ABSTRACT
A Ship collision accident represents a daily threat for vessels operating in dense traffic zones. The collision consequences may include loss of life or severe injuries if passengers are on board. The latter would be the case for ROPAX vessels, which are fairly dominant in the Baltic Sea connecting various member states. Furthermore, their routes tend to be in cross-traffic with the cargo vessels travelling through the full extent of the Baltic Sea. Therefore, it is of utmost importance to be able to assess the collision consequences for ROPAX vessels operating in the Baltic Sea with sufficient accuracy. This will result in an overview of possible damage scenarios for the actual traffic situation at a given location. As an example location the dense cross traffic between Helsinki and Tallinn will be analyzed and discussed.

The analysis procedure combines three steps: (1) determination of possible accidental scenarios based on traffic statistics; (2) assessment of the structural resistance of the colliding ship and (3) the evaluation of selected accidental scenarios using a time-efficient semi-analytical approach. The level of structural resistance of the chosen ships is assessed in a quasi-static manner using finite element method. This information is the basis for the calibration of a semi-analytical collision simulation model used to simulate large number of the accidental scenarios typical to the selected location. The presented results will be limited to the initial choice between vessels and dimensions, respectively masses, but the procedure can easily be extended to cover a vast amount of colliding vessels. However, the actual collision risk can be obtained using the presented results if the traffic along the vessels route is known.

INTRODUCTION
Dense maritime traffic zones present high collision risk for the operating vessels. In recent years approximately 20% of all serious and very serious accidents are collision accidents. The possible accidental scenarios should be identified and analyzed to reduce the risks. Therefore, accidental limit state analyses are of utmost importance, because the ship structures should be able to tolerate the service load at a reasonably safe level in the post-accidental condition. However, a ship collision accident can easily cause a limit state with undesirable damage and consequently loss of life and ship loss. Typically such collision accidents can occur under various collision scenarios, respectively ship types colliding, ship velocities and striking angles resulting in large number of scenarios to be assessed. Therefore, this paper presents methodology for the assessment of the collision damage under various scenarios in a fast and accurate manner combining numerical simulations with semi-analytical model. The presented assessment methodology is applied to simulate the collisions between a ROPAX vessel and an oil tanker both typical to the Gulf of Finland in the Baltic Sea.

First, the traffic in the Gulf of Finland is briefly analyzed in means of ship types, masses, operating velocities etc. Profound cross traffic where main shipping lines for the Ropax vessels cross with those of the tankers is identified as a typical traffic pattern. Properties of the typical ships meeting in these cross traffic zones are identified and the possible collision scenarios are assessed. Obviously, there exist a large number of possible combinations between the different types and sizes of the striking and struck ships. The analysis is here limited to a single collision pair between a ROPAX and a tanker as the paper aims to present the principal applicability of a methodology initiated in [1] and not a comprehensive risk analysis of the Gulf of
Finland. However, 75 collision scenarios are simulated for the selected ships studying the effect of collision velocity, angle and position of the contact point. The presented study does not consider the deformations of the striking ship and the forward speed of the struck ship. Assessing all these scenarios with non-linear finite element (FE) method would by extremely time-expensive. Presented assessment methodology requires only a single FE simulation and all the remaining scenarios are simulated with a semi-analytical approach.

The presented methodology differs from other simplified collision models, such as SIMCOL, DAMAGE or DTU model for example, as it requires FE simulations for calibration. This makes the approach more time expensive compared to other simplified models. On the other hand, the presented approach is not limited to a certain structural configurations and damage mechanism as several other models. Thus, the presented approach also allows to study the behavior of novel crashworthy structures in a variety of collision scenarios once their force-penetration curve is obtained for a single collision scenario.

Figure 1. Overview of the combined numerical and analytical collision damage assessment procedure

The structural resistance of the struck ship is evaluated in a single collision scenario using the current state of the art numerical collision simulation approach considering rupture of the shell plating according to [2]. The outcomes of this analysis are used to calibrate the fully dynamic semi-analytical collision model [3], which is used to evaluate the collisions scenarios constructed based on the traffic statistics. As a result, both methods will be linked through the numerically obtained force versus penetration curve in a combined procedure, see Figure 1. Thus being capable to analyze the energy available for structural deformations as well as the damage extend for various collision locations, striking angles and collision velocities. Compared to a fully coupled numerical simulation using the FE method this procedure is significantly less time consuming and results in low computational cost.

