Non-magnetic pitch and heave stabilizing T-foil

Bruno von Sicard

Master Thesis
Skrift 2002-33
Title Non-magnetic pitch and heave stabilizing T-foil
Author Bruno von Sicard
Department Division of Naval Systems, Department of Aeronautics, Royal Institute of Technology
Report references Master Thesis 2002-33
Supervisors Ph.D. Jakob Kuttenkeuler (KTH) Mats Feldtmann (FMV)
Keywords T-foil, non-magnetic, stabilization, composite

Abstract
Pitch and heave are limiting motions when driving at high speed on water. The installation of a T-foil is an effective solution that reduces these motions. Commercial T-foils are available, but today none of them are non-magnetic. This thesis studies the possibility to design a non-magnetic T-foil that can carry the considerable loads that such a construction experiences. The T-foil is designed for vessels such as the Visby Class corvette.

Vortex lattice theory is used to calculate the pressure distribution acting on the construction at different load cases. Required laminate thickness is determined by iteration using a linear finite element model of the fin.

The conclusion is that it is possible to manufacture a non-magnetic T-foil of the required size. A critical area in the construction is the T-joint between the vertical strut and the horizontal foil. Future investigations should include laboratory tests of the T-joint as well as more detailed hydrodynamic analysis for more accurate input parameters of the T-foil.
Nomenclature

\( \alpha \)  
Angle of attack

\( \beta \)  
Angle of sideslip

\( \gamma \)  
Angle of flap deflection

\( b \)  
Span width

\( b_w \)  
Half height of winglet

\( c_r \)  
Root cord

\( c_t \)  
Tip cord

\( d \)  
Depth

\( S \)  
Wing area

\( G \)  
Shear modulus

\( E \)  
Young’s modulus of elasticity

\( \nu \)  
Poisson’s ratio

\( \varepsilon \)  
Strain

\( \sigma \)  
Direct, or bending, stress

\( \tau \)  
Shear stress

\( c_l \)  
Lift coefficient

\( C_p \)  
Pressure coefficient

\( D \)  
Induced drag with winglet

\( D_0 \)  
Induced drag without winglet

\( \rho \)  
Density

\( v \)  
Ship speed

\( P \)  
Pressure

\( Re \)  
Reynolds number

Abbreviations

AR  
Aspect ratio

CFD  
Computational fluid dynamics

CFRP  
Carbon-fibre reinforced plastics

FEM  
Finite element method

FMV  
Försvarets Matrielverk, the Swedish Defence Materiel Administration

FOI  
Totalförsvarets Forskningsinstitut, the Swedish Defence Research Agency

FP  
Forward perpendicular

GM  
Metacentric height

PVC  
Polyvinylchloride
# Contents

1 INTRODUCTION .................................................................................................................. 6  
   1.1 BACKGROUND ........................................................................................................... 6  
   1.2 OBJECTIVES ............................................................................................................. 6  
   1.3 SCOPE OF WORK ....................................................................................................... 6  
   1.4 DISPOSITION ............................................................................................................. 6  

2 T-FOIL INTRODUCTION ................................................................................................... 7  
   2.1 DEFINITIONS ............................................................................................................. 7  
   2.2 EFFECT ON SHIP MOTIONS ...................................................................................... 8  
   2.3 CONCEPTS ................................................................................................................ 8  
       2.3.1 Non-retractable T-foil ....................................................................................... 8  
       2.3.2 Retractable T-foil ............................................................................................ 9  

3 VESSEL DESCRIPTION ..................................................................................................... 10  

4 THEORETICAL BACKGROUND ....................................................................................... 11  
   4.1 COMPOSITE MATERIALS ......................................................................................... 11  
       4.1.1 Reinforcement ................................................................................................. 11  
       4.1.2 Matrix ............................................................................................................. 11  
       4.1.3 Core materials ............................................................................................... 12  

5 SPECIFICATION OF REQUIREMENTS ............................................................................ 13  
   5.1 GENERAL REQUIREMENTS ...................................................................................... 13  
   5.2 CONSTRUCTION REQUIREMENTS .......................................................................... 13  
       5.2.1 Strain and tension ......................................................................................... 13  
       5.2.2 Deflection ..................................................................................................... 13  
       5.2.3 Twist ............................................................................................................. 13  
       5.2.4 T-joint efficiency ......................................................................................... 14  
   5.3 SUMMARY OF CRITERION ....................................................................................... 14  

6 GENERAL PARAMETERS .................................................................................................... 15  
   6.1 MATERIAL ................................................................................................................. 15  
   6.2 CONCEPT ................................................................................................................ 15  
   6.3 LOCATION ............................................................................................................... 15  
   6.4 DEPTH .................................................................................................................. 15  
   6.5 WINGSPAN AND CORD ........................................................................................ 16  
   6.6 PROFILES ............................................................................................................... 17  
   6.7 FLAP ...................................................................................................................... 17  
   6.8 WING TIP PLATES ................................................................................................... 17  
   6.9 SUMMARY OF PARAMETERS .................................................................................. 17  

7 LOADS ................................................................................................................................ 18  
   7.1 INPUT FOR LOAD CASES ......................................................................................... 18  
   7.2 LOAD CASES .......................................................................................................... 19  
   7.3 VORTEX LATTICE THEORY .................................................................................... 19  
       7.3.1 Vortex lattice theory model ......................................................................... 20  
       7.3.2 Results from vortex lattice theory ................................................................. 20  

8 CONSTRUCTION ................................................................................................................. 22  
   8.1 FIBRE REINFORCEMENT ......................................................................................... 22  
   8.2 FINITE ELEMENT MODEL ....................................................................................... 23  
       8.2.1 Elements ....................................................................................................... 23  
       8.2.2 Mesh ............................................................................................................. 24  
       8.2.3 Material models ............................................................................................ 24  
       8.2.4 Hinges ........................................................................................................... 25
1 Introduction

1.1 Background
The Visby Class corvette, together with other naval vessels, experiences pitch and heave as limiting motions at high speed. Accelerations tire the crew and phenomenon such as slamming results in high pressures on the bow part of the hull. The installation of a T-foil is an effective solution that reduces these effects. Several commercial T-foils are available, but today none of them are non-magnetic. Consequently, FMV is interested in a feasibility study on a non-magnetic T-foil for vessels such as the Visby Class corvette.

1.2 Objectives
The objective is to investigate if it possible to design a non-magnetic T-foil for vessels such as the Visby Class corvette. It is to examine if a non-magnetic design can carry the loads acting on the construction. Approximate laminate thickness and other parameters are to be established for a potential solution. Furthermore, it is to investigate the increase of drag regarding such an installation.

1.3 Scope of work
No hydrodynamic motion model is created due to the secrecy concerning Visby’s motions at sea. This results in that the motion damping contribution of the T-foil is not considered. Accordingly, the shape and general dimensions of the foil are estimated from similar vessels equipped with commercial T-foils.

The implementation of a T-foil on a high-speed vessel involves several hydrodynamic phenomena that should be considered. Examples are suction of air from the water surface, whirl forming, and changed suction conditions for waterjet units. Each of these phenomenon are complicated enough for there own investigation. Thus, the investigation is limited to the actual construction of the T-foil and other aspects are left for future investigation.

1.4 Disposition

![Diagram](image)

Figure 1. Thesis disposition.

After the initial T-foil introduction, vessel description and the theoretical background are requirements for the T-foil presented. A potential concept and parameters of the foil are determined, mostly based on information about T-foils from reference vessels. The pressure distribution acting on the T-foil at different load cases is calculated using standard vortex lattice theory. This pressure distribution is used as input in a finite element model of the foil. Reinforcement lay-up is determined and included in the finite element model. Laminate thickness is determined by iteration tests using the finite element model. The study is completed with a velocity and drag prediction.
2 T-foil introduction

A T-foil is a stabilizing fin that is mounted at the keel line of a vessel. It is located at the fore to damp pitch and heave motions. The name originates from that the shape looks like a capital T put upside down. The foil is normally connected to a control system that measures ship motions and adjusts the foil to counteract with this motion. There are alternative ways to alter the lift created by the T-foil, examples are trailing flaps or a pivoting foil. This chapter includes definition of parts and areas of the T-foil. Furthermore, the effect that a T-foil has on ship motions is briefly explained and different concepts are described.

2.1 Definitions

Figure 2. T-foil at the fore of a vessel.

Figure 3. T-foil definitions used in the report.
2.2 Effect on ship motions
A T-foil acts as a stabilizer for a vessel and can improve the ride by 60% working like an aerofoil [1]. The increased stability that a T-foil provides means high speeds linked with a comfortable ride. A ship and the surrounding water represents a dynamic system involving interactions between hydrodynamic forces and vessel dynamics. The ship is normally treated as a rigid body with six degrees of freedom. The primary task for a T-foil is to damp heave and pitch motion.

\[ \eta_1 = \text{surge} \]
\[ \eta_2 = \text{sway} \]
\[ \eta_3 = \text{heave} \]
\[ \eta_4 = \text{roll} \]
\[ \eta_5 = \text{pitch} \]
\[ \eta_6 = \text{yaw} \]

Figure 4. Sign convention for ship motions.

