may have been exposed to cyclic loading from opening and closing and from waves and ice. Fatigue cracking may have developed, generally starting in stress concentration points in the roots of the welds. It has, however, been difficult to determine the characteristics of the cracked surfaces due to subsequent extensive corrosion.

The stem post, folded inwards under the visor, had four transverse cracks on its front side. It is assumed that these developed during the deformation of the stem by beating on the ice prong although indications in the crack surfaces suggest that cracks may have existed before the accident.

Small paint marks from paint similar to that used on the hull were found in one of the cracks. It could, however, not be established whether these marks were flakes coming from the surrounding paint or had actually entered an existing crack during painting.

It is concluded that some cracks may have developed in some welds during the vessel's lifetime. In view of her age these cracks are considered to be normal and did not contribute to the cause or the development of the accident. Progressive cracking in some weld seams might have affected only the development of the secondary damage, once the damage had been initiated.

Two longitudinal flat bars, though shown on the visor steel drawing as running one on each side of the recess for the locating horn on the bottom plate of the visor, seem not to have been installed. The bottom of the visor therefore had no other structural continuity in its load-carrying members than its aftmost beam to which the visor locking lug was attached. The bottom is therefore considered to have been weaker than intended, in particular when taking vertical loads. This is also likely to have affected the amount of deformation occurring during the accident influencing the ability of the visor bottom structure to resist vertical forces that may have developed during the failure.

The interior of the visor shows several dirty "waterlines" indicating that water had been standing inside the visor for some time. Some oil, presumably hydraulic oil leaking from the hydraulics of the bottom lock, had floated on top and had settled on the vertical surfaces giving the "waterlines". The sealing on the forepeak deck had clearly not always been in a condition to keep the lower part of the visor watertight. The Commission has learned from individuals involved in other ferry operations that this is quite common in many ferries as the seals on the fore peak deck are so easily damaged by the rubbing action occurring during opening and closing of the visor.

The Commission has concluded that the general maintenance standard of the visor was satisfactory. The steel work was little corroded and no reduction of plate thickness, nor pitting, has been noted on the various parts collected for detailed investigation.

15.10 Failure modes and combined strength of the attachment devices

The failure pattern of all the attachments indicates an overload caused by forward-upward motion of the visor. The Commission has considered different possibilities that could have caused the attachments to fail, but has come to the conclusion that it was an external wave impact on the visor that created the necessary failure loads.

The visor of the ESTONIA was not fully watertight, and probably some water penetrated into it in the rough head and bow sea the vessel encountered. Hydrostatic pressure from trapped water inside the visor would create a resultant force directed about 45 degrees forward and down. The pressure and the resultant force would be amplified by the vertical accelerations of the bow. However, the possible amount of trapped water could not have created tension reaction forces in the attachments sufficiently high to make any of them fail. As an example, 3 m of water inside the visor would create a hydrostatic resultant force of only about 0.5 MN.

Green water on deck could be critical due to the unfavourable lever arm to the aft-positioned visor hinges. About one metre of water on the deck would double the weight of the visor, but several times this height would be needed to break the attachments. The model tests and the numerical simulations show that the probability of any significant amount of green water on deck was negligible for sea conditions at the time of the accident.

In general, the lower level of wave-induced forces on the visor occurring every few minutes in the prevailing sea condition would cause closing moments about the deck hinges. The reaction forces so created were taken up by the stem post and steel pads on the forepeak deck. The model test results indicate that the maximum closing moment including the visor's weight was about 8.0 MNm. If the stem post alone had supported the visor, the stresses from this moment would have been about 120 N/mm^2 in compression, possibly with some added bending stresses. If the visor locking devices had taken up the closing moment, the reaction forces would have been directed forward, causing compression in the lugs. The closing mode is not considered critical for the attachment system.

When the resultant wave-induced forces exceeded 2.0–2.5 MN, the line of action would pass above the hinge axis and create an opening moment. With an average period of about 10 minutes in the accident condition, the opening moments were high enough, about 3 MNm, to exceed the static weight of the visor. Less frequent, higher wave loads caused much larger opening moments. Opening moments would create tension in the visor lugs of the locking devices and forward-down compression in the visor hinge lugs. In oblique bow sea the reaction forces would be unevenly distributed between the side lugs, increasing the tension on the side that encountered the waves. This effect is clearly visible in the visor damage which shows strong movement from port to starboard.

