DEGREE PROJECT IN LIGHTWEIGHT STRUCTURES,
SECOND CYCLE, 30 CREDITS
STOCKHOLM, SWEDEN 2026

Lessons Learned from Damage History of a Corvette

KTH Master Thesis Report

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Abstract

The damage history of a corvette class provides an insight into the life cycle of a sandwich-hulled ship, with unique advantages and challenges when compared to more conventional ships. This insight can be utilized when building sandwich ships in the future. An in-depth study was done on available error reports related to the corvettes from 1997 to 2025. A total of 214 damages were identified and categorized. In addition to this, the position of each damage was analyzed.

The results show that blisters and dry spots were the most common types of damages. However, these have been greatly reduced as issues over time due to a change in the materials used in construction and repair. Delamination and debonding are common for the earlier ships, but have been eliminated for the later ships in the class. Damages associated with manufacturing have also decreased with time, as a result of more experience and better instructions. Cracks, scratches and accidents are the most common damage types when the ships are in use. More than a fourth of all damages are below the water level, which may be more serious than damages above the water level due to failure causing a severe risk while at sea. Recommendations for the planning of future sandwich vessels include studying the literature that has since developed about the use of sandwich structures in naval architecture, testing to ensure future materials are compatible, a rigid examination of docking procedures in order to minimize the risk for accidents and a proper systematization of error reporting.

Keywords

sandwich structure, composite, repair

Sammanfattning

Skadehistoriken för en korvettklass ger en inblick i ett fartyg med sandwichkonstruerat skrovs livscykel, både med unika fördelar och utmaningar jämfört med konventionella fartyg. Denna inblick kan vara användbar när man i framtiden vill konstruera liknande fartyg. En djupdykning i skadehistoriken för fartygen gjordes genom en analys av tillgängliga skaderapporter från 1997 till 2025. Totalt kunde 214 skador identifieras och klassificeras. Även skadornas position på varje fartyg analyserades.

Resultaten visar att blåsor och torrfläckar är de vanligaste skadetyperna. Dessa har dock minskat kraftigt i antal och frekvens över tid, mestadels på grund av förändringar i materialval i konstruktion och reparation. Delaminering och släpp mellan kärna och laminat är vanliga för första fartygen i klassen, men har eliminerats som skadetyper för de senare. Skador kopplade till konstruktion har också minskat med tiden, ett resultat av mer erfarenhet och bättre instruktioner. När fartygen är i bruk är de vanligaste skadorna sprickor, repor och olyckor. Mer än en fjärdedel av alla skador är under vattenlinjen, vilket kan ses som mer allvarligt då sådana skador får allvarligare konsekvenser när fartyget är i drift jämfört med skador över vattenlinjen. Rekommendationer för nästa generation sandwichfartyg inkluderar att noga studera literaturen om sandwichkonstruktioner i marinarkitektur som tillkommit på senare år, rigorös testning av material för att säkerställa kompatibilitet, undersökning av dockningsprocedurer för att minska risken för olyckor samt att utveckla ett mer effektivt system för skaderapportering och uppföljning.

Nyckelord

sandwichkonstruktion, komposit, reparation

Acknowledgements

I would like to thank Stefan Hallström and Helena Delmotte, my examiner and supervisor for this thesis respectively, for their valuable input during all phases of the thesis-writing process. I would also like to thank Emanuel Klasén of FMV, for providing the project description and my main source of error reports, as well as supervising. Also deserving of thanks are Hans Forsman and Tomas Rommer of SAAB Kockums, for allowing me a closer look at the work at the naval construction in Karlskrona.

Lastly I would like to thank FMV for providing me employment during the months writing the thesis, KTH for providing a platform for the project and Lucas Westin, who has been writing a thesis of his own relating to similar issues and providing valuable insight into his own work, which has acted as an inspiration.

Stockholm, March 2026
Edvin Svenske

Acronyms

CFRP carbon fiber reinforced plastic

CGFRP carbon glass fiber reinforced plastic

CSM chopped strand mats

FMV Swedish Defence Materials Administration

GFRP glass fiber reinforced plastic

KKRV Karlskronavarvet

KTH KTH Royal Institute of Technology

MCMV mine countermeasures vessel

NDI nondestructive inspection

NDT nondestructive testing

PVC polyvinyl chloride

WR woven roving

Contents

Chapter 1

Introduction

1.1 Background

HSwMS Visby (K31) was the first corvette developed by the Swedish Defence Materials Administration (FMV) for use at sea in the Visby-class and can be seen in Figure 1.1.1. Construction began in 1996 by Kockums AB (now Saab Kockums AB) and the official launch was in 2000. In 2002, the ship was delivered to FMV to be fitted with weapons and other combat systems. Since then, a total of five corvettes have been built in the Visby-class. These include HSwMS Helsingborg (K32), HSwMS Härnösand (K33), HSwMS Nyköping (K34) and HSwMS Karlstad (K35), all of which were launched in the years 2003-2006. A sixth ship in the Visby-class, HSwMS Uddevalla (K36), was planned but ultimately canceled in 2001 [1]. In 2009, HSwMS Helsingborg and HSwMS Härnösand were delivered to the Swedish Navy as the first of their class, fully equipped with weapon systems [2], though in version 4, which lacked features such as equipment for surface combat and mine clearance as well as a helicopter platform [3]. Every ship is now upgraded to version 5, with plans for each to be half-life modified to version 6, extending their longevity as ships in service beyond 2040 [4]. Important milestones for each ship can be seen in Table 1.1.1 and important characteristics of the corvette can be seen in Table 1.1.2.

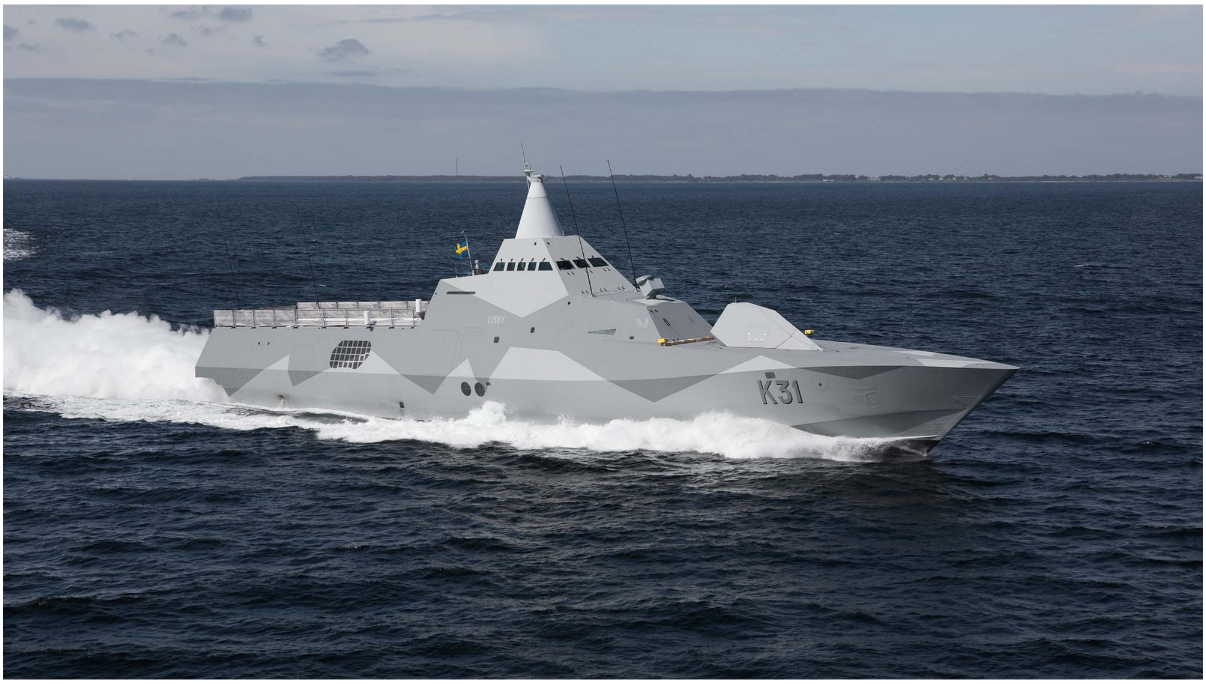


Figure 1.1.1: HSwMS Visby (K31) in use at sea [4].

Table 1.1.1: Introduction milestones for the Visby-class corvettes [2].

Ship	**Launched**	**Delivered to FMV**	**Fully equipped and in service**
HSwMS *Visby* (K31)	2000	2002	2012 [5]
HSwMS *Helsingborg* (K32)	2003	2006	(2009) 2015 [4]
HSwMS *Härnösand* (K33)	2004	2006	(2009) 2015 [4]
HSwMS *Nyköping* (K34)	2005	2006	2012 [5]
HSwMS *Karlstad* (K35)	2006	2007	2013 [6]

Notes:

- *Launched* denotes the year the hull was first floated.
- *Delivered to FMV* refers to delivery to FMV for integration of sensors, combat management systems, and weapons.

- *Fully equipped and in service* indicates acceptance into operational service by the Swedish Navy after completion of combat system integration and weapon installation. The years indicate the delivery of version 5 of each ship, while the years in parenthesis indicate delivery of version 4, subsequently upgraded to version 5.

Table 1.1.2: Main characteristics of the Visby-class corvette (version 5) [4].

Crew	43
Displacement	650 tonnes
Length overall (LOA)	72 m
Beam	10.4 m
Draft	2.4 m
Maximum speed (high-speed propulsion)	Over 35 knots
Speed (low-speed propulsion)	15 knots
Propulsion system	Combined diesel or gas turbine propulsion system: 4 gas turbines (total power 16 MW), 2 diesel engines (total power 2.6 MW), 2 KaMeWa 125-SII waterjet units and bow thruster
Helicopter capability	Platform for helicopter take-off, landing, and refueling

The Visby-class corvette was considered revolutionary for the time, considering the choice of material and the use of stealth technology. The previous classes of corvettes used by the Swedish Navy, Stockholm and Göteborg, consisted of a steel hull and aluminum superstructure and masts [7]. The hull of Visby, on the other hand, consists mostly of sandwich structures. Previously, this type of hull had been mainly used in minesweepers, with HSwMS Viksten as a very early predecessor, built in 1974 in Karlskrona. The project was a collaboration between KTH Royal Institute of Technology (KTH), Karlskronavarvet (KKRV) and FMV. This was followed by the Landsort-class mine countermeasures vessel (MCMV), of which the subclass Koster was built in 1982-1993 for use by the Swedish Navy [8]. These can be seen in Figure 1.1.2. The core of the Visby sandwich hull is of a lightweight polyvinyl chloride (PVC) foam while the skins predominately consist of carbon fiber reinforced plastic (CFRP) laminates. This keeps the weight low while providing the vessel high strength and rigidity. It also has better stealth properties compared to a steel hull, with lower radar and magnetic signature. However, one of the downsides is the poor fire resistance in composite materials [2, 9].