2.3 Concepts
Motion reduction using an active T-foil naturally falls under two main headings: non-retractable and retractable systems. Examples of non-retractable systems are bolt-on and pivoting T-foils. Retractable systems can be classified by there retracting technique, examples are along ship and vertical retraction.

2.3.1 Non-retractable T-foil
The simplest construction is a bolt-on T-foil. It is fixed to the hull and has no degrees of freedom, except for a possible flap at the trailing edge of the horizontal fin. It combines a simple design with low hydraulic consumption and easy maintenance. Moreover, it occupies no space inside the hull and the investment is relatively low. Drawbacks are increased draught, increased ship resistance even when not in use, and the vulnerability to damage.

Figure 5. Bolt-on T-foil.

Figure 6. Pivoting T-foil.

Another non-retractable alternative is a pivoting T-foil. The angle of attack can be altered thanks to a joint attachment to the hull. This is an effective design that requires moderate maintenance. All mechanical and hydraulic components can be located above the waterline, which simplifies service. It shares the same drawbacks as a bolt-on T-foil with permanent drag resistance and increased draught.
2.3.2 Retractable T-foil

When not required, the retractable T-foil can be fully or partially stowed inside the hull. This reduces drag, which results in fuel savings and increased speed. Other added benefits are reduced risk of hitting submerged objects and less draught than non-retractable T-foils.

Figure 7. T-foil with alongside retraction, vertical retraction and vertical retraction with dihedral foils

Along ship retraction
A concept with along ship retraction can have all mechanical and hydraulic components above the waterline. This implies reduced maintenance and operational problems because it can be serviced while the vessel is afloat. The drawback is that the concept requires quite a lot of inner volume and it is a complicated construction.

Vertical retraction
A solution with vertical retraction of the strut means partially less drag when retracted. Inner volume requirement is moderate and it is a relatively simple construction. When the horizontal foil is fully retracted it is not the maximum draught point, but it is still sensible to damage. The foil could not be serviced when vessel is afloat.

An alternative concept is vertical retraction with dihedral foils so that the foil is fully concealed when retracted. A requirement is that the dihedral angle of the foil is about the same as the angle of the bottom rise. This construction is most suitable on ships with little bottom rise. The Visby Class corvette, with its sharp v-formed bow, needs a foil with a span of about three times the span of a horizontal foil for the same projected area.

<table>
<thead>
<tr>
<th>Simplicity of construction</th>
<th>Non-retractable Bolt-on</th>
<th>Pivoting</th>
<th>Retractable Along ship</th>
<th>Vertical</th>
<th>Vertical with dihedral foil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Auxiliary power requirement</td>
<td>Simple</td>
<td>Moderate</td>
<td>Complicated</td>
<td>Moderate</td>
<td>Moderate</td>
</tr>
<tr>
<td>Space occupied in hull</td>
<td>None</td>
<td>Moderate</td>
<td>Moderate</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Increase ship's resistance when not required</td>
<td>High</td>
<td>High</td>
<td>None</td>
<td>Moderate</td>
<td>None</td>
</tr>
<tr>
<td>Service</td>
<td>Dry-dock</td>
<td>Dry-dock</td>
<td>Afloat</td>
<td>Dry-dock</td>
<td>Dry-dock</td>
</tr>
<tr>
<td>Maintenance</td>
<td>Low</td>
<td>Moderate</td>
<td>Moderate</td>
<td>Moderate</td>
<td>Moderate</td>
</tr>
<tr>
<td>Draught increase</td>
<td>3 m</td>
<td>3 m</td>
<td>0 m</td>
<td>0 m</td>
<td>0 m</td>
</tr>
<tr>
<td>Investment (in relation to other concepts)</td>
<td>Low</td>
<td>Reasonable</td>
<td>High</td>
<td>Reasonable</td>
<td>High</td>
</tr>
<tr>
<td>Vulnerable to damage when not in use</td>
<td>Very</td>
<td>Very</td>
<td>No</td>
<td>Little</td>
<td>No</td>
</tr>
</tbody>
</table>

Table 1. Properties of different T-foil concepts.
3 Vessel description

The T-foil that is designed in this feasibility study is not intended for a certain type of vessel. The main purpose of the investigation is to examine the possibilities to build a non-magnetic T-foil. However, vessels that are kept in mind for this T-foil are YS-NY and the Visby Class corvette. YS-NY is at the design stage and data about the vessel is scarce. Hence, the Visby Class corvette will act as design parameter for the foil.

The Visby Class corvette is a joint project in which the parties involved include the Swedish Defence Materiel Administration (FMV), Kockums, the Saab Group, the Swedish Defence Research Agency (FOI) and the Royal Institute of Technology (KTH). The first ship was launched in 2000 and will be fully equipped and tested in 2004. The multi-purpose vessels are flexible surface combatants designed for a wide range of roles. They can be fitted out for anti-surface warfare, anti-submarine warfare, mine countermeasures, patrol and more. The Visby Class corvette is designed to have excellent characteristics both at high speed and at low speed. Self-defence features are extremely small radar cross-section, low IR signature, low acoustic and hydroacoustic signatures and good anti-magnetic properties [2].

<table>
<thead>
<tr>
<th>General data</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Length overall</td>
<td>73 m</td>
</tr>
<tr>
<td>Beam</td>
<td>10.4 m</td>
</tr>
<tr>
<td>Displacement</td>
<td>600 tonnes, fully equipped</td>
</tr>
<tr>
<td>Draught</td>
<td>2.4 m</td>
</tr>
<tr>
<td>Crew</td>
<td>43</td>
</tr>
<tr>
<td>Hull material</td>
<td>Sandwich construction CFRP</td>
</tr>
<tr>
<td>High-speed machinery</td>
<td>4 gas turbines, 4000 kW each</td>
</tr>
<tr>
<td>Low-speed machinery</td>
<td>2 diesel engines, 1300 kW each</td>
</tr>
<tr>
<td>Propulsion</td>
<td>2 waterjet propulsors</td>
</tr>
<tr>
<td>Speed</td>
<td>&gt;35 knots</td>
</tr>
<tr>
<td>Radius of inertia, roll</td>
<td>2.7-3.0 m</td>
</tr>
<tr>
<td>GM</td>
<td>~ 2 m</td>
</tr>
</tbody>
</table>

Table 2. General data Visby Class corvette [2].

The Visby Class corvette is designed to operate in the Baltic and the Kattegatt, as well as in the Nordic Sea and the Mediterranean. The vessel should be able to operate at high speed in rough sea. The availability in the Baltic and the Kattegatt will be close to one hundred percent, while the availability in the Nordic Sea will be about 90%, calculated on a full year. Hence, significant wave heights at high speed should amount to at least 4 m [3]. The hull is constructed using a sandwich design consisting of a PVC core with carbon fibre/vinylester laminate faces. This construction result in high strength and durability, low weight, good shock resistance, integrated low magnetic signature. The hull is built of panels manufactured by vacuum injection that are later joined into larger sections. This methods account for a high fraction of fibres and good laminate quality. The material reduces the structural weight with about 50 percent compared to a conventional steel hull [4].
4 Theoretical background

The hull of the Visby Class corvette is constructed using a sandwich design consisting of a PVC core with carbon fibre/vinylester laminate. This is also the material used in the T-foil model. A brief summary of composite materials characteristics introduces terms and concepts.

4.1 Composite materials

Composite materials consist of reinforcement and matrix. In general, the reinforcement carries the load and the matrix holds the reinforcement together. Characteristics vary with fibre and matrix material. The general characteristics of composites are summarised in table 3.

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific strength &amp; stiffness</td>
<td>High price</td>
</tr>
<tr>
<td>Low thermal coefficient</td>
<td>Impact properties</td>
</tr>
<tr>
<td>Corrosion resistive</td>
<td>Manufacturing</td>
</tr>
<tr>
<td>Parts integration</td>
<td>Water uptake</td>
</tr>
<tr>
<td>Tailored properties</td>
<td>Non-destructive testing</td>
</tr>
<tr>
<td>Fatigue properties</td>
<td>Load introduction</td>
</tr>
<tr>
<td>Electrical insulation</td>
<td>Sensitive to holes/cutout</td>
</tr>
<tr>
<td>Thermal insulation</td>
<td>Joining</td>
</tr>
</tbody>
</table>

Table 3. Advantages and disadvantages of composites [5].

4.1.1 Reinforcement

The reinforcement is the constituent that primary carries the structural loads in a composite. Accordingly, the reinforcement plays an important role in determining stiffness and strength of the composite as well as several other properties. Composite reinforcement may be in the form of fibres, particles, or whiskers. Fibres are widely used and the most common forms of fibrous reinforcement in composite applications are glass, carbon, and aramid [5].