The attachment system was statically undetermined and the distribution of reaction forces was therefore affected by the stiffness of the structure as well as by the play in the locks. By studying different levels and combinations of wave load components and different possible distribution of reaction forces, an estimate of the total load-carrying capacity before failure of any of the attachments has been obtained. The estimated strength of the individual attachments is described earlier in this chapter. Assuming that all locks worked efficiently and using realistic correlations of wave load forces and moments obtained from model tests in port bow seas, it is estimated that the combined strength of the attachment system would be exceeded by an external resultant wave load of 7–9 MN, corresponding to opening moments 13–20 MNm.

Most likely the port side lock failed first, possibly at a lower load level than the maximum estimated above. The subsequent failure could have occurred either by shearing of the port hinge lugs, or by tension in the bottom lock. The estimated necessary level of wave load for either of these possible second failure modes is about the same. Hence, the complete failure sequence could have required only one or two wave impacts. If only the port lock failed in a first large wave impact and the other attachments remained intact, then the visor was probably kept in place – appearing undamaged – for a significant period. The hypothesis of a side lock failing first is supported by the similar damage pattern incurred by the visor attachments of DIANA II in 1993.

Figure 15.4 illustrates an example of a possible reaction force distribution over the attachments when the port side lock fails. The load on the hinges, though large, is acting in an uncritical direction while the bottom lock and the starboard side lock are loaded only to about half of the critical level. A possible reaction force distribution after the port side lock has failed is shown in Figure 15.5.

The final stage of the attachment failures leading to the loss of the visor took place in the remaining hinge lugs and in the lifting actuator sealings and mounting platforms when the visor was free to move. Significant forces in the actuators are judged to have developed only after the locks had failed. The maximum necessary resultant wave load to fail the actuators simultaneously would be about 6 MN, but they most likely failed in sequence under dynamic conditions at a significantly lower level.

The extreme value distribution of wave-induced loads given in 12.3 for the accident condition indicates a theoretical probability of more than 5% that a single wave load would exceed the largest estimated combined strength of the attachments during 30 minutes at a speed of about 14 knots in oblique bow seas with a significant wave height of 4.0–4.1 m. The probability of wave loads exceeding the attachment's strength increases rapidly with increasing wave heights.

The Commission concludes that the largest forces generated by sea loads under the prevailing conditions were higher than the combined strength of the attachments and hence caused the failure of these and the subsequent loss of the visor.

It is notable that the ultimate strength of the visor attachment system was exceeded already for a load level about equal to the design load used, and that this load level developed in a sea condition that was far from the worst the ship could have been expected to encounter. There was consequently no margin of safety incorporated in the visor attachment system.

15.11 Design considerations

After having studied the design, manufacturing and procedures for approval, the Commission finds that none of the parties involved considered the visor attachments as critical components for the

Figure 15.4 Example of reaction force distribution resulting in port side lock failure.