Figure 1.1.2: Early sandwich ships: HSwMS Viksten [10] (above) and HSwMS Kullen, a Koster-class ship [11] (below).

The stealth properties of Visby distinguish it from its predecessors. The stealth technology is the main reason for the characteristic design of Visby. It utilizes large, flat and angled surfaces in order to minimize the optical and infrared signature. This makes it hard for an enemy to detect, whether they are using radar, hydroacoustic or infrared technology. Sensors and weapons are hidden in the hull when not in use, and the exhaust gases are cooled down in order to decrease the heat signature. Beyond the use of stealth technology, Visby has an extensive list of applications, including surface combat, submarine hunting, escort and mine clearance [12].

Despite 25 years of use, no thorough analysis of common damages to the corvettes has been performed. The same is true regarding the repair and maintenance methods commonly employed. If the Swedish Navy decides to procure new corvettes in the future, such an analysis could be a useful addition in planning design, manufacturing and repair routines. The purpose of this report is to provide a framework in which the most common types of damages, repair methods and service routines are documented, systematized and categorized in order to come to an understanding of how these impact the operational life cycle of the vessel. Strengths and weaknesses in the design, manufacturing and repair can be identified and the gathered information be used to make the next generation of vessels more cost effective, safer and easier to repair.

1.2 Problem statement

As mentioned in section 1.1, no detailed analysis of the operational life cycle of any of the Visby-corvettes has previously been performed. This leaves a gap of knowledge that will be bridged by compiling available information regarding damages, repair and maintenance of Visby. A suitable problem statement is thus: **Classify and categorize reported damages, repair and maintenance protocols in a manner that sheds light on the operational life cycle of the Visby-class corvette, as well as providing background and a framework for similar vessels in the future.**

In order to ease understanding of the different aspects of the problem statement, a number of questions can be formulated and subsequently answered in chapter 7:

1. **Do all the ships in the Visby-class have a similar distribution of damages, in type and position?**
2. **Does the damage distribution differ for different phases of the ships, e.g. before launch and when the ships are in service?**
3. **Is any area of the ship disproportionally prone to damages?**

1.3 Scope and limitations

Though repair and maintenance as well as damage history of other composite sandwich ships might also be of interest, this report will mainly focus on the Visby-class corvettes. This is mostly due to access to error reports and technical orders outlining maintenance procedures being limited to the Visby-class, as well as time being a limiting factor. Certain care will be taken to ensure that classified information is not included, as this can negatively impact national defense. The main sources used will be error and repair reports provided by FMV.

Chapter 2

Literature Review

2.1 Composite materials in naval architecture

The use of sandwich structures in naval architecture is a relatively new phenomenon, replacing hulls made out of steel or wood. The use of composite materials, however, started after World War II in order to address the corrosion related to wood, steel and aluminum and has only increased since. Weight reduction was another concern, as steel weighs considerably more than composite materials. Salt and corrosive seawater are a particular problem for sea vessels and can be mitigated by the use of thermoset resins in specific components. MCMVs cannot have steel hulls because it is magnetic and the hulls used to be built entirely out of wood for this reason. Wood requires extensive maintenance and is sensitive to saltwater. Therefore, alternatives were investigated and MCMVs were among the first ships with composite hulls. The first ship with a hull made up of glass fiber reinforced plastic (GFRP) was HMS Wilton, a MCMV built for the British Royal Navy in 1973 [13].

The Visby-class corvette has a uniquely high ratio of carbon fibers to glass fibers and was the first ship in the world with a significant carbon fiber composite content in its hull, carbon glass fiber reinforced plastic (CGFRP) as opposed to GFRP, the latter being the most commonly used composite material in naval architecture historically. Most of Visby consists solely of CFRP. Alongside achieving electromagnetic shielding, the weight of the hull was reduced by 30 % compared to one consisting of GFRP only. Though the cost was at least five times that of glass fiber at the time of construction, it was found that it was cheaper to use more CFRP for two reasons; the weight reduction meant a reduction in fuel consumption [13] and the panel skins could be made of fewer layers but maintain the same properties, meaning the cost for labor decreased, compensating for the more expensive material used [8]. One additional benefit that drives down costs is the decreased need for maintenance, with the cost for the maintenance for the first 20 and 10 years of the aforementioned HSwMS Viksten and Koster respectively consisting only of the paint used for repainting [8].

2.2 Sandwich structures

2.2.1 Strengths and weaknesses

A sandwich structure consists of a thick lightweight core and two thin skins that are made of a stiffer material. This ensures that the entire structure remains lightweight. Stiff skins provide high bending stiffness while the core supports the shear and out-of-plane compressive stresses, preventing global and local instabilities. The weight reduction means larger cargo capacity, fuel savings, lower inertia, and increased ship stability and buoyancy. Common core materials are polyester foam, balsa and honeycomb while the skins usually consists of composite materials or steel. In naval architecture, aramid, carbon and glass fibers are commonly used as skins instead of steel [13]. As previously mentioned, the first sandwich ship built for naval purposes was minesweeper HSwMS Viksten, consisting of GFRP laminates of woven roving (WR) and chopped strand mats (CSM) along with a PVC foam core [8].

Since both the composites used in the skins and the material used in the core are organic, they are easily combustible and emit heavy smoke when exposed to heating. Accordingly, lack of fire resistance compared to steel is a major downside with the use of sandwich structures. However, testing has found that sandwich panels adhere to SOLAS standard fire test which requires the structure to:

• be constructed of steel or equivalent material
• be stiffened in a suitable way
• prevent penetration of smoke and flames for a maximum of 60 minutes during a standard fire test

• be constructed in such a way that the rise of temperature on the non-exposed side remains below 139 °C.

Apart from not being made of steel, all the requirements were fulfilled with the exception that the stability is not satisfied when one of the skins has been burnt off. However, this can be remedied by adding stiffeners to both sides of the bulkheads, which then provides the required stability with just one skin [8]. Another downside compared to conventional materials like steel is that the cost of the materials as well as the labor intensity required to manufacture sandwich structures makes it expensive. This limits its use in naval architecture internationally [13].

2.2.2 Failure modes

There are multiple ways a sandwich structure can fail. Some of these failure modes are presented in Figure 2.2.1:

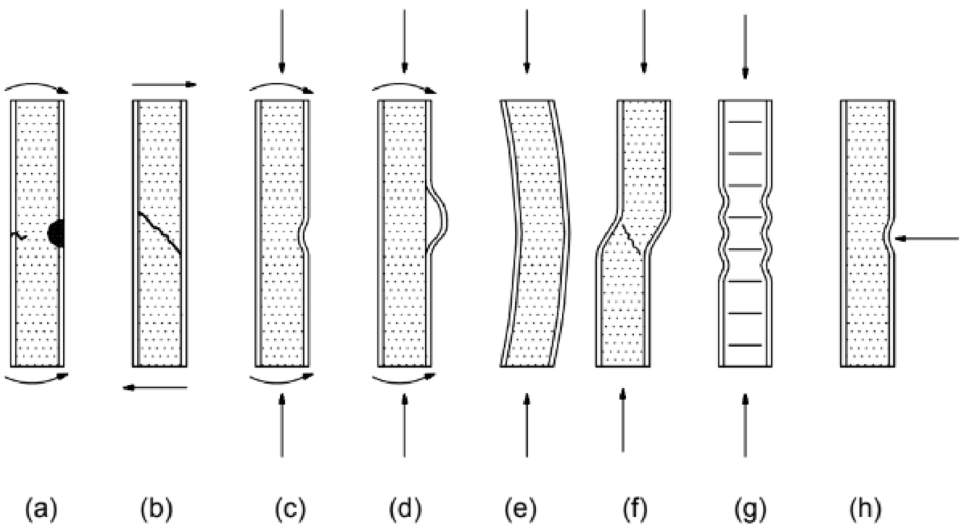


Figure 2.2.1: Failure modes in sandwich beams. (a) Skin yielding/fracture, (b) core shear failure, (c and d) skin wrinkling, (e) general buckling, (f) shear crimping, (g) skin dimpling and (h) local indentation [14].

(a) *Yielding or fracture of the skin in tension or compression.*

This means one or both of the skins yields or even worse, fractures, as a result of tension or compression. Yielding means that the material doesn't break but becomes permanently deformed and either expands or contracts while fracture means a shattering of the skin, the latter being more catastrophic than the former. The former means the skins still maintain load-bearing properties while the latter means the skin lack them entirely, at least locally at the point of the fracture.

(b) *Core shear failure*.

The core carries almost the entirety of the transverse forces in a sandwich structure and therefore is subjected to shear. Therefore, shear failure is a common mode of failure.

(c and d) *Skin wrinkling*.

Skin wrinkling can occur when the sandwich structure is subjected to an in-plane compressive buckling or bending load, or a combination of the two. The skins can buckle both inwards and outwards.

(e) *General buckling*.

Buckling doesn't always damage the structure permanently but should be avoided since a buckled structure may lose its capability of fulfilling its purpose. The buckling load may also be the ultimate load bearing capacity since in its buckled shape, the sandwich structure may not sustain any more load. A buckled sandwich usually retains its original state if unloaded, if the skins have not yielded, and the resulting damage might be hard to detect. If the deformation is controlled, the load will drop after buckling, and if the loading continues the deformation will increase until failure. Final failure can occur in several ways: (i) the skin on the compressive side fails in compression, (ii) the skin on the compressive side fails by wrinkling (iii) the structure fails by core shear fracture.

(f) *Shear crimping*.