<table>
<thead>
<tr>
<th></th>
<th>Glass fibres</th>
<th>Carbon fibres</th>
<th>Aramid fibres</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density, ( \rho ) [kg/m(^3)]</td>
<td>~2500</td>
<td>1700 – 2000</td>
<td>~1400</td>
</tr>
<tr>
<td>Elastic modulus, ( E_t ) [GPa]</td>
<td>70 – 90</td>
<td>160 – 820</td>
<td>130 – 190</td>
</tr>
<tr>
<td>Tensile strength, ( \sigma_t ) [MPa]</td>
<td>3.5 – 4.8</td>
<td>1.4 – 7.0</td>
<td>3.4 – 4.1</td>
</tr>
<tr>
<td>Strain to failure, ( \varepsilon_t ) [%]</td>
<td>4.5 – 5.8</td>
<td>0.4 – 2.2</td>
<td>2.0 – 2.8</td>
</tr>
<tr>
<td>( T_{\text{max}} ) continuous use [°C]</td>
<td>300 – 350</td>
<td>500 – 600</td>
<td>250</td>
</tr>
<tr>
<td>Stiffness</td>
<td>Low</td>
<td>Very high</td>
<td>High</td>
</tr>
<tr>
<td>Corrosion resistance</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>Cost</td>
<td>Inexpensive</td>
<td>Expensive (10 x glass)</td>
<td>Expensive</td>
</tr>
</tbody>
</table>

Table 4. Properties of common fibrous reinforcements: glass-, carbon- and aramid fibres [5].

4.1.2 Matrix

The matrix has several functions: it works as an adhesive that holds the reinforcement in place, it transfers external loads to the reinforcement, and it protects the reinforcement from the surrounding environment. Furthermore, the matrix prevents buckling of the fibres in compression and distributes the load between surrounding fibres if an individual fibre breaks.

Important issues when selecting a polymer matrix concern the reinforcement-matrix compatibility in terms of bonding, mechanical properties, thermal properties, cost and processability. Among polymer matrices are the use of thermosets clearly dominating in
structural composite applications. Thermosets popularity is due to good mechanical and thermal properties, low cost, and low viscosity to mention a few.

The most common thermoset polymer matrices are unsaturated polyesters, vinylesters and epoxies. Unsaturated polyesters dominate the market, while epoxies are often used in high-performance applications. Vinylesters does in most cases represent a compromise between unsaturated polyesters and epoxies [5].

<table>
<thead>
<tr>
<th></th>
<th>Unsaturated polyester</th>
<th>Vinylester</th>
<th>Epoxy</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Density, $\rho$ [kg/m$^3$]</strong></td>
<td>1100 - 1230</td>
<td>1120 - 1130</td>
<td>1100 - 1200</td>
</tr>
<tr>
<td><strong>Elastic modulus, $E$ [GPa]</strong></td>
<td>3.1 - 4.6</td>
<td>3.1 - 3.3</td>
<td>2.6 - 3.8</td>
</tr>
<tr>
<td><strong>Strength, $\sigma$ [MPa]</strong></td>
<td>50 - 75</td>
<td>70 - 81</td>
<td>60 – 85</td>
</tr>
<tr>
<td><strong>Strain to failure, $\varepsilon$ [%]</strong></td>
<td>1.0 - 6.5</td>
<td>3.0 - 8.0</td>
<td>1.5 – 8.0</td>
</tr>
<tr>
<td><strong>Cost</strong></td>
<td>Low</td>
<td>Medium</td>
<td>Medium</td>
</tr>
<tr>
<td><strong>To work with</strong></td>
<td>Easy</td>
<td>Medium</td>
<td>Difficult</td>
</tr>
</tbody>
</table>

Table 5. Properties of common thermosets: unsaturated polyester, vinylester and epoxy [5].

### 4.1.3 Core materials

Separating the faces with an intermediate core increases the flexural rigidity of a composite. This is known as the sandwich concept and it offers an alternative to a thicker and stronger laminate without significant weight increase. The faces mainly experiences compressive or tensile stress, while the core is exposed to lateral loads. Hence, the shear strength and modulus are the most relevant properties of a core material. The most common sandwich core types are wood, honeycomb, and polymer foam cores [5].

<table>
<thead>
<tr>
<th></th>
<th>Wood cores</th>
<th>Honeycombs</th>
<th>Polymer foam cores</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Density, $\rho$ [kg/m$^3$]</strong></td>
<td>90 – 180</td>
<td>30 – 200</td>
<td>30 – 200</td>
</tr>
<tr>
<td><strong>Elastic modulus $E_c$ [GPa]</strong></td>
<td>2000 - 5000</td>
<td>400 – 2000</td>
<td>10 - 350</td>
</tr>
<tr>
<td><strong>Shear strength, $\tau_c$ [MPa]</strong></td>
<td>1.8 – 3.5</td>
<td>0.4 – 4.1</td>
<td>0.2 – 3.3</td>
</tr>
<tr>
<td><strong>Temperature tolerance</strong></td>
<td>Moderate</td>
<td>Low to high</td>
<td>Low to high (80-200)</td>
</tr>
<tr>
<td><strong>Moisture tolerance</strong></td>
<td>Sensitive</td>
<td>Sensitive</td>
<td>Good</td>
</tr>
<tr>
<td><strong>Conformability</strong></td>
<td>Poor</td>
<td>Good</td>
<td>Good to excellent</td>
</tr>
<tr>
<td><strong>Machining</strong></td>
<td>Simple</td>
<td>Difficult</td>
<td>Simple</td>
</tr>
<tr>
<td><strong>Cost</strong></td>
<td>Inexpensive</td>
<td>Expensive</td>
<td>Varies with material</td>
</tr>
<tr>
<td><strong>Face lamination</strong></td>
<td>Face may be laminated directly onto core</td>
<td>Difficult to bond faces to</td>
<td>Faces may be laminated directly onto</td>
</tr>
<tr>
<td><strong>Other</strong></td>
<td>Balsa dominates</td>
<td>Aluminium or aramid fibre paper most common</td>
<td></td>
</tr>
</tbody>
</table>

Table 6. Properties of common core types: wood, honeycombs and polymer foam cores[5].
5 Specification of requirements

The purpose with a T-foil is to decrease accelerations onboard as well as to reduce impact forces on the hull in rough sea. Ship motions degrade the operability and limiting values of accelerations would be an appropriate criterion. In this analysis are information about the vessel such as hull shape, weight distribution and ship motions classified. Therefore, no direct connection will be made to the effect on the ship’s motions of the T-foil.

5.1 General requirements

Requirements are drawn up for construction of the T-foil. No requirements are set for the shape of the foil, since this initial investigation excludes the coupling to ship motions. The following general requirements must be fulfilled:

- **R1** Non-magnetic
- **R2** Minimise weight
- **R3** Manage operation in 40 knots
- **R4** Minimise cubic space in hull
- **R5** Not increase draught of vessel when not active
- **R6** Construction safety factors: 2 (core) and 3.5 (carbon laminate)

5.2 Construction requirements

5.2.1 Strain and tension

Construction requirements for the laminate are set for strain instead of tension. This is because the model has varying thickness and strain does not vary with section area as tension does. The ultimate strain in the 1-direction for the carbon fibre that is modelled is 1.5%. A safety factor of 3.5 results in a maximum model strain of 0.43%. Ultimate strain in the 2-direction is 0.5%, which results in a maximum model strain of 0.14%.

The core consists of a uniform material that is dominantly exposed to shear. Therefore, requirements concern shear strength. Divinycell HD 250 is an appropriate core material with ultimate shear strength 4.5 MPa. The safety factor of 2 results in a maximum shear strength of 2.25 MPa.

5.2.2 Deflection

The midpoints between the hinges on the flap are to be deflected a maximum of 30 mm in the y-direction. No other requirements for deflection are to be concerned.

5.2.3 Twist

Twist can be defined as the angle between the tip chord and the root chord. A twisted wing has a different angle of attack at the tip compared to the root. Consequently, the pressure distribution will differ, as well as the lift. A limitation of the twist is required to assure that load cases are accurate enough. A maximum twist angle is also necessary for the control system to work properly. The control system requirement is assumed to be the twist angle that results in a 10% difference in lift force.
The effect on the pressure acting on the foil is controlled by varying twist in the vortex lattice theory model and analysing the result. Calculations and evaluation are found in appendix A. The result from this evaluation is that a maximum twist of 2˚ is allowed. This is tested for the main wing, but the result is assumed to be about the same size for the strut and the flap. The criterion is therefore applied at the foil, the flap and the strut.

5.2.4 T-joint efficiency
The T-joint between the foil and the strut is exposed to great stresses. The joint is complex to model and will not be included in the finite element analysis. Instead is a reference study used to estimate if it is possible to carry the loads acting on the T-joint.

Calculations, that are found in appendix B, implies that the strain close to the T-joint is not allowed to be over 40% of the ultimate strain. Considering a safety factor of 3.5 results in a maximum strain of 11.4% of the ultimate. Since the ultimate strain for carbon fibres are 1.5% in the 1-direction, the allowed strain is 0.114 x 1.5 = 0.17%. The corresponding value in the 2-direction is 0.114 x 0.5 = 0.057%.

5.3 Summary of criterion

<table>
<thead>
<tr>
<th></th>
<th>Laminate</th>
<th>T-joint</th>
<th>Core</th>
<th>Twist</th>
<th>Deflection</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \varepsilon_1 )</td>
<td>0.43%</td>
<td>0.17%</td>
<td>2.25 MPa</td>
<td>2 degrees (general)</td>
<td>30 mm (flap between hinges)</td>
</tr>
<tr>
<td>( \varepsilon_2 )</td>
<td>0.14%</td>
<td>0.06%</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 7. Summary of construction criterion.
6 General parameters

General parameters of the T-foil are considered to be material, concept, location, depth, wingspan, cord, profiles, flaps and wing tip plates.