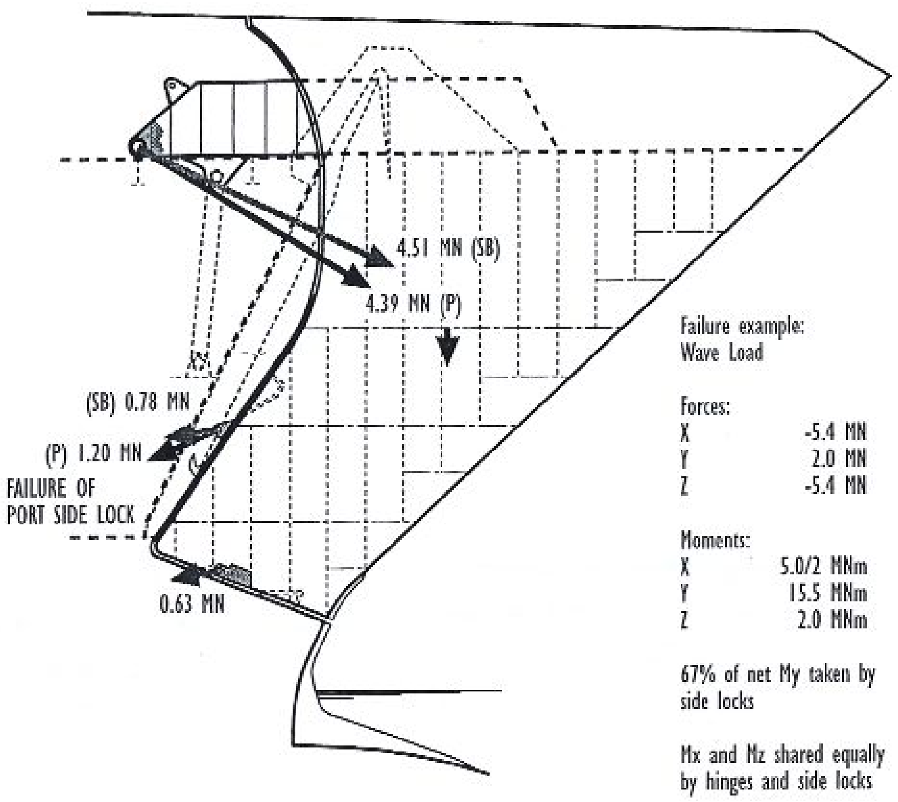
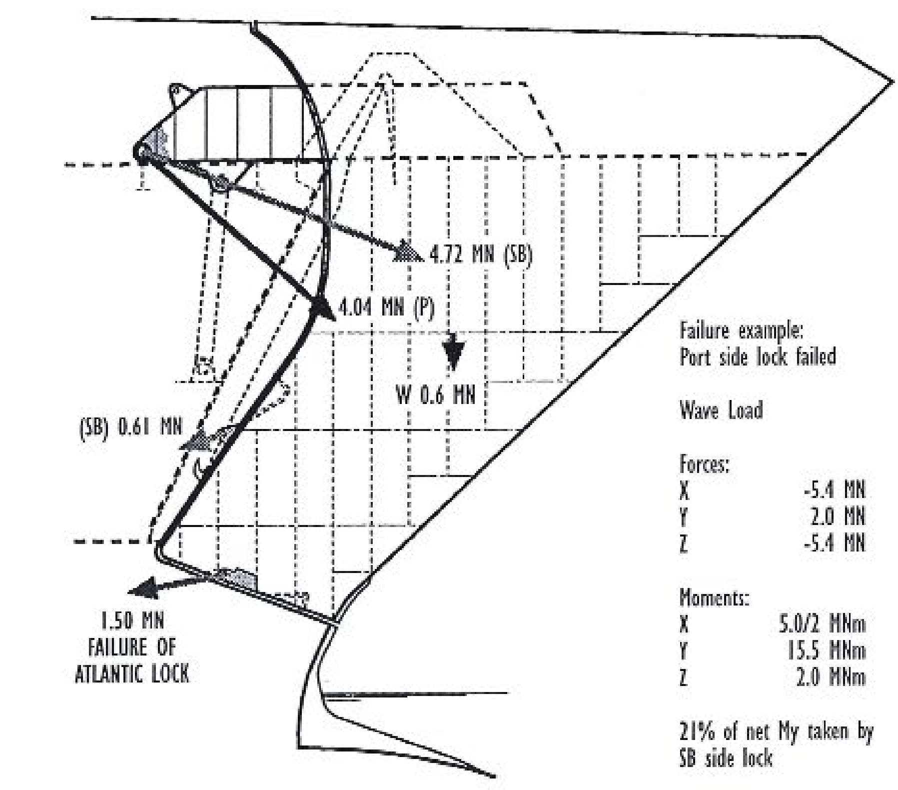


Figure 15.5 Example of reaction force distribution after the port side lock had failed.



safety of the ship. There is however no indication that the routines in this respect deviated in general from routines followed by other parties for other newbuildings in the Baltic area at the time. Information has been found, however, that in some other parts of the world in the 1970s visors and their attachments were more thoroughly designed and considered critical for the vessel's safety.

The ESTONIA was designed and built after a decade of very rapid development in shipbuilding and naval architecture. Ship sizes increased, shipyard technology was modernised and new computer-based direct methods for calculation of structural strength and wave-induced loads were introduced in the design process. As a consequence, experience lagged behind technological development. Ships are in general highly optimised with regard to structural strength, and experience from damage, incidents and accidents has always been an important basis for the development of codes and procedures.

Ro-ro passenger ferries for the Baltic traffic developed very fast during the 1970s as described in Chapter 10. The ESTONIA was at the time of newbuilding among the largest bow visor ferries ever designed, and experience from similar designs was obviously limited.

Today with the outcome known, it is easy to find several items to criticise in the design of the visor. However, if anyone had made a rational analysis of the concept, the same items could have been found open to criticism even at the time the ship was designed. Here are listed a few such design considerations that the Commission regards as important.

All attachment points for a bow door should be regarded as highly loaded design items and subjected to detailed load and strength analysis.