Shear crimping also appears due to buckling loads. This manifests as a short wavelength buckle. It is generally caused by the low shear modulus of the sandwich core [15].

(g) *Skin dimpling*.

Skin dimpling occurs when a large part of the skin is unsupported and buckling may occur in this region locally. This is the most common mode of failure when using a honeycomb structure with thin skins.

(h) *Local indentation*.

Local indentation of the core occurs at concentrated loads, for example fittings, joints or corners. These can be prevented by applying the load over a larger area or by using a stiffer core locally.

Apart from these, two important failure modes are debonding and delamination. Debonding refers to separation between the skin and the core. These can occur due to thermal stresses. The skin and core material have different thermal coefficients, with the core usually being a good insulator meaning there is a high thermal gradient over the bond line if the skin is heated. High shear stresses develop at the bond line between the skin and the core, which can cause debonding [14].

Delamination means that the layers in the composite skins themselves separate. This is an atypical failure mode for sandwich structures since the core in most cases has a lower tensile strength than the interlaminar strength of the laminate. For high density cores, like PVC foam cores often are, delamination can be a critical failure mode. Delamination can occur due to a tensile load transverse to the laminate or due to an out-of-plane shear load. Impact damages are the most common reason for delamination.

Chapter 3

Inspection, classification of damages and repair methods for Visby

3.1 Inspection

Regular inspections are important to ensure the safety of the ship and to discover damages which might undermine structural integrity. There are a few nondestructive inspection (NDI) and nondestructive testing (NDT) methods that are commonly used in industry for surveying sandwich structures and composites for damages. The most important of these are documented in Table 3.1.1.

• Visual inspection: NDI by visual means is by far the most common inspection method as well as the most economic one. Most damages are discovered this way. Blisters, wrinkles and scratches can be discovered by this method and once a damage has been discovered, it is not uncommon to move on to NDT in order to investigate the severity or origin of the damage.

• Tap test: Also know as cointapping, it entails experienced personnel using an small object like a coin, tapping it against the surface of the structures and listening for a difference in sound in order to determine if and where delamination between the skin and the core has occurred. This is the cheapest and easiest type of NDT method available and is surprisingly reliable. A ringing sound indicates a well-bonded solid structure while a dull or thud like sound indicates a discrepant area. Rapid tapping is required to achieve the desired effect and deliberate design choices can mean that a dull sound is produced, meaning the personnel doing the cointapping need to be knowledgeable about the geometry of the structure beforehand.

• Ultrasonics: This is used to find internal delamination and voids not discoverable by the above mentioned methods. Ultrasonic waves are transmitted into the structure and are either absorbed or reflected back. This is then compared to a reference ultrasonic screening of the same structure undamaged in order to detect deviations.

• Radiography: Better known as X-ray, this NDI method allows one to view the interior of the structure without damaging it. An X-ray is sent through the structure and the absorption is recorded onto film, allowing clear images of the structure to be developed. This is especially useful for surveying the core of the sandwich structure for damages. It is however expensive and requires extensive safety procedures for the personnel involved.

• Shearography: Also known as lasershearography, this NDI method utilizes laser in order to detect defects by measuring the variations in reflected light from the surface of the structure. An original image is recorded, and then the structure is then subjected to heating, changes in pressure or acoustic vibrations, after which a second image is recorded by the same process. Changes in the surface contour indicate debonding or delamination and is visible on the video display. This is a particularly common method when examining sandwich structures.

• Thermal inspection: This refers to methods that use heat-sensing devices to measure temperature variations for the structure under inspection. Usually, a heat source generates elevated temperatures, after which the temperature of different parts of the structure is measured. Free areas conduct heat more efficiently than areas with defects, the amount of heat absorbed and reflected indicating the quality of the bond between the skins and core of a sandwich structure. This can then be used to find cracks, debonding, panel thinning and water exposure in the structure.

The Visby-type corvettes are dry-docked once a year and the ships are inspected. The main methods used to inspect the Visby-type corvette while being serviced are **visual inspection**, **cointapping** and **lasershearography** [17]. Taking a core sample by means of drilling is also frequently used.

Table 3.1.1: Common NDI and NDT methods [16].

Method	Structure	Damage detected	Reliability
Visual	All	Surface damage	Good
Tap test	Thin laminate	Delamination near surface	Good
	Thin skin sheet	Lack of bond	Good
		Debond near surface	Good
		Voids	Poor
		Blown core (core damage)	Poor
		Lack of tie-in at closure	Good
		Lack of tie-in at core splice	Poor
Ultrasonics	All	Delaminations	Good
		Lack of bond	Good
	Sandwich	Crushed core	Poor
		Blown core (core damage)	Poor
		Water in core	Poor
Radiography	All	Debonds/delaminations	Poor
		Delaminations in corners	Good
	Sandwich	Node separation	Good
		Crushed core	Good
		Blown core (core damage)	Good
		Water in core	Good
Shearography	All	Debonds/delaminations	Good
Thermography	All	Debonds/delaminations	Good
	Sandwich	Water in core	Good

3.2 Classification of damages

When damages are found using one or more of the methods described in section 3.1, a damage and repair report is established. The damage type is described, as well as the probable cause of the damage. The repair procedure used is also rigorously described. A different template is used depending on which part of the ship is affected (port, starboard, weather deck, bottom paneling, stern or cannon). The damage position is then given as an X- and Y-coordinate with an appropriate origin. An example of such a template can be seen in Figure 3.2.1.

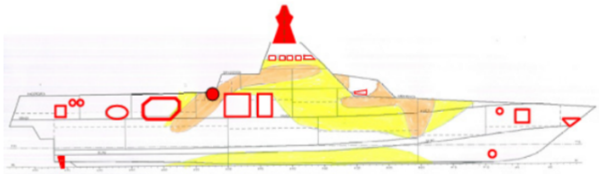


Figure 3.2.1: Template for damage and repair report for starboard side of the ship [18].

The damage position determines whether or not conventional repair methods described in section 3.3 can be used (for Zone X, special procedures are always required). They are categorized according to their location on the ship [19]:

- **Zone A:** Area with high levels of strain in the laminates.
- **Zone B:** Area with medium high levels of strain in the laminates.
- **Zone C:** Area with low levels of strain in the laminates.
- **Zone X:** In this area, the structure is provided with additional reinforcements or has special features that make repairs complex. Repair materials must therefore always be provided by the respective manufacturer of the structure. Repair cannot be conducted according to regular protocols.

The zoning system as applied to the starboard side can be seen in Figure 3.2.2.

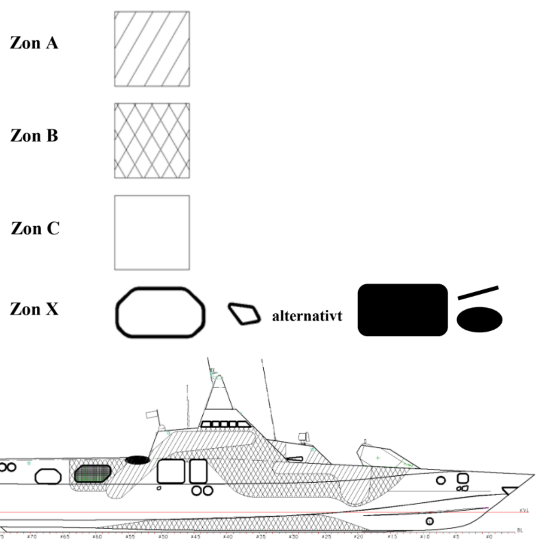
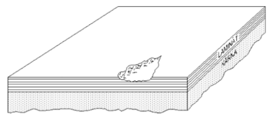
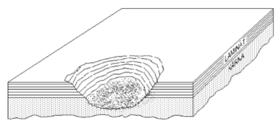
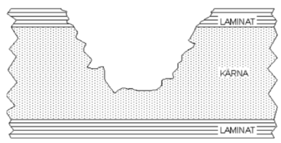
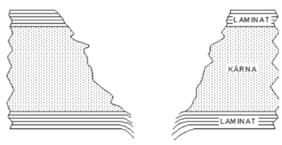


Figure 3.2.2: Zones legend (above) and an illustration of the zones on the starboard side of the ship (below) [19].

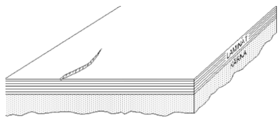
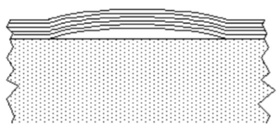
Damages are then classified according to different criteria. These are documented in Table 3.2.1.

Table 3.2.1: Damage types in sandwich structures and corresponding failure modes [19].

Damage type	**Damage definition**	**Illustration**	**Corresponding failure mode**
Laminate damage (Single skin laminate)	Crush, shear or impact damage affecting one or several plies of the skin laminate. The damage does not extend into the core material. Depending on the size, this type of damage may have limited influence on the structural strength.		Yielding or fracture of the skin, delamination
Laminate damage (Single skin laminate + shallow core damage)	Crush, shear or impact damage affecting one or several plies of the skin laminate. The damage extends into the core material to a depth of less than half the core thickness. Depending on the size, the damage may affect the structural strength.		Yielding or fracture of the skin, delamination, core shear failure
Laminate damage (Single skin laminate + deep core damage)	Crush, shear, or impact damage affecting one or several plies of the skin laminate. The damage extends into the core material to a depth greater than half the core thickness.		Yielding or fracture of the skin, delamination, core shear failure
Laminate damage (Both skin laminates + core damage)	Crush or shear damage affecting both skin laminates and the core material. This type of damage has a significant influence on the structural strength.		Yielding or fracture of the skin, delamination, core shear failure

Continued on next page

Table 3.2.1: Damage types in sandwich structures and corresponding failure modes (continued).

Damage type	**Damage definition**	**Illustration**	**Corresponding failure mode**
Scratch	Superficial scratches or scoring in the skin laminate with a maximum depth of approximately 1 mm. These damages are generally shallow and have negligible influence on the structural strength. However, the damage may worsen if not properly repaired.		No structural failure mode (cosmetic damage)
Blister	Separation between the core material and the skin laminate. Once a blister has formed it may grow. Heating from solar radiation and trapped excess pressure in the core cells may cause gas accumulation in the blister, increasing pressure and worsening the damage.		Debonding

Depending on the damage type and zone, different acceptable damage sizes are established and the repair procedure is determined accordingly. The operational procedure is documented in Table 3.2.2.