SCENARIO DESCRIPTION

The collision risk increases in dense traffic zones, especially if there is a profound cross traffic, see Figure 2. This cross traffic zone can be found between Helsinki and Tallinn in the Baltic Sea, where the passenger traffic between the two capitals is crossing with the eastbound and westbound oil and cargo traffic. The potential striking ships, primarily tankers, travel in East-West or West-East direction (Figure 3a), whereas the potential struck ships, primarily ROPAX vessels, travel in South-North or North-South direction (Figure 3b). Therefore, the presented procedure will concern collisions between a striking tanker and a struck ROPAX.
Traffic data for the area of interest was obtained from Automatic Identification System (AIS) recorded in July 2007. The data processing is described in detail in [4].

The tanker mass in the analysis was chosen to be 46 000 tons, which is the average mass of a tanker sailing through the crossing area analyzed in this paper, see Figure 4. The chosen mass may be interpreted as the upper end of the range of the typical tankers calling at Sköldvik harbor or approximately 36 000 DWT vessel.

Distribution of the operating velocities in E-W route is presented in Figure 5. The velocity data for tankers was obtained from processed AIS data by filtering the data according to ship type and route. The velocity of the ROPAX ship is disregarded in the analysis and the ship is considered motionless before the collision. This results in somewhat overestimated transverse extent of damage and underestimated longitudinal extent. Considering the velocity distribution in Figure 5, the possible collision scenarios are analyzed under the velocities 5, 7 and 9 m/s. These velocities present the upper and lower bound of typical velocity as well the average velocity.

The reference striking and struck vessel

In order to present the feasibility of the procedure a reference ROPAX vessel is chosen following the statistics presented in previous section together with one potential striking tanker. The main particulars for the ROPAX are: \( L=188.3 \text{ m}, B=28.7 \text{ m}, T=6 \text{ m}, C_b=0.63 \) and ice class 1AS. The scantlings are obtained from an actual new building; see Figure 6. Hence, the main particulars of the struck ROPAX vessel and the stricking tanker are given in Table 1.
A COMBINED NUMERICAL AND SEMI-ANALYTICAL COLLISION DAMAGE ASSESSMENT PROCEDURE

This chapter combines the research work according to [2] and [5] and introduces a combined numerical and semi-analytical procedure to assess ship collision damage. Hence, this combination will allow for an accurate estimation of the structural damage as well as the accurate estimation of the available energy for structural deformations for a given collision scenario. Furthermore, due to the fast semi-analytical computations and the reasonable extrapolation of the numerical results this procedure is computationally less expensive when compared to fully coupled simulations using FEM. Therefore, a nonlinear finite element method is only used once to simulate the ship collision for a pre-defined vessel struck at pre-selected vertical striking positions by a rigid indenter. Deformable indenter would yield to more accurate description of structural damage; the approach using the rigid indenter is conservative and presents the most unfavorable situation. This provides the force versus penetration curve, respectively the structural collision resistance. The analytical collision analysis is calibrated based on this structural collision resistance and estimates the change in available energy for structural deformation considering different longitudinal striking locations and angles. A principal definition of the collision event is presented in Figure 7 together with the main forces that act and the coordinate systems. Note that the $\beta$ describes the deviation from a right angle collision i.e. typical symmetrical collision is denoted by $\beta=0$.

### Table 1. Main dimensions of the ships used in the analysis

<table>
<thead>
<tr>
<th>Ship\Parameter</th>
<th>ROPAX</th>
<th>Tanker</th>
</tr>
</thead>
<tbody>
<tr>
<td>L [m]</td>
<td>188</td>
<td>190</td>
</tr>
<tr>
<td>B [m]</td>
<td>28.7</td>
<td>24</td>
</tr>
<tr>
<td>T [m]</td>
<td>6</td>
<td>12</td>
</tr>
<tr>
<td>$C_r$ [-]</td>
<td>0.62</td>
<td>0.8</td>
</tr>
<tr>
<td>Vol [m$^3$]</td>
<td>20 078</td>
<td>45 850</td>
</tr>
<tr>
<td>Mass [t]</td>
<td>20 178</td>
<td>46 082</td>
</tr>
<tr>
<td>kxx [m]</td>
<td>7.175</td>
<td>6.00</td>
</tr>
<tr>
<td>kyy [m]</td>
<td>47</td>
<td>47.50</td>
</tr>
<tr>
<td>kzz [m]</td>
<td>47</td>
<td>47.50</td>
</tr>
</tbody>
</table>