6.1 Material
The same composition of material is used in the T-foil as in the hull of Visby. This is due to the fact that the fixation of the T-foil to the vessel is facilitated if the same materials are used. It is also materials that are well known to the yard building Visby.

The core is Divinycell HD250, which features good dynamic properties and high ductility with good processing characteristics for dynamically loaded applications [7]. More detailed properties of the core are found in table 13. The face is a carbon fibre/vinylester laminate with properties described in table 14.

6.2 Concept
It is not possible with a fixed T-foil because of requirement R5. Furthermore, a potential T-foil concept is mainly determined by the space inside the hull that can be spared. A potential concept could be a T-foil that is vertically retracted according to the middle solution in figure 7. The modelling of such a foil is complicated since the lifting device is not known. Because of this a bolt-on T-foil selected to act as base for further design. A bolt-on T-foil is assumed to experience the same problems as a not retracted vertically retractable T-foil.

6.3 Location
Athwartships location of the T-foil is naturally set to the centreline so that no rolling moment is induced when the control system is not activated. The x-position of the foil is vital for the heave and pitch motions. Investigations on a 145 m monohull at 45 knots with three different foil positions show that the foil positioned at the bow is by far the most effective in reducing the pitch and heave motion of the ship [8]. This thesis is supported by the fact that most installed T-foils are located close to the bow. In accordance to this is the longitudinal location set to just rear of the bow bilge. For the Visby Class corvette the longitudinal location is approximately 5 m behind the forward perpendicular.

6.4 Depth
The length of the vertical strut mainly determines the total depth of the T-foil. A principal concern when determining strut length is foil-hull interaction. A short strut can disturb the flow around the hull and thus decreasing the efficiency of the hull. Another concern is that the T-foil should be deep enough to be submerged most of the time. Discussions about interaction between hull and T-foil are made with fluid dynamics expert Hans Liljenberg at SSPA [9], indicated that a reasonable depth is about 1 meter below the keel line. Linear scaling from reference vessel NGV 3 result in a depth of 1.25 m [10]. The construction depth of the T-foil is set to 1.0 meter.

<table>
<thead>
<tr>
<th>Vessel</th>
<th>Length [m]</th>
<th>Weight [tonnes]</th>
<th>Speed [knots]</th>
<th>T-foil depth [m]</th>
<th>Scale factor</th>
<th>Visby T-foil depth [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGV 3</td>
<td>134</td>
<td>870</td>
<td>40</td>
<td>2.5</td>
<td>0.53</td>
<td>1.25</td>
</tr>
</tbody>
</table>

Table 8. Linear scaling of T-foil depth, based on length.
6.5 Wingspan and cord

<table>
<thead>
<tr>
<th>Vessel</th>
<th>Length [m]</th>
<th>Weight [tonnes]</th>
<th>Speed [knots]</th>
<th>Cord [m]</th>
<th>Area [m$^2$]</th>
<th>Scale factor</th>
<th>Visby cord [m]</th>
<th>Visby area [m$^2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SuperSeaCat</td>
<td>100</td>
<td>340+</td>
<td>40</td>
<td>2.7</td>
<td>13.4</td>
<td>0.71</td>
<td>1.93</td>
<td>7.13</td>
</tr>
<tr>
<td>Evolution 10B</td>
<td>98</td>
<td>200+</td>
<td>38</td>
<td>2.4</td>
<td>20</td>
<td>0.73</td>
<td>1.75</td>
<td></td>
</tr>
<tr>
<td>NGV 3</td>
<td>134</td>
<td>870</td>
<td>40</td>
<td>13.4</td>
<td>20</td>
<td>0.53</td>
<td>7.13</td>
<td></td>
</tr>
<tr>
<td>RRNVC</td>
<td>146</td>
<td>4480</td>
<td>45</td>
<td>20</td>
<td>13.4</td>
<td>0.50</td>
<td>10.00</td>
<td></td>
</tr>
</tbody>
</table>

Table 9. Parameters for reference T-foils and scaling to Visby T-foil, based on length.

The lift of a wing is proportional to the fin area. Hence, it is natural to first determine the required area and then cord and span. A reasonable area is assumed to be 4-8 m$^2$, based on linear scaling from other vessels and discussion with Hans Liljenberg at SSPA. The area is set to 6 m$^2$.

![Lift vs Aspect Ratio](image)

Figure 9. Lift and induced drag as a function of aspect ratio. NACA 0012, vortex lattice theory, $S=6m^2$, $\alpha=10^\circ$

The relationship between lift/drag and AR is shown in figure 9. The conclusion is that the greater AR the better. The dip of the drag at small aspect ratios can probably be derived from limitations in the model.

A direct limit of the span is the breadth of the vessel, so that the foil does not collide with the dockside when moored. Another concern is the strength of the foil. Constructing a foil with a 10 m span results in a cord of 0.6 m, if the area is set to 6 m$^2$. This requires a lot of the construction considering the forces that it will be exposed to. To have a reasonable AR and still a possibility to construct the foil, the span is set to 4.8 m. The base cord is set to 1.5 m and the wingtip cord 1.0 m. This results in a foil with a higher AR compared to the reference foils in table 9. The varying cord forms an arrow like shape that renders the possibility for self-cleaning from seaweed and other buoyant objects.
6.6 Profiles
A two-dimensional wing profile is determined by its camber, thickness distribution and thickness form. Both the profile of the strut and the horizontal foil must be symmetric, accordingly having no camber. The purpose of the strut is to lower the horizontal foil and not to generate any lift. It must be wide enough to enclose the mechanical control system for the flap. NACA 16-021 is used as profile for the strut, which results in a width of 0.315 m.

The horizontal foil must be symmetric so that the flap can be controlled to generate lift in both vertical directions. Another reason is that when the T-foil is not active it is supposed to generate zero lift. The profile should also have a small drag coefficient at different angles as well as not stalling to easily. The thickness ratio of the horizontal foil is set to 12%, based on comparison with commercial T-foils. The result is that the thickness varies from 18 cm at the root to 12 cm at the tip. NACA 0012 is applied for the horizontal foil.

6.7 Flap
The lift properties of a foil are dependent on the wind flow pass the foil. The lifting properties can be enhanced by the use of a flap at the trailing edge of the wing. The flap adjusts the camber of the wing so that lift can be generated both up and down. Comparing the flap cord of commercial T-foils results in that the flap cord is set to 1/5 of the foil root cord, which equals 0.3 m.

6.8 Wing tip plates
Tip plates or winglets are intended to prevent the formation of tip vortices and thereby decrease induced drag. They do succeed to some extent but not without a penalty. The plates themselves cause skin friction and form drag, which might be larger than the savings. There are differing opinions about the efficiency of winglets and the subject is too complex to be fully evaluated in this report. Instead, a simple test is made based on vortex lattice theory. The efficiency test of the tip plates in appendix C indicates that it takes about 8% height of the winglet compared to wingspan for a 10% decrease of induced drag. Assuming that the T-foil increases the total ship resistance with one percent, the decrease in total resistance is about one per mille. This is a neglectable difference and therefore are no winglets included on the T-foil. A better way of improving lift/drag ratio is to increase the aspect ratio.

6.9 Summary of parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal location</td>
<td>Leading edge 5 m astern of FP</td>
</tr>
<tr>
<td>Athwartships location</td>
<td>Centreline</td>
</tr>
<tr>
<td>Depth, ( d )</td>
<td>1.0 m</td>
</tr>
<tr>
<td>Wingspan, ( b )</td>
<td>4.8 m</td>
</tr>
<tr>
<td>Cord strut</td>
<td>1.5 m</td>
</tr>
<tr>
<td>Cord foil, root, ( c_r )</td>
<td>1.5 m (incl. flap)</td>
</tr>
<tr>
<td>Cord foil, tip, ( c_t )</td>
<td>1.0 m (incl. flap)</td>
</tr>
<tr>
<td>Aspect ration</td>
<td>3.84</td>
</tr>
<tr>
<td>Wing profile</td>
<td>NACA 0012, thickness 12%</td>
</tr>
<tr>
<td>Strut profile</td>
<td>NACA16 021, thickness 21%</td>
</tr>
<tr>
<td>Cord flap</td>
<td>( 0.20c = 0.30 ) m</td>
</tr>
</tbody>
</table>

Table 10. Summary of T-foil parameters.
7 Loads

The maximum load that can act on the T-foil is limited by the maximum lift the wing profiles can generate. As the angle of attack increases over $c_{l_{\text{max}}}$, the wing stalls and lift decreases. Consequently, the angle of attack at $c_{l_{\text{max}}}$ acts as input angle in the load cases. After a number of critical load cases are determined, the next step is to estimate the pressure acting on the T-foil at these load cases. The pressure distribution is calculated using vortex lattice theory.

7.1 Input for load cases

To determine the maximum load that acts on different areas of the foil are lift coefficients for respectively profile studied.

The foil profile NACA0012 is studied with flap deflected at 60° and assumed standard roughness and $Re = 6 \times 10^6$. As seen in figure 10, maximum $C_l$ is 1.9 and located at $\alpha = 5^\circ$. It should be noted that this is a higher value than the one achieved for zero flap deflection and could therefore be used as maximum for the wing configuration. In practice it is not possible to have a flap deflection of 60° since the response time will be too long. Comparing other commercial T-foils results in a more realistic flap deflection of 30°, which is used as input. Assuming linear relationship between $\gamma$ and $c_{l_{\text{max}}}$ results in that $\alpha = 9^\circ$ for flap deflected 30°.