Table 3.2.2: Maximum allowable damage size and required actions [19].

Damage type	**Maximum allowable damage size**			**Damage zone X**
	Damage zone A	**Damage zone B**	**Damage zone C**	
Laminate damage of type: Single skin laminate Single skin laminate + shallow core damage Single skin laminate + deep core damage Both skin laminates + core damage	≤ **Ø 125 mm.** Repair with a temporary repair (methods 11 or 12 in Table 3.3.2) as soon as possible as the damage has a major impact on radar signature. Permanent repair to be carried out at the next dry docking.	≤ **Ø 200 mm.** Repair with a temporary repair (methods 11 or 12 in Table 3.3.2) as soon as possible as the damage has a major impact on radar signature. Permanent repair to be carried out at the next dry docking.	≤ **Ø 400 mm.** Repair with a temporary repair (methods 11 or 12 in Table 3.3.2) as soon as possible as the damage has a major impact on radar signature. Permanent repair to be carried out at the next dry docking.	This zone carries a heavy load/has a complex structural arrangement. The responsible purchaser of the relevant subsystem is responsible for the development of repair procedures.

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Table 3.2.2: Maximum allowable damage size and required actions (continued).

Damage type	**Maximum allowable damage size**			**Damage zone X**
	Damage zone A	**Damage zone B**	**Damage zone C**	
Scratch	**Depth ≤ 1 mm and length ≤ 200 mm.** The damage shall be documented. No immediate action is required provided the damage is monitored and followed up at the next dry docking in accordance with the maintenance plan.	**Depth ≤ 1 mm and length ≤ 300 mm.** The damage shall be documented. No immediate action is required provided the damage is monitored and followed up at the next dry docking in accordance with the maintenance plan.	**Depth ≤ 1 mm and length ≤ 600 mm.** The damage shall be documented. No immediate action is required provided the damage is monitored and followed up at the next dry docking in accordance with the maintenance plan.	This zone carries a heavy load/has a complex structural arrangement. The responsible purchaser of the relevant subsystem is responsible for the development of repair procedures.

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Table 3.2.2: Maximum allowable damage size and required actions (continued).

Damage type	**Maximum allowable damage size**			**Damage zone X**
	Damage zone A	**Damage zone B**	**Damage zone C**	
Blister	≤ **Ø 150 mm** or propagation **less than 200 mm.** Distance between multiple blisters exceeds 200 mm. The damage shall be documented. No immediate action is required provided the damage is monitored and followed up at the next dry docking in accordance with the maintenance plan.	≤ **Ø 225 mm** or propagation **less than 400 mm.** Distance between multiple blisters exceeds 500 mm. The damage shall be documented. No immediate action is required provided the damage is monitored and followed up at the next dry docking in accordance with the maintenance plan.	≤ **Ø 300 mm** or propagation **less than 600 mm.** Distance between multiple blisters exceeds 700 mm. The damage shall be documented. No immediate action is required provided the damage is monitored and followed up at the next dry docking in accordance with the maintenance plan.	This zone carries a heavy load/has a complex structural arrangement. The responsible purchaser of the relevant subsystem is responsible for the development of repair procedures.

3.3 Repair

Depending on the nature and severity of the discovered damages, different repair methods may be employed. Before the inspection and repair procedures are started, the suspected damaged area is cleaned using water and washing powder or acetone. This is to remove particles, dirt and oil to prevent further contamination of the damaged area. If the laminate is contaminated, acetone is used for cleaning. For the cleaning of the core, a vacuum cleaner is used. The repair manual for the Visby corvette prescribes twelve different repair methods, these are documented in Table 3.3.1.

Table 3.3.1: Repair methods used to repair the Visby-class corvette [17].

No.	Repair method description
1	*Spackling of superficial defects.* This method is for restoring small, superficial defects in the laminate by means of spackling.
2	*Recessed lap joint, bevel joint, wet lamination.* This method describes the procedure for preparation and wet lamination of laminate damage.
3	*Injection of blister, double shell.* This method involves repairing the blister without having to saw away the laminate. This is done by pouring matrix plastic into the blister through drilled holes. It is not possible to suck plastic into the blister because the negative pressure causes the laminate to be pressed against the core, thus preventing the flow. Vacuum is used to remove the excess matrix after the blister has been filled.
4	*Recessed lap joint, bevel joint, wet lamination, core repair.* This method describes the procedure for preparation and wet lamination of damage in the outer laminate and superficial damage in the core.
5	*Recessed lap joint, bevel joint, wet lamination, core replacement.* This method involves repairing damage to the outer laminate and core.
6	*Recessed layer patches, bevel joint, wet lamination, core replacement, thorough damage.* This method involves repairing thorough damages that requires repair of both laminates and replacement of the core.
7	*Recessed lap joint, bevel joint, vacuum injection.* This method describes the procedure for preparation and vacuum injection of damage in laminates.
8	*Recessed lap joint, bevel joint, vacuum injection, core repair.* The method describes the procedure for preparation and injection for damage to the outer laminate and superficial damage to the core.
9	*Recessed lap joint, bevel joint, vacuum injection, core replacement.* This method involves repairing damage to the outer laminate and core.
10	*Recessed lap joint, bevel joint, vacuum injection, core replacement, thorough damage.* This method involves repairing thorough damages that requires repair of both laminates and replacement of the core.

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No.	Repair method description
11	*Temporary weatherproofing/signature-adapting covering.* This method is aimed at protecting a laminate damage and, to the greatest extent possible, minimizing the radar signature of a laminate damage that is of such a size and nature that a complete repair does not have to be carried out immediately.
12	*Temporary weatherproofing covering.* This method is to protect laminate damage that is of such a size and nature that a complete repair does not have to be carried out immediately. Here, GFRP is used rather than CFRP.

The damage type and if it is above or below the waterline as well as inside or outside determines which repair method is used. The methods to be used in each case are listed in Table 3.3.2.

Table 3.3.2: Repair methods according to damage location and damage type [19]. Method numbers correspond to Table 3.3.1.

Damage location	Damage type	Repair method
Outside above waterline	Single face laminate	7, 11
Outside above waterline	Single face laminate + shallow core damage	8, 11
Outside above waterline	Single face laminate + deep core damage	9, 11
Outside above waterline	Both face laminates + core damage	10, 11
Outside above waterline	Blister	3
Outside below waterline or inside	Single face laminate	2 or 7
Outside below waterline or inside	Single face laminate + shallow core damage	4 or 8

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Table 3.3.2: Repair methods according to damage location and damage type (continued).

Damage location	Damage type	Repair method
Outside below waterline or inside	Single face laminate + deep core damage	5 or 9
Outside below waterline or inside	Both face laminates + core damage	6 or 10
Outside below waterline or inside	Scratch	1
Outside below waterline or inside	Blister	3

Finally, the results are controlled after the repair has been completed. The steps for the control are the following [19]:

1. Visual inspection.
2. Cointapping or alternatively lasershearography.
3. Flatness measurement with respect to radar target signature.
4. The result added to the repair protocol.

Chapter 4

Methodology

4.1 Data collection

The data collected for this study consisted of error, inspection, damage, reparation and service reports through the years 1997-2025. Along with these, technical drawings of the ships with the location of each defect were included as well. Internal manuals outlining procedures for repair and maintenance were also used in the analysis.

4.2 Data analysis

In order to gain an insight into the types of defects and damages typically seen on the ships, a quantitative approach was used for each ship, where the type of defect was identified through error reports and counted in a comparison with other type of defects. This was in order to gain an insight into what type of defects are the most common. Secondly, an analysis of the exact placement was conducted in order to determine if some sections are more vulnerable than others. A rough chronology of damages was also included, in order to see if certain defect types became more or less common over time.

Chapter 5

Results

5.1 Classification of damages

5.1.1 Damage types

The classification of damages differs slightly from the one established and explained in Table 3.2.1, partly because most of the error reports are from before that particular standard was established and partly because all damages do not fit neatly in an established category. Therefore, the categories differ from Table 3.2.1. Damages were instead classified by how they were named in the individual error reports, as well as some slightly different defects being put in the same category due to this making classification easier as well as having similar causes and causing similar issues. For the first three ships, a complete illustration of the position of most defects that lead to the hull being repaired was included, making a sectional analysis much easier. Figure 5.1.1 - Figure 5.1.4 show the distribution of identified defects for each ship in the Visby-class. The results are summarized in Table 5.1.1. Only those defects whose type could be clearly identified and categorized are included.