### 3.1 Quasi-static numerical collision simulation

The solver LS-DYNA version 971 is used for the collision simulations. A three dimensional model of the ROPAX vessel is built between two transverse bulkheads spaced at 26.25 m, see Figure 8, and the translational degrees of freedom are restricted at the plane of the bulkhead locations. The remaining edges are free.

Figure 6. Main frame of the struck ROPAX vessel

Figure 7. Definition of the collision event ($L_c$- eccentricity between the initial contact point and the origin of the coordinate system that locates at the centre of gravity of the ship, $\beta$- collision angle).

Figure 8. FEM model and striking location
The structure is modeled using quadrilateral Belytschko-Lin-Tsay shell elements with four nodes and 5 integration points through their thickness. The characteristic element-length in the contact region is 50 mm to account for the non-linear structural deformations, such as buckling and folding. The element length dependent material relation and failure criterion according to [2] is utilized for the simulations; see Figure 9. A comparison discussing the applicability and influence of this material relationship including failure for collision simulations is presented in [6]. Standard LS-DYNA hourglass control and automatic single surface contact (friction coefficient of 0.3) is used for the simulations. The collision simulations are displacement-controlled. The rigid bow, see Figure 10, is moved into the ship side structure at a constant velocity of 10 m/s. This velocity is reasonably low so as not to cause inertia effects resulting from the ships’ masses, see [7]. Furthermore, the rigid indenter results in the maximum energy absorption of the side structure alone, which is needed for a comparison and can be considered conservative and thereby suitable for a fast prediction. The resulting force versus penetration curve is shown in Figure 14 with thin line. The structural damage at the initiation of tearing of outer hull and of inner hull is shown in Figure 11.

Figure 9. Strain versus stress relation for mild steel (a) and failure strain versus element length (b) [2]

Figure 10. Rigid intender, respectively bow

2.3 Dynamic semi-analytical collision simulation
The procedure presented above is computationally expensive and thus, not always applicable to study a large number of collision scenarios. Here we present an approach that benefits from the numerical simulations and can be applied to simulate a large number of scenarios. The approach is based on a semi-analytical collision simulation model [2, 3]. This semi-analytical simulation model uses a simplified approach to evaluate the structural resistance in ship collisions. Each element of the penetrating bow in contact with the struck ship is subjected to a certain surface traction. The total contact force in collision is evaluated by integrating the normal and tangential surface tractions, $p$ and $q$, over the whole contact surface $S^*$ (see also Figure 12):
\[
\mathbf{F}_C = \mathbf{F}_p^d + \mathbf{F}_q^d = \int_{\mathcal{S}^*} p \mathbf{n}_q^d dS^* + \int_{\mathcal{S}^*} q \mathbf{\lambda}_q^d dS^* = \\
\int_{\mathcal{S}^*} p \mathbf{n}_q^d dS^* + \int_{\mathcal{S}^*} \mu p \mathbf{\lambda}_q^d dS^* = p \int_{\mathcal{S}^*} (\mathbf{n}_q^d + \mu q \mathbf{\lambda}_q^d) dS
\] (1)

Elaborate derivation of the above equations is presented in [3].

The surface tractions \( p \) and \( q \) describe the structural resistance the penetrating bow experiences on its surface. These obviously depend on the structural configuration of the struck ship and on the relative position between the ships i.e. on the penetration depth. This dependence can be calibrated by looking at the numerically evaluated force-penetration curve. Only the normal traction is to be calibrated due to the assumed proportionality between the traction components in eq. (1). The value of traction \( p \) and its variation as a function of penetration has to assure that the semi-analytical simulation model considers a similar force-penetration curve as evaluated in numerical simulations.