NACA 021-16 maximum lift coefficient is achieved at $\alpha = 16^\circ$. This is the angle that is used as input for maximal T-foil sideslip pressure acting on the strut.
7.2 Load cases

The critical load cases that are considered are based on the angles of attack discussed in chapter 7.1. Sea condition is not taken into account since the maximum lift that a profile can generate is determined by the stall angle of attack. The weight of the T-foil is excluded from the load cases since the pressure acting on the construction is dominant. The load cases of interest are described in table 11.

<table>
<thead>
<tr>
<th>v [knots]</th>
<th>α [˚]</th>
<th>β [˚]</th>
<th>γ [˚]</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>40</td>
<td>8</td>
<td>0</td>
<td>Upwards lift</td>
</tr>
<tr>
<td>L2</td>
<td>40</td>
<td>-8</td>
<td>0</td>
<td>Downwards lift</td>
</tr>
<tr>
<td>L3</td>
<td>40</td>
<td>8</td>
<td>0</td>
<td>Upwards lift, only from right half of foil</td>
</tr>
<tr>
<td>L4</td>
<td>40</td>
<td>-8</td>
<td>0</td>
<td>Downwards lift, only from right half of foil</td>
</tr>
<tr>
<td>L5</td>
<td>40</td>
<td>8</td>
<td>16</td>
<td>Upwards lift plus sideslip</td>
</tr>
<tr>
<td>L6</td>
<td>40</td>
<td>-8</td>
<td>16</td>
<td>Downwards lift plus sideslip</td>
</tr>
</tbody>
</table>

Table 11. Summary of load cases, definitions in figure 3.

7.3 Vortex lattice theory

The pressure distribution acting on the T-foil is calculated using vortex lattice theory. A Matlab based software called Tornado [12] employed. Tornado is based on standard vortex theory, which originates from potential flow theory. Lattice vortex theory works with a horseshoe-arranged vortex for every panel. The vortex consists of a bound vortex and two free vortices. All vortices counteract and strength is adjusted according to a non-slip condition for every panel. A primary assumption in vortex lattice theory is the small angle of attack. Hence, caution is advised when examine large angles as well as rotational speeds. Fuselage effects and friction drag is not concerned and thickness effects of the lifting surface are neglected, as are compressibility effects [12].

The output of Tornado is $\Delta C_p$, which is the difference between the pressure coefficient on the up- and downside of the wing. The actual pressure difference can be calculated using the following relationship:

$$C_p = \frac{P - P_\infty}{\frac{1}{2} \rho \omega v_\infty^2}$$

$$P = \frac{1}{2} \rho \omega v_\infty^2 C_p + P_\infty \quad \text{where} \quad P_\infty = \rho g h \quad \text{and} \quad h \text{ is the depth from the surface.}$$

In reality, two different pressures are acting on the wing, one on the upside and another on the downside. This differs from applying $\Delta P$ on the downside as is done in this model. The difference is important when studying local effects but is assumed to have acceptable effect on the global situation that is studied in this model.
7.3.1 Vortex lattice theory model

The vortex lattice theory model includes all parts of the T-foil, i.e. strut, foil and flap. The hull of the ship and the water surface are not included in the model since the critical angles of attack are not dependent on these parameters. As mentioned before, there cannot be greater force acting on the T-foil then at $c_{l,max}$ since the force decreases when the T-foil stalls.

The number of panels that are used in the model is $8 \times 8$ on each side of the foil, including the flap. The strut is modelled with $5 \times 6$ panels. A convergence study of the number of panels on the foil is found in appendix D.

![Figure 12. Vortex lattice theory model](image)

7.3.2 Results from vortex lattice theory

The total forces acting on the T-foil for each load case is calculated using vortex lattice theory and summarized in table 12.

<table>
<thead>
<tr>
<th>Load case</th>
<th>X [kN]</th>
<th>Y [kN]</th>
<th>Z [kN]</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>-48</td>
<td>2234</td>
<td>0</td>
</tr>
<tr>
<td>L2</td>
<td>-48</td>
<td>-2234</td>
<td>0</td>
</tr>
<tr>
<td>L3</td>
<td>-24</td>
<td>1117</td>
<td>0</td>
</tr>
<tr>
<td>L4</td>
<td>-24</td>
<td>-1117</td>
<td>0</td>
</tr>
<tr>
<td>L5</td>
<td>-80</td>
<td>2095</td>
<td>-184</td>
</tr>
<tr>
<td>L6</td>
<td>-80</td>
<td>-2095</td>
<td>-184</td>
</tr>
</tbody>
</table>

Table 12. Summary of total forces calculated with vortex lattice theory. Coordinates according to definition in figure 3.

The pressure distributions for three typical load cases are shown in figure 13 to 15. The pressure distribution for load case L3 and L4 can be derived from L1 and L2 respectively, using only the pressure on the right side of the foil and flap.
Figure 13. $\Delta C_p$ distribution load case L1.

Figure 14. $\Delta C_p$ distribution load case L2.

Figure 15. $\Delta C_p$ distribution load case L5.
8 Construction

The construction phase starts with determining fibre lay-up angles that are to be used in the T-foil. The finite element model is described and different idealizations are explained. The calculated pressure is applied to the model and tests are made to determine laminate thickness for different areas and layers.

8.1 Fibre Reinforcement

Most parts of the T-foil are dimensioned by stiffness. Consequently, lay-up angles are determined to fulfil requirements on twist and deflection. One exception is the T-joint where strength is more critical than stiffness. It should be noted that a set-up with potential lay-up angles are considered and no further test are made to find the optimal lay-up angles for different areas.

The strut is exposed to transverse forces that deflect the construction in the z-direction. Fibres in the 0-direction counteract this deflection. Twist is minimised by fibres in the 45/-45-direction. A fairly thick profile indicates that only a small proportion of 45/-45 is required.

The horizontal foil is exposed both to great deflection in the y-direction and twist of the wingtips. Fibres in the 0-direction control deflection and fibres in the 45/-45-direction counteracts against twisting the foil.

The flap is exposed to great forces when at maximum deflection. Fibres in the 45/-45-direction are required to counteract the twist of the flap. Fibres in the 0-direction are important to control the vertical deflection between the hinges.

Figure 16. Lay-up angles
8.2 Finite element model

A finite element model of the T-foil is created in ANSYS. The purpose with the model is to find the thickness of each lamina that fulfils construction requirements. The model encompasses all of the T-foil that is important for construction. No parts of a retracting mechanism or flap controlling mechanism are included. The top of the vertical strut is modelled as it is fixed to frames inside the hull. The T-foil is symmetric around the centreline of the vessel, both sides are included as some load cases are anti symmetric. The model is divided into two parts, the actual T-foil and the trailing flap. These two parts are connected with hinges at three points, one in the middle and one at each wingtip respectively.

![Finite element model of T-foil.](image)

The analysis is static using the maximum dynamic pressures when the foil is immersed. Slamming pressures are not included. Deformation is assumed proportional to force and linear static analysis is used [13]. Global deflections are expected to be relatively accurate while stresses can be unrealistic due to the linear analysis. Evaluations of laminates are based on strains and the core is based on shear stress.

8.2.1 Elements

The model consists of shell elements modelling the face and solid elements modelling the core. SHELL99, a linear layered structural shell element is employed, as linear calculations are accurate enough. The core is modelled with the structural solid element SOLID95.

![Exploded foil profile, constructed of shell elements- and solid elements.](image)
SHELL99 is an 8-node, 3-D shell element with six degrees of freedom at each node. It is designed to model thin to moderately thick plate and shell structures with a side-to-thickness ratio of roughly 10 or greater [14]. No evaluation of SHELL99 is made due to earlier shown stability.

SOLID95 is a 20-node, 3-D structural solid element with three degrees of freedom per node: translations in the nodal x-, y-, and z-directions. The element can tolerate irregular shapes without as much loss of accuracy [14].

8.2.2 Mesh
A relatively coarse mesh is used since global effects are studied. The application of simple load cases in an initial state resulted in the determination of the mesh size. No convergence study is made.

8.2.3 Material models

Core
The core is PVC and the material properties are from Divinycell HD 250.

<table>
<thead>
<tr>
<th>Divinycell HD 250</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density, $\rho = 250$ kg/m$^3$</td>
</tr>
<tr>
<td>Poisson’s ratio, $\nu = 0.32$</td>
</tr>
<tr>
<td>Young’s modulus, $E = 220 - 355$ MPa</td>
</tr>
<tr>
<td>Shear modulus, $G = 110$ MPa</td>
</tr>
</tbody>
</table>

Table 13. Core material properties [7].

The core is modelled as a linear isotropic material with $E_x = 287$ MPa and $\nu_{xy} = 0.32$. The core is almost exclusively exposed to shear, which implies that using a constant Young’s modulus instead of a varying induces acceptable errors.