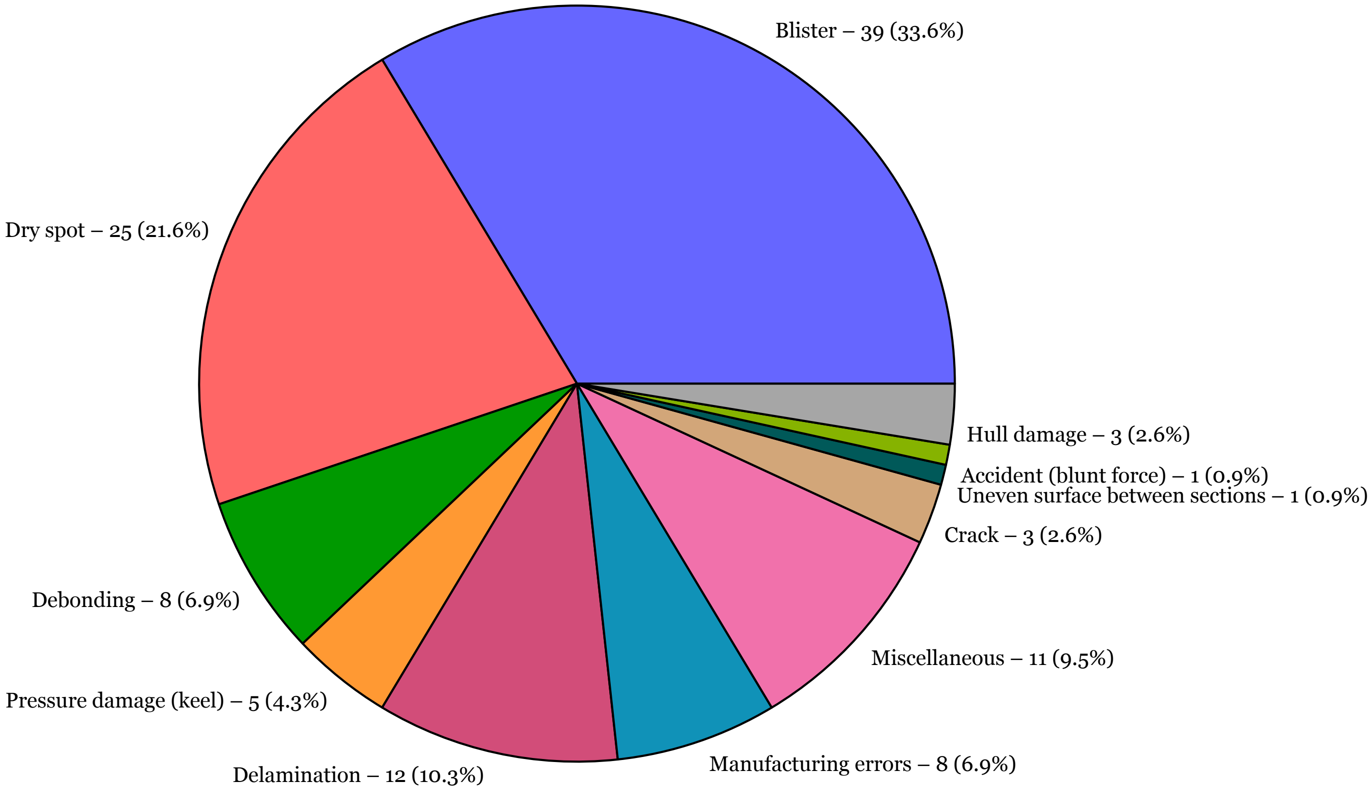


Figure 5.1.1: Distribution of defect types in damage history of HSwMS Visby (K31) (total number of cases: 116).

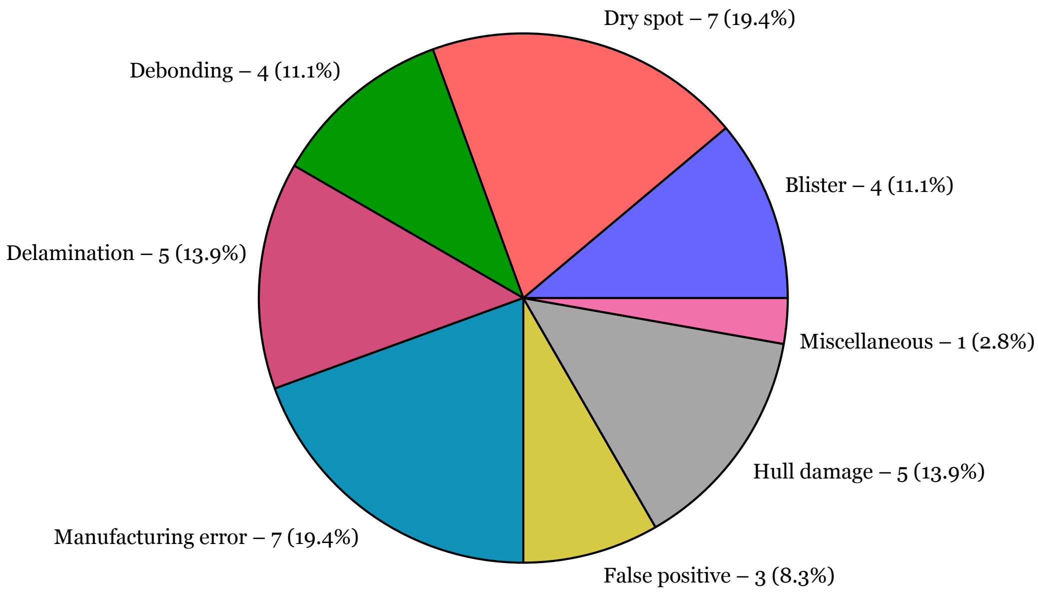


Figure 5.1.2: Distribution of defect types in damage history of HSwMS Helsingborg (K32) (total number of cases: 36).

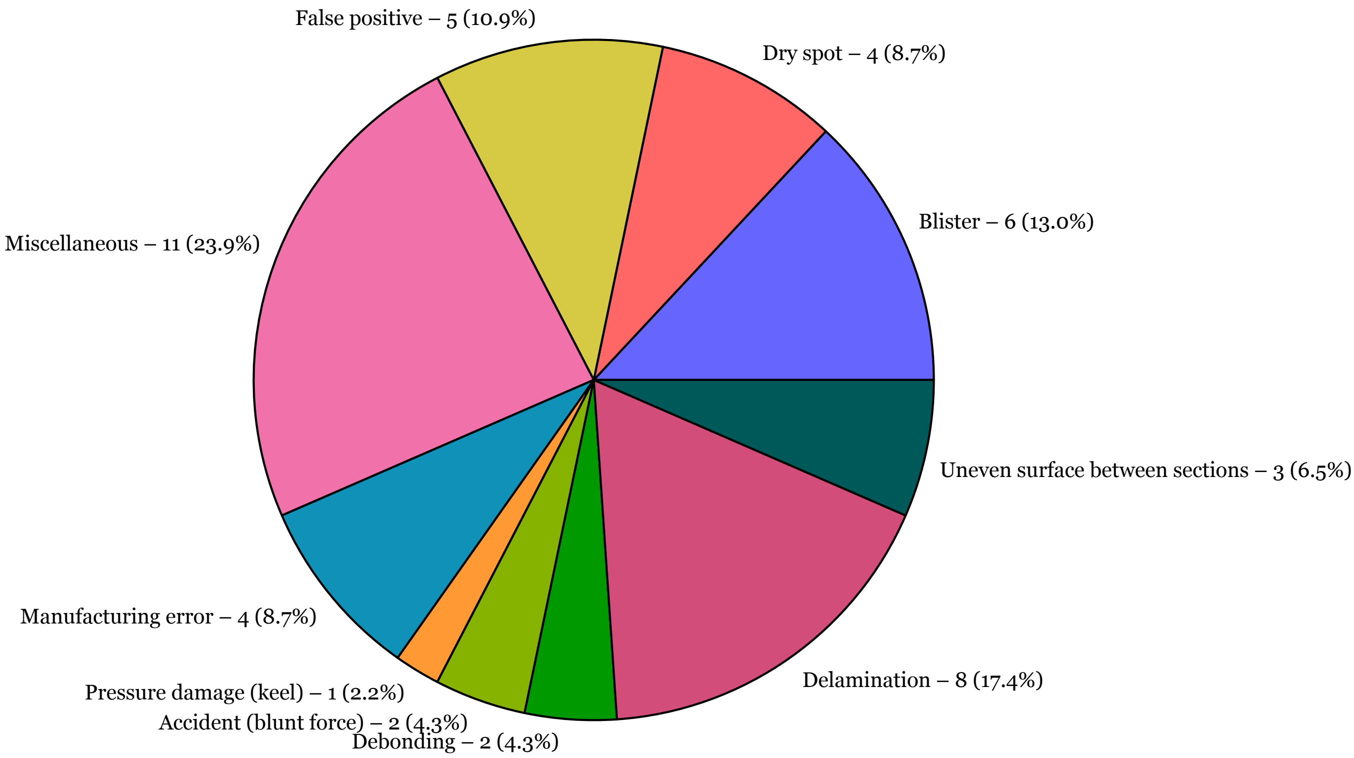


Figure 5.1.3: Distribution of defect types in damage history of HSwMS Härnösand (K33) (total number of cases: 46).

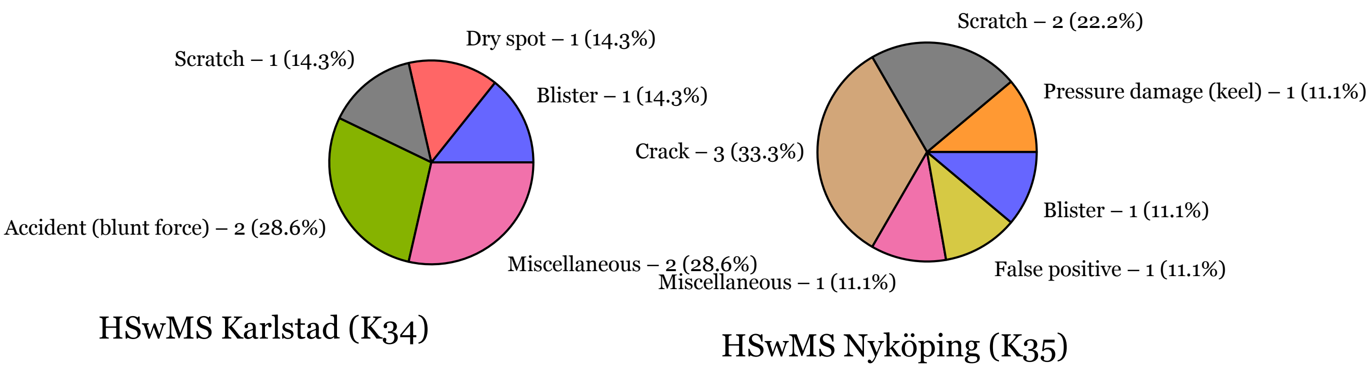


Figure 5.1.4: Distribution of defect types in damage histories of HSwMS Karlstad (K34) (total number of cases: 7) and HSwMS Nyköping (K35) (total number of cases: 9).

Table 5.1.1: Distribution of damage types across Visby-class corvettes. Values are given as number of cases with percentage of total damage cases for each ship in parentheses. The final column shows the total number of cases across all ships with percentage of all recorded damages.