Where operating experience is limited and design rules and recommendations give little support, it is of utmost importance to make a failure consequence analysis. Even a very simple analysis would in this case have highlighted the critical interconnection between visor and ramp and the possible consequence of water on the car deck after failure of the visor attachments. The conclusion would then have been either to separate the two barriers or to incorporate a very large safety margin in the design of the attachments.

The design load calculation and the assumption of equal distribution of forces on the attachment lugs for which there was also support from some classification societies' design rules at that time, had no basis in physics. The reaction forces obtained were not in balance with the external load, and no specific directions of forces were determined. Since the design pressure head was equally distributed over the shell of the visor, oblique loading was not even considered. The Commission is of the opinion that even very simplified design calculations of vital items should include analysis of different possible load directions and failure modes. In a statically undetermined system of supporting points, either detailed analysis including flexibility should be performed or sufficient strength should be assessed for any combination of reduced system that could be evaluated by simple equilibrium of forces.

Locking devices of the common design such as those installed on the ESTONIA are subject to wear and corrosion on the locking bolts and mating lugs, leading to play in the arrangement. Some initial play is also built in, to safeguard functioning during opening and closing of the devices. The play was about 10 mm in the ESTONIA's locking devices and extensive play of about 35 mm is known from other ships. Play between the connecting parts has the consequence that the contact load distribution between the locking devices is undeterminable and in an extreme condition one single device may be subjected to the entire external load. Play in a connection subjected to dynamic loads will always lead to accelerated wear and may induce fatigue. The Commission is therefore of the opinion that locking devices should be of such design that play is eliminated during closing and bow doors should, in the closed position, be physically tightened against mating surfaces.

The local design of the ESTONIA's visor attachments shows weakness particularly because the lowered strength in the shearing mode had been ignored. The hinges were weak due to weld shear and bending of lug rims induced by vertically directed reaction. The side lock induced shear in the visor aft plating in all load modes, and the bottom lock design capacity would have been limited by shear of the visor lug tip even if the forepeak assembly had been welded to better standards.

15.12 Comparison of design requirements and actual installation

The design requirements for the visor attachment devices at the time the vessel was built generally indicated a design load level of about 1 MN per device based on an even distribution of the bow load on all the attachment points. This applied to the way the loads were determined by the yard, and also followed from the rules of some other classification societies at that time.

The ultimate failure load, corresponding to the 1 MN design load, would in the simplified analysis made by the yard have been about 3 MN per device taken as the ratio between ultimate strength and permitted stress. However, in a mixed design where various design elements are included and different failure modes will develop sequentially, this relationship is not directly applicable.

The failure load of the bottom and side locking devices as installed has been determined to be about 1.5 MN per device, account taken of the uncertainty in load direction and failure modes.

It seems obvious to the Commission that the ultimate load-carrying capability of the attachment system and its individual devices would have been considerably higher if the reduced strength in the shear mode had been considered and the manufacture would have been according to the design intent.

The design loads used were, however, low and it is noteworthy that even an installation fully meeting the design assumptions applicable at the time of construction would not in all cases have withstood the hydrodynamic forces generated during the night of the accident, considering the increasing wave heights. As an illustration, the model test results show that the maximum opening moment generated by wave loads would be more than three times higher than estimated for the accident condition in bow seas with a significant wave height of 5.3 m and a speed of 10 knots.

15.13 Class and administration implementation requirements

A number of serious incidents are referred to in Chapter 11. The cases mentioned are those for which the Commission has found information without extensive research. The ships involved were in most cases operating in Scandinavian waters. It is fair to assume that a number of incidents have taken place also in other trading areas.

In the individual ship involved in an incident, the relevant structures were in most cases reinforced during the necessary repair. In several cases reinforcements were also made on sister ships. However, in some cases the classification society involved was satisfied with a repair restoring the strength of the device to the original standard. This was the case e.g. after the DIANA II incident in January 1993. The vessel was at that time 13 years old and the damage seems to have been regarded as isolated and no further alarms were raised or action taken.

The Commission has noted that in several cases the affected Administration communicated with the classification society involved and was satisfied with the information that the strength requirements had been increased. This would apply, however, to new ships only. Retroactive upgrading of existing ships through rules and regulations with retroactive effect has generally been considered unacceptable within the shipping industry and this attitude has been accepted within IMO as well as amongst classification societies.

The Commission finds this attitude unacceptable in cases of incidents with serious safety implications. The Commission is of the opinion that all amendments to requirements, founded on actual risks having become known, should lead to requirements with retroactive effect, both in IMO regulations and in the rules of the classification societies. The Commission has also noted that a move in that direction has taken place since the ESTONIA accident.