Face

<table>
<thead>
<tr>
<th>Carbon fibre/vinylester lamina</th>
<th>Lamina model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight fraction fibres: 51%</td>
<td>$E_x = 114$ GPa</td>
</tr>
<tr>
<td>Fibres in $0^\circ$-direction: 100%</td>
<td>$E_y = E_z = 9$ GPa</td>
</tr>
<tr>
<td>Density = 1600 kg/m$^3$</td>
<td>$\nu = 0.3$</td>
</tr>
<tr>
<td>$E_{90} = 9$ GPa</td>
<td>$G_{xy} = 3$ GPa</td>
</tr>
<tr>
<td>$G_{12} = 3$ GPa</td>
<td>$G_{xz} = 3$ GPa</td>
</tr>
<tr>
<td></td>
<td>$G_{yz} = 110$ MPa</td>
</tr>
</tbody>
</table>

Table 14. Face material properties [15].

Table 15. Modelled face material properties.

The carbon fibre/vinylester lamina is modelled as a linear orthotropic material. It is assumed that Young’s modulus is the same in the z-direction as in the y-direction, i.e. $E_x = E_y$. Poisson’s ratio is set to 0.3, which is a value that has been used in tests with similar materials and shown accurate. Shear modulus is assumed to be the same in the xz-direction as in the xy-direction. Shear modulus in the yz-direction is set to the shear modulus of the core.
8.2.4 Hinges
Three hinges connect the flap to the foil. One is positioned in the middle of the flap and the other two are at the wingtips. The hinges are modelled by linking degrees of freedom for the concerned nodes. The coupling in the middle comprises coupling of translation in $x$-, $y$- and $z$-direction. The two couplings at the wingtips include translation in $x$- and $y$-direction.

Figure 19. Coupled degrees of freedom, hinge model.

8.2.5 Flap
The flap is arranged at a horizontal level to facilitate a better view of deflection and strain. This differs from the real situation where the flap is deflected at up to 30 degrees. A force is added in the $x$-direction to compensate the difference of the forces acting on the hinge. The size and application of these forces are presented in appendix E. Rotation of the flap is controlled by fixation of the upper part of the lever, where the actual control mechanism for the flap would connect.

8.2.6 T-joint
No phenomenon such as buckling occurs as the finite element analysis is based on linear theory. Hence, the stress close to the joint between strut and foil rises to an unreasonable level. The stress is plotted as a function of the distance from the joint to determine where this happens, see figure 20. The conclusion is that the stress is accurate to about 2.5 cm from the joint. Hence, strains that should fulfil requirements will be checked at a distance of 3 cm from the joint.

Figure 20. Stress in the laminate at the upside of the horizontal foil. Load case L3.
8.2.7 Attachment to hull

The fixation of the T-foil to the vessel can be done in different ways dependent on the distance between the sections onboard. This model is fixated to two sections. The strut is fixed at the vertical edges both in front of and back of each section. The marked edges in figure 21 are fixed in all six degrees of freedom.

![Figure 21. Attachment of T-foil to two sections of the vessel.](image)

A concept with a vertically retractable T-foil would probably not have a similar fixation design. But when immersed, the forces acting on the T-foil needs to be transported into the hull reinforcing construction. It is assumed that the flexible attachment areas of a retractable T-foil are of the same dimension as in this model. Therefore, the strains can be expected to be of the same dimension as well.

8.3 Input loads

The pressure difference calculated with vortex lattice theory is given for a horizontal surface. Pressure application in the finite element model is made on element at one side of the foil. These elements have different angles to the horizontal plane along the wing profiles. Hence, this solution may introduce errors in the total pressure resultants. To control this are the total structural reaction forces in the finite element model compared to the resultants calculated with vortex lattice theory.

<table>
<thead>
<tr>
<th></th>
<th>Vortex lattice theory</th>
<th>Finite element model</th>
<th>FEM/VLT</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>2215 kN</td>
<td>2014 kN</td>
<td>0.91</td>
</tr>
<tr>
<td>Y</td>
<td>-48.3 kN</td>
<td>-83.6 kN</td>
<td>1.73</td>
</tr>
</tbody>
</table>

Table 16. Comparison of pressure resultants from vortex lattice theory and finite element model. Load case L1

The comparison is made for load case L1, which represents the greatest difference between the load cases. The acceptable difference in the x-direction is mainly due to the application of the pressure on elements with varying angle to the xz-plane. The greater difference in the y-direction can also be derived from the pressure application in the finite element model. This difference is larger than expected, but is accepted since it is conservative and the resultants in the y-direction are small compared to the x-direction.
8.4 Analysis and results
Initially are critical load cases for different parts of the T-foil determined. Laminate thickness is determined in an iterating process by testing different thickness in different layers.

8.4.1 Critical load cases
Critical load cases for different areas are established and presented in table 17.

<table>
<thead>
<tr>
<th>Area</th>
<th>Critical load cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upside wing</td>
<td>L2, L6</td>
</tr>
<tr>
<td>Downside wing</td>
<td>L1, L5</td>
</tr>
<tr>
<td>Twist wing</td>
<td>L1, L2, L3, L4</td>
</tr>
<tr>
<td>Strut</td>
<td>L3, L4</td>
</tr>
<tr>
<td>Deflection strut</td>
<td>L3, L6</td>
</tr>
<tr>
<td>Twist strut</td>
<td>L3</td>
</tr>
<tr>
<td>Fixation points</td>
<td>L3, L4</td>
</tr>
<tr>
<td>Flap</td>
<td>L1, L2, L3, L4</td>
</tr>
<tr>
<td>Flap arm</td>
<td>L1, L2, L3, L4</td>
</tr>
<tr>
<td>Twist flap</td>
<td>L1, L2, L3, L4</td>
</tr>
</tbody>
</table>

Table 17. Critical load cases for different areas.

As shown in table 17, several load cases have the same effect on some areas. Hence, a reduction of critical load cases can be done to L1, L2 and L3. It is found that the downside of the horizontal foil experiences the same strains as the upside. Consequently, only L2 and L3 are required to determine laminate thickness, see figure 22.

Figure 22. Required load cases for construction.
8.4.2 Lay-up thickness

Approximate thickness for different areas are determined after repeated test using the finite element model. Strain in the 1- and 2-direction are controlled in the laminate and shear stress is controlled in the core. The result is summarised in table 18. Note that values should only be taken as guidelines for the required laminate thickness.

<table>
<thead>
<tr>
<th>Lay-up</th>
<th>Thickness [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strut</td>
<td>0 / 45 / -45</td>
</tr>
<tr>
<td>Hull attachment</td>
<td>0 / 45 / -45</td>
</tr>
<tr>
<td>Foil</td>
<td>0 / 45 / -45</td>
</tr>
<tr>
<td>Flap</td>
<td>0 / 45 / -45</td>
</tr>
<tr>
<td>Flap lever</td>
<td>0 / 45 / -45</td>
</tr>
</tbody>
</table>

Table 18. Summary of laminate parameters.

**Strut**

Strut lay-up thickness is determined by L3. The strut laminate needs a total thickness of about 10 mm, disregarding T-joint and attachment area. Twist is not critical, but strain in the 1-direction is. An adequate lay-up is 0/45/-45 with thickness 6/2/2 mm respectively. One could believe that since twist is no problem only 0 degree fibres results in the smallest deflection of the strut. This is not the case, probably because of the wide shape of the profile. Thickness 6/2/2 results in a small $\varepsilon_1$ and does not result in great strains at the fixation points that the alternative with all the fibres in 0 degrees does.
**Hull attachment**

The hull attachment areas on the strut have great strains at the lower part. Using twice as thick laminate, i.e. 20 mm, results in acceptable strains.

An alternative solution with a vertical retractable T-foil is assumed to experience the same dimension of strains around the fixation areas, as discussed in 8.2.7. Consequently, it should also be possible to use such a concept, seen from a constructional point of view.

**Flap**

Estimations show that 30 mm deflection in the y-direction at the midpoint between the hinges results in $\epsilon = 0.08\%$, calculations in appendix F. This is much lower than the requirement of 0.43%, which indicates that the strength is not critical in the flap, but stiffness is.

A difficult requirement to fulfil is the maximum twist angle of 2 degrees at the tip of the flap. The flap is exposed to great pressures and to fulfil the twist requirement a great part of the laminate is required in the 45- and –45-direction. A lay-up that fulfils the twist requirement and a maximum distance between foil and flap of 30 mm is 0/45/-45 with thickness 5, 20 and 20 mm. Such a thick laminate is difficult to manufacture and not applicable in the flap construction, regarding the total thickness of the flap. Consequently, inner reinforcement has to be implemented or other twist requirements. Introducing additional hinges makes it possible to decrease the laminate thickness, but not much since the twist is still a great problem. A quick test is made with twist requirement of 5 degrees and ignored deflection. The total thickness of the laminate could then be reduced 20 mm, i.e. roughly half the thickness.

**Flap lever**

The lever controlling the flap is not considered in the finite element analysis. The lever requires a special arrangement in the same way as the T-joint. However, it is found that the force required to control the flap does not seem to introduce strains greater than in the attachment areas. This force is dependent on what control speed that is needed. In the finite element analysis are only static force is applied, which keeps the flap at a state of equilibrium. It is concluded that the flap arm requires a similar construction as the T-joint at the actual foil and with a laminate thickness of about 20 mm.