Damage type	K31	K32	K33	K34	K35	Total (all ships)
Blister	39 (33.6%)	4 (11.1%)	6 (13.0%)	1 (14.3%)	1 (11.1%)	51 (23.8%)
Dry spot	25 (21.6%)	7 (19.4%)	4 (8.7%)	1 (14.3%)	0 (0.0%)	37 (17.3%)
Miscellaneous	11 (9.5%)	1 (2.8%)	11 (23.9%)	2 (28.6%)	1 (11.1%)	26 (12.1%)
Delamination	12 (10.3%)	5 (13.9%)	8 (17.4%)	0 (0.0%)	0 (0.0%)	25 (11.7%)
Manufacturing error	8 (6.9%)	7 (19.4%)	4 (8.7%)	0 (0.0%)	0 (0.0%)	19 (8.9%)
Debonding	8 (6.9%)	4 (11.1%)	2 (4.3%)	0 (0.0%)	0 (0.0%)	14 (6.5%)
False positive	0 (0.0%)	3 (8.3%)	5 (10.9%)	0 (0.0%)	1 (11.1%)	9 (4.2%)
Hull damage	3 (2.6%)	5 (13.9%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	8 (3.7%)
Pressure damage (keel)	5 (4.3%)	0 (0.0%)	1 (2.2%)	0 (0.0%)	1 (11.1%)	7 (3.3%)
Crack	3 (2.6%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	3 (33.3%)	6 (2.8%)
Accident (blunt force)	1 (0.9%)	0 (0.0%)	2 (4.3%)	2 (28.6%)	0 (0.0%)	5 (2.3%)
Uneven surface between sections	1 (0.9%)	0 (0.0%)	3 (6.5%)	0 (0.0%)	0 (0.0%)	4 (1.9%)
Scratch	0 (0.0%)	0 (0.0%)	0 (0.0%)	1 (14.3%)	2 (22.2%)	3 (1.4%)
Total	**116**	**36**	**46**	**7**	**9**	**214**

- **Blister**: See Table 3.2.1.
- **Dry spot**: Appears when the matrix does not properly impregnate the fibers in the laminate, leaving dry areas and making the structure weaker.
- **Miscellaneous**: This includes defects that do not fit in other categories, such as incorrectly placed holes or drilled holes for core tests that need repair.
- **Delamination**: See subsection 2.2.2.
- **Manufacturing error**: Includes only errors made when manufacturing sandwich panels, such as leakage while injecting the matrix.
- **Debonding**: See subsection 2.2.2.
- **False positive**: Appears when cointapping or other NDT or NDI methods indicates an irregularity, but the structure is undamaged. For example, delamination might be expected due to observed paint peeling, but no delamination is found.
- **Hull damage**: Damages to the hull due to various reasons, such as steel scaffolding used when repairing or heavy objects placed on the hull.
- **Pressure damage (keel)**: Damages to the keel of the ship due to hydrodynamic pressure.
- **Crack**: Cracks often appear in the resin used to even out surfaces after a repair has been made. They can also appear due to regular use.

- **Accident (blunt force)**: Accidents caused by the ship hitting something, causing damages to the hull.
- **Uneven surface between sections**: This means sandwich sections are not perfectly level on the ship, affecting the stealth characteristics.
- **Scratches**: See Table 3.2.1.

5.1.2 Damage positions

Whether or not a defect is inside or outside, and above or below the waterline, determines the repair method used in accordance with Table 3.3.2. Also important are the zones as described in Figure 3.2.2 and Table 3.2.2, as this determines the thresholds for the allowable size of a defect before a permanent repair is needed. The result of this analysis is shown in Table 5.1.2. Table 5.1.3 shows the damage type of each identifiable defect below the waterline for each ship.

Table 5.1.2: Distribution of defect locations across Visby-class corvettes. Values are number of cases with percentage of each ship's total defects in parentheses. The final column shows totals across all ships with percentage of all recorded hull repairs.

Location	K31	K32	K33	K34	K35	Total (all ships)
Above waterline	94 (69.6%)	95 (90.5%)	70 (65.4%)	2 (66.7%)	5 (71.4%)	266 (74.5%)
Below waterline	41 (30.4%)	10 (9.5%)	37 (34.6%)	1 (33.3%)	2 (28.6%)	91 (25.5%)
Zones						
Zone A	22 (16.3%)	19 (18.1%)	15 (14.0%)	0 (0.0%)	0 (0.0%)	56 (15.7%)
Zone B	2 (1.5%)	6 (5.7%)	13 (12.1%)	1 (33.3%)	3 (42.9%)	25 (7.0%)
Zone C	107 (79.3%)	77 (73.3%)	74 (69.2%)	2 (66.7%)	4 (57.1%)	264 (73.9%)
Zone X	4 (3.0%)	3 (2.9%)	5 (4.7%)	0 (0.0%)	0 (0.0%)	12 (3.4%)
Total	**135**	**105**	**107**	**3**	**7**	**357**

Table 5.1.3: Distribution of damage types below the waterline for Visby-class corvettes. Values are given as number of cases with percentage of total below waterline cases for each ship in parentheses. The final column shows the total number of cases across all ships with percentage of all recorded damages below the waterline.

Damage type	K31	K32	K33	K34	K35	Total (all ships)
Blister	19 (59.4%)	2 (20.0%)	4 (25%)	1 (100%)	0 (0.0%)	26 (41.9%)
Dry spot	5 (15.6%)	3 (30.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	8 (12.9%)
Miscellaneous	0 (0.0%)	1 (10.0%)	5 (31.3%)	0 (0.0%)	0 (0.0%)	6 (9.7%)
Pressure damage (keel)	5 (15.6%)	0 (0.0%)	1 (6.3%)	0 (0.0%)	1 (33.3%)	5 (4.8%)
Delamination	0 (0.0%)	2 (20.0%)	1 (6.3%)	0 (0.0%)	0 (0.0%)	3 (5.2%)
Accident (blunt force)	1 (3.1%)	0 (0.0%)	1 (6.3%)	0 (0.0%)	1 (33.3%)	3 (3.2%)
Debonding	1 (3.1%)	0 (0.0%)	1 (6.3%)	0 (0.0%)	0 (0.0%)	2 (3.2%)
Manufacturing error	1 (3.1%)	1 (10.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	2 (3.2%)
Uneven surface between sections	0 (0.0%)	0 (0.0%)	2 (12.5%)	0 (0.0%)	0 (0.0%)	2 (3.2%)
Scratch	0 (0.0%)	0 (0.0%)	1 (6.3%)	0 (0.0%)	1 (33.3%)	2 (3.2%)
False positive	0 (0.0%)	1 (10.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	1 (1.6%)
Total	**32**	**10**	**16**	**1**	**3**	**62**

5.2 Chronology of error reports

Table 5.2.1 and Figure 5.2.1 show the number of error and service reports per year and ship. Note that each report can contain multiple defects and that they are sorted by date the defects were discovered. Table 5.2.2 shows how many reports are from each phase of the ship as explained in Table 1.1.1. Table 5.2.3 and Figure 5.2.2 show the distribution of damages before launch and in service respectively for K31.

Table 5.2.1: Number of error and service reports per vessel and year.

Year	K31	K32	K33	K34	K35	Total
1997	1	2	0	0	0	3
1998	3	0	0	0	0	3
1999	8	1	0	0	0	9
2000	8	3	0	0	0	11
2001	0	0	7	0	0	7
2002	11	1	7	0	0	19
2003	2	2	4	0	0	8
2004	7	3	2	0	0	12
2005	8	7	7	0	0	22
2010	0	1	2	0	0	3
2011	0	0	2	0	0	2
2012	1	0	0	0	1	2
2013	1	1	0	1	0	3
2014	5	0	0	0	0	3
2016	1	0	0	1	0	2
2017	2	1	0	0	0	3
2018	1	0	0	0	0	1
2021	7	0	0	0	0	7
2022	1	0	0	0	1	2
2024	5	0	0	2	2	9
2025	0	0	0	6	0	6
Total	**72**	**22**	**31**	**10**	**4**	**137**