Traction that changes as depicted in Figure 13 results in force-penetration curve shown with a bold line in Figure 14. Figure 13 also presents the penetration depths at which the outer and inner plating is breached in FE simulations. Initially the traction \( p \) is constant (line AB) and the total contact force increases as a function of increasing contact surface. Just before the tearing of the outer plating the resistance drops significantly (line BC). The traction remains constant at relatively low value (CD) until the penetrating bow contacts with the inner hull (DE) that locates at 6.05 m from the outer hull. The inner hull presents significant resistance until it’s tearing (FG) after which the resistance gain drops to relatively low level (GH).

The distance at which the traction value changes due to the tearing of the plating has about 0.5m shift compared to the distances to breach the plating in numerical simulations. When the plating is thorn open its resistance reduces rapidly not only at the regions immediately around the tearing zone, but also in the adjacent regions. The shift is necessary to simulate the reduction of resistance in wider area over the penetrating bulb.

In Figure 15 the deformation energy-penetration curve obtained by semi-analytical approach is compared to that obtained numerically.
To assess the calibrated semi-analytical model, the energy-penetration curves are evaluated for 45 deg and 30 deg angle collisions. The comparison in Figures 16 and 17 reveals good agreement between the two methods. Thus, the semi-analytical model that is calibrated in a right angle collision is capable of simulating the structural response in oblique angle collisions. In oblique angle collisions the inner hull is breached at 6.7 m of transverse penetration in 30 deg angle collision and at 6.6 m at 45 deg collision. It is interesting to note, that the transverse penetration depth required to breach the inner hull is only slightly affected by the collision angle.

3. RESULTS OF SEMI-ANALYTICAL APPROACH

The semi-analytical model is applied to assess the accidental damage in collision scenarios defined above. Effect of collision velocity, angle and eccentricity of the contact point is studied. The collision angle $\beta$ and eccentricity $L_C$ are defined in Figure 7. The results of the coupled numerical and analytical collision damage procedure are presented in Figures 18 and 19. The Figure 18 reveals the effect of the collision angle and velocity. The collision velocity obviously has a significant effect on the deformation energy $E_D$ and for the extent of damage. In case of the collisions at amidships (Figure 18), the inner hull of the ROPAX is penetrated even with the lowest velocity collision. Only in the collisions under 45 and -45 deg, the inner hull remains intact. Oblique angle collisions excite ship motions and thereby reduce the available deformation energy. As expected the longitudinal penetration is largest in the case of collisions under large angles. The eccentricity of the contact point reduces the deformation energy and the transverse penetration, but increases the longitudinal penetration, see Figure 19. Knowing the damage lengths at different eccentricities helps to assess whether a certain scenario will damage more than a single watertight compartment.

As the inner hull is penetrated in the majority of the collision scenarios, it can be concluded that a possible collision between a ROPAX and a tanker would in the studied region would result in major damage and flooding of the ROPAX ship.
Figure 18. Influence of striking angle and collision velocity on deformation energy and on the extent of transverse and longitudinal penetration \((L_c = 0)\)

Figure 19. Influence of striking location and collision velocity on deformation energy and on the extent of transverse and longitudinal penetration \((v_0 = \text{const} = 7 \, \text{m/s})\)
DISCUSSION AND CONCLUSIONS
A combined numerical and semi-analytical collision damage assessment procedure has been presented and applied to study possible collision scenarios between a ROPAX and a tanker typical to the Gulf of Finland in the Baltic Sea. While the numerical simulation using FE analysis did not describe any specific collision scenario, the simulations with semi-analytical models always reflect a certain scenario with defined ship masses, velocities, collision locations and striking angles. Thereby, the result is a scenario specific damage description through which this approach extends the information obtained with a single FE-simulation to actual collision scenarios. Thus, allowing, to detect possible critical scenarios and thereby to develop new safety measures, such as improved structural arrangements. The computational time for a FE-based damage assessment is usually several hours compared to less than three minutes for one semi-analytical simulation.

The presented method still suffers from several limitations. The assumption of rigid indenter does not consider the possible deformations of the striking ship. Inclusion of deformable striking ship would allow for more precise description of structural damage. The forward speed of the struck ship was motionless prior the collision, simplifying the collision scenarios considerably. The simplified model is capable of including the forward speed, but the effect of the forward speed on the traction-penetration curve is still to be studied and validated.

ACKNOWLEDGMENTS
This research work has been financially supported by the European Social Fund (grant agreement no. MJD110) and by Estonian Science Foundation (grant agreement ETF8718). This help is here kindly appreciated.

REFERENCES