**Foil**

The horizontal foil is the part of the T-foil that requires the thickest laminate, apart from the flap. There is no requirement for the deflection at the wingtips, but estimations shows that it can be approximately 100 mm deflection in the y-direction and still fulfil strain requirements for the laminates. This is if the T-joint requirement is not taken into account. If the T-joint requirements are included, only 70 mm deflection in the y-direction is accepted at the tip, appendix F.

It is possible to use a varying laminate thickness along the wingspan. The result is a small strain close to the joint that increases out towards the wingtips. This method is used and it requires about 30 mm laminate at the root and 5 mm at the wingtips. Transverse forces increases with the distance from the wingtips towards the root. The torque on the other hand increases with the square of the distance. Since torque is most critical for the wing it is assumed that the thickness can follow an $x^2$-curve. This indicates that the 30 mm laminate at the root is only required for a short distance from the joint.
Strain requirements are critical, not twist. Distributing the fibres evenly between the three different lay-up angles results in acceptable strain, but great deflection at the wingtips. Half the deflection is achieved if 60 percent of the fibres are situated in the 0-direction and the rest in 45/-45. Twist is not a problem even when all the fibres are in the 0-direction, but it results in greater strains.

Figure 25. Strains in 1-direction, laminate, L2, without T-joint reinforcement to show strain distribution.

Figure 26. Strains in 1-direction, laminate, L2.

The models that are plotted in figure 25 and 26 do not include T-joint reinforcement. This is to illustrate the problems with the strain close to the T-joint.
9 Velocity and drag prediction

Two methods are employed to estimate the drag that the T-foil adds to the drag of the vessel. The first method used is a classic semi empirical method that is based on several reference tests. The other approximation is based on vortex lattice theory.

It should be noted that even though the T-foil adds drag, it makes it possible to control the pitch of the vessel. Therefore, an optimal trim can be obtained resulting in decreased fuel consumption and probably greater speed. The following estimations are only made to understand the dimension of the drag created by the T-foil compared to the total drag of the vessel.

9.1 Semi empirical method

Holtrop & Mennen’s semi empirical method is known as a reliable method [16]. For more accurate values are CFD-calculations or tank tests the only option. The method is based on information from references and calculations are found in appendix G.

The result is that the drag of the T-foil is 19 kN, which equals about under 1% of the resistance of a vessel such a Visby.

9.2 Vortex lattice theory

Calculations are made with software Tornado. Tornado is described in 7.3.

Drag is calculated with 9° angle of attack and a flap angle of 30°. This is the maximum drag the T-foil creates and is therefore adjusted as if the drag was sinusoidal, see appendix H. The result shows that the adjusted drag of the T-foil is 31 kN, which equals just over 1% of the total drag.
10 Conclusions

It is most likely possible to manufacture and install a non-magnetic T-foil of the size required by a vessel such as the Visby Class corvette. But this feasibility study shows on some problems that must be examined closer. The primary constructional concern is the T-joint between the vertical strut and the horizontal foil. Estimations indicate that a very thick laminate is required close to the joint. However, these initial estimations are based on several assumptions and this area should therefore be examined closer. The next step is to test the T-joint in laboratory for more accurate results.

The result also showed on a very thick laminate on the flap, which is not possible to manufacture. The laminate thickness of the flap is strongly connected to the requirements of twist and deflection. Hence, studying the effect that deflection and twist have on lift and drag is recommended.

An important step in continued work is to include more detailed hydrodynamic studies for more accurate size and shape of the fin. It should be noted that the aspect ratio of the T-foil in the analysis is high compared to commercial T-foils. More detailed hydrodynamic investigations could also show if the requirements are reasonable. It is also important to determine a potential T-foil concept for the vessel, so that the right input parameters can be modelled. Future development should also include optimising lay-up angles, which can save weight due to reduced laminate thickness.

A limitation in this study is the load cases. The flap deflection angle needs to be checked with a control system. Perhaps is only a deflection half the value possible, which would change all load cases dramatically. Another possible source of error is the finite element model. A non-linear model is more time consuming but includes effects such as buckling. Other areas that are of interest are fatigue and effects of slamming.
Acknowledgements

Ph.D. Jakob Kuttenkeuler, supervisor, for useful discussions, great commitment and admirable accessibility.
Mats Feldtmann, FMV, for supplying me with an interesting thesis assignment.
Magnus Eriksson, FMV, for always helping me with Visby related question.
Karl Garme and Anders Rosén, Division of Naval Systems, for constant backup with all kinds of issues.
Ph.D. Stefan Hallström, Division of Lightweight Structures, for support on lightweight construction matters.
References


Appendix A – Effect of twist on pressure distribution

Twist is varied in the vortex lattice theory model and the resulting pressure distribution is analysed. Geometry input is the horizontal part of the T-foil at 40 knots and the flap angle is set to zero. Chord wise pressure distribution does not differ much for small twist angles, therefore are the total lift and drag as well as the span wise force per meter evaluated for different twist angles.

![Graph of Lift vs. Twist](image1)

![Graph of Drag vs. Twist](image2)

Figure 27. Lift as function of twist.

Figure 28. Drag as function of twist.

Drag is about 50 times smaller than lift and operates in a direction in which the foil can take great loads. Thus, drag is neglected because it is not a constructional problem. The values for $\alpha = 5^\circ$ are not as important as the one for $\alpha = 10^\circ$, since the loads are much smaller. A limit of 10% difference from the untwisted lift at $\alpha = 10^\circ$ results in a maximum twist of 3 degrees.

![Span load graph](image3)

Figure 29. Span load [N/m] at $\alpha = 10^\circ$, alternating twist: $0^\circ$ - $3^\circ$.

The span load increases 4% when twisted $2^\circ$. The corresponding value two meters from the middle is 10%. Thus, a maximum twist of $2^\circ$ is allowed for an accuracy of 10%.
Appendix B – T-joint efficiency

Requirements in the T-joint area are estimated using a reference report “T-joints in Sandwich Structures” [6]. It is assumed that the strain in the lamina of the horizontal foil is connected to the ultimate load of the T-joint. Failure loads for different T-joints in the reference report are studied and related to the T-foil configuration.

**Symmetric load**

Calculation of strains for test specimens with symmetric loads are made based on the deflection at the mid point. These calculations assume radial deflection, no shear and that all of the displacement given in the report is for the horizontal part of the specimen. Strains are calculated from given deflections, $dx$ according to:

a) $r$ is solved from $(r - dx)^2 + \left(\frac{L}{2}\right)^2 = r^2$, $L =$ length of specimen

b) Lamina radius, $R = r \pm \frac{l}{2}$

c) New length of lamina, $l = \frac{2\varphi}{360} \cdot 2\pi R$

where $\varphi = \arcsin\left(\frac{L}{2r}\right)$

d) Strain in lamina, $\varepsilon = \frac{l}{L} - 1$

![Figure 30. Definitions.](image_url)

<table>
<thead>
<tr>
<th>Specimen</th>
<th>$\varepsilon_t$</th>
<th>$\varepsilon_c$</th>
<th>$\varepsilon_{t,\text{ult}}$</th>
<th>$\varepsilon_{c,\text{ult}}$</th>
<th>$\frac{\varepsilon_t}{\varepsilon_{t,\text{ult}}}$</th>
<th>$\frac{\varepsilon_c}{\varepsilon_{c,\text{ult}}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0062</td>
<td>0.00148</td>
<td>0.028</td>
<td>0.015</td>
<td>0.22</td>
<td>0.10</td>
</tr>
<tr>
<td>2</td>
<td>0.0093</td>
<td>0.00630</td>
<td>0.028</td>
<td>0.015</td>
<td>0.33</td>
<td>0.42</td>
</tr>
<tr>
<td>3</td>
<td>0.0189</td>
<td>0.00916</td>
<td>0.028</td>
<td>0.015</td>
<td>0.68</td>
<td>0.61</td>
</tr>
<tr>
<td>4</td>
<td>0.0182</td>
<td>0.00903</td>
<td>0.028</td>
<td>0.015</td>
<td>0.65</td>
<td>0.60</td>
</tr>
<tr>
<td>6</td>
<td>0.0073</td>
<td>0.00093</td>
<td>0.015</td>
<td>0.008</td>
<td>0.49</td>
<td>0.12</td>
</tr>
<tr>
<td>7</td>
<td>0.0182</td>
<td>0.00903</td>
<td>0.028</td>
<td>0.015</td>
<td>0.65</td>
<td>0.60</td>
</tr>
</tbody>
</table>

Table 19. Results from calculations of ultimate strains [6]. Note that specimen no. 5 is not included since the mix of fibre types results in an ultimate strain that is not known.

The results in table 19 shows that the T-joint broke at a strain of 10 to 65 % of the ultimate strain for the lamina. Note that it is assumed that specimen 1 failed because of tension at 22% of the ultimate strain.

There are several differences between the T-joints in the reference report and the T-foil. The ones in Rosander’s report must be possible to laminate on top of the inside of the hull. Special arrangements considering strengthening of the hull is not possible. The T-foil is considered as a one-off project and special arrangements that increase the performance of the T-joint are many. The conclusion is drawn that it should not be a problem to increase the performance of
the T-foil joint with two times what the joints in the reference report perform. Thus, 40% of the ultimate strain will be allowed in the connecting laminas.