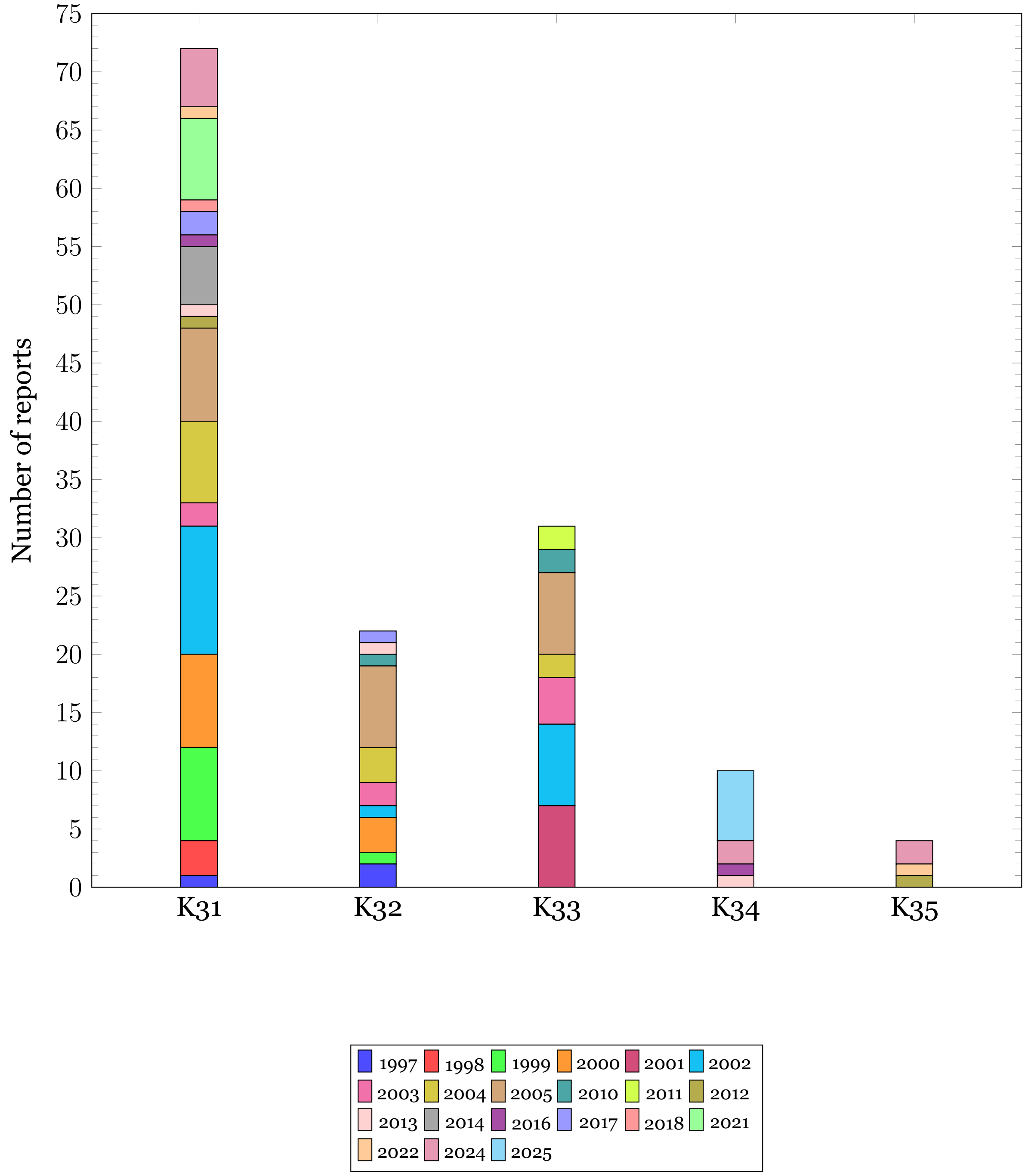


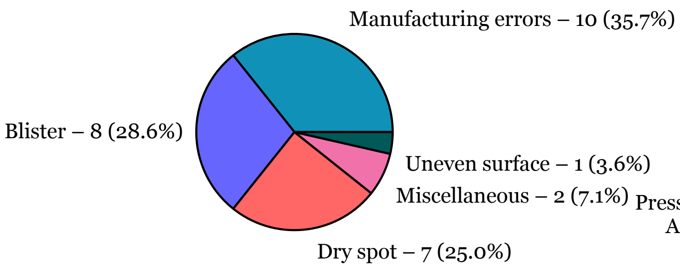
Figure 5.2.1: Chronological distribution of error, damage and service reports per vessel. Each stacked segment represents one year.

Table 5.2.2: Distribution of error and service reports across phases of the Visby-class corvettes as explained in Table 1.1.1 Values are given as number of reports with percentage of total reports for each vessel in parentheses. The final column shows the total number of reports per phase across all ships with percentage of all reports.

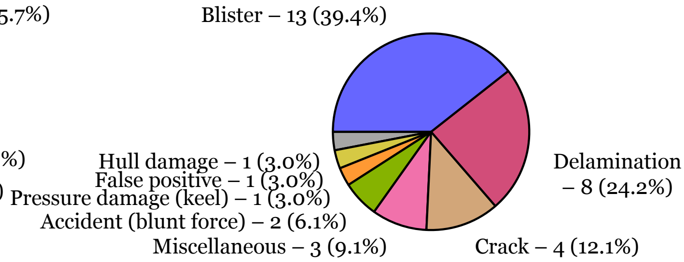
Phase	K31	K32	K33	K34	K35	Total
Before launch	20 (27.8%)	9 (40.9%)	20 (64.5%)	0 (0%)	0 (0%)	49 (35.8%)
Launch–delivery	11 (15.3%)	10 (45.5%)	7 (22.6%)	0 (0%)	0 (0%)	28 (20.4%)
Delivery–in service	16 (22.2%)	2 (9.1%)	4 (12.9%)	0 (0%)	1 (25%)	23 (16.8%)
In service	23 (31.9%)	1 (4.5%)	0 (0%)	10 (100%)	3 (75%)	37 (27.0%)
Total reports	**72**	**22**	**31**	**10**	**4**	**137**

Table 5.2.3: Distribution of defect types for HSwMS Visby (K31) before launch and in service. Values are given as number of cases with percentage of total cases within each phase in parentheses.

Damage type	Before launch	In service
Blister	8 (28.6%)	13 (39.4%)
Dry spot	7 (25.0%)	0 (0.0%)
Delamination	0 (0.0%)	8 (24.2%)
Manufacturing errors	10 (35.7%)	0 (0.0%)
Miscellaneous	2 (7.1%)	3 (9.1%)
Crack	0 (0.0%)	4 (12.1%)
Uneven surface between sections	1 (3.6%)	0 (0.0%)
Accident (blunt force)	0 (0.0%)	2 (6.1%)
Hull damage	0 (0.0%)	1 (3.0%)
False positive	0 (0.0%)	1 (3.0%)
Pressure damage (keel)	0 (0.0%)	1 (3.0%)
Total	**28**	**33**



K31 before launch



K31 in service

Figure 5.2.2: Comparison of defect type distributions for HSwMS Visby (K31) before launch (total number of cases: 28) and in service (total number of cases: 33).

Chapter 6

Discussion

6.1 Damage types

6.1.1 Blisters

Blisters make up 23.8 % of all identified damages and is the most common defect type. The trend seems to be fewer and fewer for each subsequent ship, with some minor exceptions. The chronology of error reports provides strong indications why this is the case. From 1997-2005, on HSwMS Visby K31, NORPOL ® FI-165 was used. This is a polymer based bonding paste, used to cover small imperfections and holes, especially after taking a core sample by drilling to see of the core is damaged. It was also used to make the surface of the core even before lamination. However, FI-165 was causing major issues, the main one being blisters. Blisters in relation to FI-165 was mentioned in a total of two error reports while debonding, delamination and cracks caused by FI-165 were mentioned in one error report respectively. This type of polyester resin started being phased out in 2004 due to these issues, and by the end of 2005 it was replaced by NORPOL FI-184 [20], a vinyl ester based bonding paste which seems to have reduced the number of reported cases of blisters in particular. Fewer cracks and fewer instances of debonding were also reported as a result of the change of resin.

For K33, blisters were an issue for a long time but had slightly different causes compared to K31. In 2001, a vinyl ester based resin was used, causing issues in combination with the glass fibers used. These fibers are no longer in use and have since been replaced. The WR was too tight and the vinyl ester had a viscosity that was too high, meaning that the resin failed to impregnate the fibres, causing blisters from the air trapped within. This was remedied by switching to HYDREX ® 200-M800, a polyester based resin. Used in tandem with this was also NORPOL FI-165, which was used to make surfaces even all the way up to 2005. Another issue causing blisters on K33 was the matrix material used, meaning the plastic resin that impregnates the fibers and make it a solid laminate. Before 2002, DION ® 9100-M800 was used for hand-layup processing, which caused issues with blisters. From 2002 onwards, DION 9500-M800 [21] was used exclusively in the manufacturing process. In 2001, blisters made up 37.5 % of all defects while for the years 2002-2011 blisters only made up 0.3 %, meaning that the problem has been virtually eliminated. Since at least 2012, NORPOL FI-184 was exclusively used on all ships.

6.1.2 Dry spots

When it comes to dry spots, material selection also seems to play a big role in their decline in recent years. Here, it was the matrix material that was causing issues, more specifically the matrix material used when injecting panels. For K33, DION 9500-501 [22] was used from up until 2002, an epoxy based vinyl ester resin. The viscosity of the resin was too high, causing dry spots due to poor impregnation. This was the replaced by DION 9102-501 [23], which has a lower viscosity. This has since been used on all ships for injection of panels. For ships K31, K32 and K33, the years 1997-2002 dry spots made up 15.7 % of all defects, while years 2003-2018 dry spots were 7.4 % of all defects, a 47.2 % decrease.

6.1.3 Manufacturing errors

Also of interest is that manufacturing errors as a defect type got less prominent for each ship. This indicates that lessons learned from the construction of previous ships were incorporated when constructing the newer ships in the Visby-class. This includes issues like leakage while injecting panels and mistakes during the curing of the panels or cutting of the panels to the correct size. In the year 2000, the hardener was modified after issues related to the curing of the panels, resulting in a decrease of reported issues. From the years 1997-2002, there were a total of eleven error reports mentioning issues like miscommunication, reparations done without official documentation and in the wrong manner, without consulting relevant involved parties and operators not being careful enough when doing quality control, mixing hardeners or measuring for flatness. One specific example was in 2001, when erroneous injection strategies systematically caused issues, leading to a course in injection strategies later in the same year. Also, written instructions were increasingly implemented and standardized in order to mitigate the risk of miscommunication associated with instructions given orally alone. Since 2011, all personnel working with composite materials in relation to the Visby ships have had to pass both a theoretical and a practical test, leading to better operators and fewer errors during manufacturing [24]. As Table 5.2.3 shows, unsurprisingly, manufacturing errors tend to be more prominent before the ship is launched as opposed to when the ship is in service. Its decrease from the first two ships to the third can be seen by examining K33: while 64.5 % of all error reports were from before the ship was launched, manufacturing errors make up only 8.7 % of identifiable defects. For K31, 27.8 % of error reports were from before launch, while for K32 the percentage was 40.9 %. For these ships, manufacturing errors made up 6.9 % and 19.4 % respectively. This effectively means that manufacturing errors were not as prominent in the construction of K33 compared to K31 and K32.

6.1.4 Keel damage due to pressure

Another type of defect that declined over time was keel damages due to hydrodynamic pressure. In 2002, pressure damages were discovered on K31 and it was decided that the keel of all subsequent ships would be reinforced. Since then, fewer issues with pressure damage were reported, indicating that the reinforced keel were successful in limiting pressure damages.

6.2 Chronology

An important aspect when analyzing damage distribution is how and when damages appear. One important distinction to make is damages incurred during construction (before launch) and damages incurred when the ship is in service. Both of these hold unique insights when analyzing the life cycle of a vessel: before launch highlight issues that occur due to errors in production, material selection and panel fitting while error reports from when the ships are in service shows damages that likely have their origin in the regular use of the ship. Both are important to gain an insight into how production, maintenance and repair as well as regular use can impact damage frequency and distribution.