![Figure 31: Principal sketch of reference T-joint to the left [6] and joint on T-foil to the right.](image)

**Anti symmetric load**

The anti symmetric load set-up in the reference report are difficult to compare with the T-foil. Therefore, another way of estimating the ultimate load for the anti symmetric case is established. The symmetric and the anti symmetric set-ups in the reference report are compared and then applying the relationship on the T-foil.

A correction factor has to be calculated to make the two set-ups comparable regarding geometry. Studying failure modes of the specimens in Rosander’s report leads to the assumption that torque and force have an equal effect on the ultimate load for the T-joint. The torque acting on the joint is proportional to the width, b. This is not the case for the drag/compression force acting on the joint, which is independent of the width. To make both testses comparable the anti symmetric load should be multiplied with $0.5P_{\text{sym}}/P_{\text{antisym}} = 0.42/0.30 = 1.4$. This is if only torque caused the failure in the joint. However, the drag/compression force affects the joint as well and this force needs no correction factor since it is not dependent on the width. Hence, the resulting factor is $k = (1*1+1*1.4)/2 = 1.2$.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>$P_{\text{SYM}}$ [kN]</th>
<th>$P_{\text{antisym}}$ [kN]</th>
<th>$1.2 \times P_{\text{antisym}}/P_{\text{sym}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 – F</td>
<td>10.2</td>
<td>5.1</td>
<td>0.60</td>
</tr>
<tr>
<td>2 – D</td>
<td>10.5</td>
<td>9.1</td>
<td>1.04</td>
</tr>
<tr>
<td>3 – E</td>
<td>12.0</td>
<td>8.3</td>
<td>0.83</td>
</tr>
<tr>
<td>7 – C</td>
<td>14.8</td>
<td>5.8</td>
<td>0.47</td>
</tr>
</tbody>
</table>

Table 20. *Comparison between symmetric and anti symmetric set-ups [6].*

The lowest ratio between anti symmetric and symmetric forces is 0.47 as shown in table 20. This means that it only took about half the load to break the joint in the anti symmetric load set-up compared to the symmetric. It must be remembered that these values are adjusted and are only valid for the particular series that has been compared. Expecting a similar behaviour in the T-foil joint implies that the T-joint can take twice as much load in the symmetric case as in the anti symmetric. If the maximum lift is denoted L in a symmetric load case for the T-foil, the maximum lift in the anti symmetric load case will be L/2. Therefore, it is assumed that anti symmetric load case is not a problem if the joint can hold for the symmetric load.

**Conclusion**

The conclusion is that the strain close to the T-joint is not allowed to be over 40% of the ultimate strain.
Appendix C – Tip plates

Tip plates are evaluated with a simple test using vortex lattice theory. Starting with the 6 m² foil without winglets that is established earlier, and then increasing the size of the winglet at constant lift, AR and angle of attack. Induced drag is compared for different sizes of winglets. It should be noted that the test does not consider the influence of skin friction or form drag.

As shown in figure 33 it takes about 8% height of the winglet compared to wingspan for a 10% decrease of induced drag. Assuming that the T-foil increases the total ship resistance with one percent, the decrease in total resistance is about one per mille.
Appendix D – Panels in Vortex lattice model

A simple model is applied to evaluate the number of panels that should be used to calculate the pressure distribution. The variation of induced lift and drag is calculated for different number of panels and the convergence is studied. Calculations are made for the horizontal foil without flap at constant speed and constant angle of attack.

As seen in figure 34, the result of the vortex lattice theory model had little difference even with a small number of panels. Using $8 \times 8$ panels on the foil results in a difference of 0.5% in drag and 3% in lift of respectively convergence value. This is accurate enough and has a reasonable solving time and is therefore used in the vortex lattice theory model.
Appendix E – Hinge force compensation

The force compensating the fact that the flap is modelled horizontally in the finite element model is calculated. A simple estimation of the force uses the horizontal component of the total pressure acting on the flap.

![Figure 35. Force components on flap.](image)

Total pressure on flap, $P_f = 118$ kPa, load case L1.
Area of flap, $A = 1.44 \text{ m}^2$

→ Force on flap, $F_f = 118 \text{ kPa} \times 1.44 \text{ m}^2 = 170 \text{ kN}$

Horizontal component, $F_h = \cos(70) \times 170 \text{ kN} = 58 \text{ kN}$
Vertical component, $F_v = \cos(30) \times 170 \text{ kN} = 147 \text{ kN}$

It is assumed that the horizontal component is distributed on the hinges as $\frac{1}{4}$ on each tip hinge and $\frac{1}{2}$ on the hinge in the middle:

Hinge in the middle: $F = 0.5 \times 58 \text{ kN} = 29 \text{ kN}$
Hinges on tip: $F = 0.25 \times 58 \text{ kN} = 14.5 \text{ kN}$

The vertical component is not adjusted. Consequently, conservative forces will be applied in the vertical direction, i.e. 170 kN instead of 147 kN.
Appendix F – Flap/foil deflection, strain requirement

Flap and foil deflection results in strain in the laminas. An estimation of the strain is based on the deflection at the midpoint. Assumptions are radial deflection and no shear. Strain is calculated using the following method:

a) \( r \) is calculated from \( \left( r - dx \right)^2 + \left( \frac{L}{2} \right)^2 = r^2 \), where \( L \) = length of part

b) Lamina radius, \( R = r \pm \frac{t}{2} \), where \( t \) = profile thickness

c) New length of lamina, \( l = \frac{2\varphi}{360} \frac{2\pi R}{2} \)

where \( \varphi = \arcsin \left( \frac{L}{2r} \right) \)

d) Strain in lamina, \( \varepsilon = \frac{l}{L} - 1 \)

Flap

Input: \( L = 2.4 \) m and \( t = 0.06 \) m
\( dx \) is varied and a deflection of 30 mm at the midpoint between the hinges results in \( \varepsilon = 0.0017 \) in tension.

Foil

Input: \( L = 4.8 \) m and \( t = 0.075 \) m
\( dx \) is varied and a deflection of 70 mm at the tip results in \( \varepsilon = 0.0015 \) in tension.
Appendix G—Appendage resistance, semi empirical method

Holtrop & Mennen’s semi empirical method is employed to estimate the added drag of the T-foil [17]. The appendage resistance is determined from:

\[
R_{APP} = 0.5 \rho V^2 S_{APP} (1 + k_2)^2 C_F
\]

where

\[
\rho = \text{Density of water, 1025 kg/m}^3
\]
\[
V = \text{Ship speed, 18 m/s (35 knots)}
\]
\[
L = \text{Typical length, 1.5 m}
\]
\[
S_{APP} = \text{Wetted area, } 2 \times (1 \times 1.5) + 2 \times 6 = 15 \text{ m}^2
\]
\[
C_F = \frac{0.075}{(\log_{10} \text{Re} - 2)^3} = 2.61 \times 10^{-3}
\]
\[
\text{Re} = \frac{V L}{\nu} = 22.7 \times 10^{-6}
\]
\[
\nu = 1.19 \times 10^{-6}
\]
\[
1 + k_2 = \text{Coefficient as given in table:}
\]

<table>
<thead>
<tr>
<th>Approximate 1 + (k_2) values</th>
</tr>
</thead>
<tbody>
<tr>
<td>rudder behind skeg</td>
</tr>
<tr>
<td>rudder behind stern</td>
</tr>
<tr>
<td>twin-screw balance rudders</td>
</tr>
<tr>
<td>shaft brackets</td>
</tr>
<tr>
<td>skeg</td>
</tr>
<tr>
<td>strut bossings</td>
</tr>
<tr>
<td>hull bossings</td>
</tr>
<tr>
<td>shafts</td>
</tr>
<tr>
<td>stabilizer fins</td>
</tr>
<tr>
<td>dome</td>
</tr>
<tr>
<td>bilge keel</td>
</tr>
</tbody>
</table>

The T-foil is best compared with stabilizer fins since they both act in a relatively undisturbed free stream, meaning that \(1 + k_2 = 2.8\).

Calculation of the resistance:

\[
R_{APP} = 0.5 \times 1025 \times 18^2 \times 15 \times 2.8 \times 2.6 \times 10^{-3} = 18.2 \text{ kN}
\]
Appendix H – Appendage resistance, vortex lattice theory

Calculations with the vortex lattice theory model results in an induced drag of 48 kN, for $\alpha = 9^\circ$ and $\gamma = 30^\circ$. This is the maximum value that is obtained. Assuming that the ship makes a sinusoidal movement in the waves would result in that the flap would also need to have a sinusoidal deflection. Consequently, induced drag assumes to vary as a sinus function.

![Figure 37. Absolute sinusoidal resistance.](image)

The average value of an absolute sinusoidal function:

$$\int_0^\pi \sin(x) \, dx = \left[ -\cos(x) \right]_0^\pi = -\cos(\pi) + \cos(0) = \frac{1 + 1}{\pi} = \frac{2}{\pi} = 0.64$$

The average value of resistance is $0.64 \times 48 \text{ kN} = 31 \text{ kN}$.

It should be noted that this estimation assumes that the T-foil has zero drag when flap is not deflected. This is not true, but the drag when the flap is deflected zero degrees is very small compared to the drag at thirty degrees.