All error reports for K33 were from before the ship was fully in service, while for K32, 96.5 % were. Conversely, all reports for K34 were from when the ship was fully in service while for K35, 75 % of reports were from when the ship was in service. This provides an excellent insight into which damage types are common for the ships when in service. K31 had the largest quantity of error reports in each category, which enables an analysis of damage distribution from before launch and from when the ship was in service. Table 5.2.3 shows that for K31, blisters remained an issue both from before launch until the ship was in service. Dry spots disappeared as an issue, likely due to reasons discussed in subsection 6.1.2. Manufacturing errors naturally disappeared as a damage type, while delamination, cracks, accidents, hull damage and pressure damages to the keel all appeared when the ship was in service. Similar results can be found in Figure 5.1.4, which are almost fully from when K34 and K35 were in service. Here, scratches, cracks, pressure damages and accidents can all be seen. Interestingly, while delamination and debonding are frequently reported in the damage histories of K31, K32, and K33, they are entirely absent in the records for K34 and K35. The reason for this discrepancy is not entirely clear. However, one possible explanation is that material selection and construction practices for the later vessels were informed by the issues encountered in the earlier ships in the Visby-class. This may have led to improved material compatibility and, consequently, a reduced occurrence of such defects. Common damage types for all ships in service, though, are cracks, scratches and accidents. The first two are easily repaired and usually not a major issue, but accidents can cause costly damages and are usually avoidable, especially when related to docking as discussed in section 6.3. This is an area of potential improvement.

6.3 Damage positions

As can be seen in Table 5.1.2, 25.5 % of all damages are below the waterline. Since the vast majority of the area of the ship is above the waterline, this means that the area below the waterline is more prone to damages. Damages below the waterline are more serious than damages above it since they can cause severe issues while the ship is in service and can't be temporarily fixed using methods 11 and 12 in Table 3.3.2. However, they can be repaired using methods 2 and 4-6 in Table 3.3.2, using wet lamination rather than vacuum injection, the latter being more complicated and expensive [25]. This is due to the need for more exact panels to comply with the flatness requirements that gives the ship its stealth characteristics. Table 5.1.3 shows the frequency of each damage type below the waterline. As can be seen, blisters and dry spots continue to be the most common damage types, together making up 58.6 % of all damages below the waterline, making up an even higher proportion than on the ships as a whole. Most likely, this is due to K31 having the most identifiable damages, with an even higher proportion of blisters than the one documented in Table 3.2.1. This is in large part due to lack of clear documentation for a multitude of damages on the later ships in the Visby-class, see section 6.5.

As discussed in subsection 6.1.4, pressure damages to the keel is a factor in explaining why there are so many damages below the waterline, a problem that has been nearly eradicated since the keel on all ships were reinforced. Another issue contributing to damages below the waterline are accidents, which in many cases involve damages when docking the ships, usually affecting the ship below the waterline. An error report from 2005 suggested an inventory of all docking spots used for the Visby corvettes, to gain an insight into why docking accidents happen. Acquiring larger spherical fenders at each docking site was also suggested. This was never properly examined and docking damages still occur with some frequency.

6.4 Repair

Some insight can be gained by studying the repair methods used in practice. Since dry spots and blisters make up 41.1 % of all reported damages, the repair of these are the most prevalent and frequently reported. Dry spots are consistently repaired by sanding down the affected laminate and laminating once more. Blisters, on the other hand, differ in the repair procedure depending on a few different factors. Usually, a blister is repaired using method 3 as described in Table 3.3.2, where the blister is injected with additional matrix material without the laminate having to be sawed off. However, if the blister was in an area that has already been repaired, particularly with FI-165 as discussed in subsection 6.1.1, a full repair was often deemed necessary. This meant the laminate was sanded down, the core was cut out in the affected area, and fully or partially replaced, usually by bonding it on in small strips. It was then injected again, and left to cure. This is more expensive, labor intensive and time consuming than simply injecting, and thus it was used more sparsely and only when the structural integrity of both laminate and core had been undermined through previous temporary repairs. With the phasing out of FI-165, this type of blister become more rare and repaired in a less intrusive manner involving only vacuum injection, saving both time and money.

6.5 Error and service reports

How detailed and thorough an error report is has a significant impact on how difficult it is to analyze the damage history of each ship, in terms of classification of damage type, position of each damage and how repair was carried out. While many error reports were of a high quality, containing detailed information about damage type, position and repairs made, sometimes even detailed information about what likely caused the damage, many of the reports lacked significant detail. This made them difficult to analyze. Examples include a lack of details about the nature of the damages (damages labeled simply as ”indications” or ”defects”), lack of detail about how the damages were repaired and difficulty in locating where the defect was located. This is clearly illustrated by the discrepancy between damages documented in Table 5.1.1 and Table 5.1.2, where the latter shows 143 more total damages than the former. This discrepancy is especially noticeable for K33, where only 43 % of all defects that resulted in hull repair were identifiable, the reasons being some missing reports and some reports being of a low quality, where damages are simply labeled ”defects”, making them difficult to categorize properly. This likely skewed the results of this study somewhat. In theory, this should be rectified by using the damage and repair report protocol described in section 3.2, though these are a recent addition and are not used exclusively. In fact, from 2021-2025 only service reports were attainable, which are more sparse when it comes to details about the nature of the damage as well as the position on the ship. A more efficient system for reporting damages and repairs and the damage history of each section would be readily available to the relevant operators would make it easier to find patterns and potentially prevent similar damages in the future. There is in fact already a protocol for how repairs are supposed to be documented in order to make future repairs more efficient [26], but this is not always applied in practice.

Chapter 7

Conclusion

7.1 Key findings

The questions posed in section 1.2 may now be answered:

1. **Do all the ships in the Visby-class have a similar distribution of damages, in type and position?** No, the distribution of damage types differ significantly between the different ships in the Visby-class. This is due to a multitude of factors. Firstly, the distribution of error reports with regard to the different phases of the ship differ widely for each ship, meaning some have more from before the ship was launched and others have more from when the ship was in service. This leads to some ships having more reported issues with, for instance, manufacturing, while others have more reported issues resulting from regular use in service, such as cracks. Secondly, issues associated with the construction of the first ships in the Visby class were a learning experience when planning the construction of the later ships. This means issues resulting mostly from material choices such as blisters and dry spots were greatly reduced. Delamination and debonding have also been all but eliminated, leaving damages related to use such as scratches, cracks and accidents as the major damage types. This is a hopeful sign, since many of the issues associated with the earlier ships have been solved. The distribution of damage positions are divided into four zones with different thresholds for how large damages one can accept before a permanent repair is necessary. They are also categorized as above or below the waterline. The distribution of damages in each zone is remarkable similar for

each ship, while damage distribution above and below the waterline is similar for every ship, with K32 being the lone exception, having fewer damages below the waterline than average.

2. **Does the damage distribution differ for different phases of the ships, e.g. before launch and when the ships are in service?** Yes, unsurprisingly, manufacturing errors are common before the launch of each ship, mostly disappearing in later phases. Delamination first appears as a damage type for K31 when in service, however, K34 and K35 doesn't show the same pattern. This indicates that delamination doesn't necessarily result from ordinary use, but from unique conditions for K31, likely related to the materials used. Instead, hull damage, cracks, scratches and accidents are the most common damage types when the ships are in service. With the exception of accidents, which are often related to docking and at least to a certain degree avoidable, these damage types are inevitable and will keep appearing to a certain extent when the ships are in service.

3. **Is any area of the ship disproportionally prone to damages?** Yes, around a fourth of damages are below the waterline, which is a problem since damages in this area can cause severe issues if they occur when the ship is in service and cannot be temporarily fixed. Comparing the damage distribution above and below the waterline shows that accidents are more likely to cause damages below the waterline than above it. Hydrodynamic pressure causing damages to the keel is also not entirely uncommon, though has decreased by means of reinforced keels.

Additionally, below are more important findings from the study of the damage history of the Visby corvettes:

- Blisters make up a plurality of damages on K31 and K33, but have been massively reduced on the newer ships. Similarly, dry spots make up a large fraction of damages for K31 and K32, but have been reduced for the newer ships. The same goes for delamination and debonding. The mitigation of these damage types over time can be explained by a change of materials in the manufacturing of the sandwich panels.

- Issues related to manufacturing has decreased over time, as personnel were trained better through official certification and instructions were properly codified.

- The quality of error reports is inconsistent, making it difficult to determine the nature and cause of some of the damage patterns over time.

7.2 Recommendations

Many of the common damages to the Visby corvettes, at least in the construction phase of the early ships, were related to the materials in the composites not being optimal when used together. This lead to many recurring defects such as blisters and dry spots, something that has largely been rectified over time and decreasing with each ship in the class. For future composite vessels, great care should be taken in the material selection. Visby was among the first sandwich ships built for naval purposes, which meant a certain level of immaturity and experimentation when designing and constructing the vessels. Since then, a rich literature of scientific studies regarding sandwich structures and composite materials has developed, particularly when it comes to naval architecture [13, 27]. This literature should be carefully examined when developing new composite vessels, as well as not making the same mistakes with material selection that the Visby project initially did. Extensive testing of material combinations could also be done, in order to ensure compatibility.

The prevalence of docking damages in the damage histories of the Visby-class corvettes is indicative of poor planning, as most of these damages are preventable if greater care was taken to ensure proper adaptations at the docking ports. This includes acquiring big spherical fenders for each port that holds a Visby-class corvette. Ensuring that every port that temporarily houses a ship in the Visby-class holds a high enough standard and is suitable for docking of the ship is essential in preventing this kind of blunt force damage, which is costly to repair.

Finally, making every error report follow the same procedure, where the type of damage is documented, how the damage was inflicted, the exact position of the damage as well as a detailed account of the repair procedure. Having a proper system for this reporting to be easily available to relevant parties would make common issues easier to identify and prevent, both regarding damage type and position on the ship. This would make follow up of damages much easier and more efficient. A unified system of reporting should also be developed.

7.3 Future Work

Due to constraints in time, not every available service report ever written about Visby could be studied. These were largely written when the ships were in service and additional insight into which damages are common when the ships are in use could be gained by also analyzing these.

Studying the damage history of similar sandwich vessels, such as the MCMVs in the Koster-class, could provide valuable insight into similarities and differences in damage frequency and type, helping to distinguish issues specific to the Visby-class from those inherent to sandwich structures in general. Also of interest in that regard is comparing the materials used in each class of vessel, to see if any difference in the prevalence of certain damages can be observed. Koster does not have the rigid stealth requirements that Visby does, giving it more flexibility when choosing construction materials and methods, optimizing mostly for weight. A comparison between the construction and repair methods for the panels of each class would therefore also be of interest, to see which materials and methods were chosen to suit the purpose of each vessel.

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TRITA-SCI-GRU 2026:027