Research Article

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Effect of pitting corrosion position to the strength of ship bottom plate in grounding incident

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Abstract: Pitting corrosion is the most common, dangerous, and destructive corrosion type in marine and offshore structures. This type of corrosion can reduce the strength of the ship plate, so investigating it using several numerical grounding scenarios is needed to determine the significant degradation of the strength of the structural plate. In this study, a finite element study was used to evaluate the influence of pitting corrosion location on the strength of the bottom plate ship in grounding simulation. This study simulated 14 scenarios using different pitting positions on the bottom plate. Finite element using explicit dynamic simulation in LS Dyna software was employed to evaluate the strength of the bottom plate on the ship. The output parameters, such as reaction force and plate deformation, were assessed to compare the grounding simulation results. The simulation indicates that the location of pitting corrosion will affect stress concentration, crack initiation, reaction force, and penetrating position when the crack nucleates. The result shows the critical position of the pit, which is located near the stress concentration ring (nearly 100 mm from the center of the plates) in the plain plates.

Keywords: pitting corrosion, finite element, grounding case, location of pitting, ship plate

1 Introduction

Grounding is an accident in the ship caused by hitting other objects in the sea. The grounding effect causes several accidents on the ship. Based on data from National Transportation Safety Committee (KNKT), between 2008 and 2021, Indonesia had 10 of 152 incident cases of Indonesian seawater grounding [1]. Another statistic of accidental ship reports in Europe shows that grounding had almost 13% of cases in 2014–2021 [2]. A grounded ship can lead to flow stuck in the shipping lane, while in the worst case, the ship structure will crack and causes causality.

Corrosion needs to be considered in maritime structure on operational. Ship bottom plates in ballast tanks exposed to seawater have chemicals and bacteria, which will increase the corrosion risk. The operational ballast tank is filled with seawater to increase ship stability under different loading conditions. Although the coating is applied on the double bottom structure to protect from corrosion, its effectivity in the double bottom will decrease due to time operations, which can lead to an increased corrosion rate [3]. The double bottom is a narrow area in the ship that is hard to maintain and inspect, increasing the corrosion risk. Based on the probability analysis, the maximum depth of corrosion in the double bottom structure can gain 2.8 mm [4]. Pitting corrosion is a local corrosion type in the metal structure. This kind of corrosion commonly has less reduced steel area than universal corrosion.

Previous research shows that pitting corrosion can reduce the strength plate in the ship hull construction when holding compression, bending, tension, and torsional load [5–7]. Local corrosion plates have a small influence on tensile and yield stress; in other cases, local corrosion significantly affects mechanical properties [8]. Corroded plates are calculated to predict the ultimate strength of the ship using the finite element method [9,10]. Pitting corrosion can reduce the ship’s strength, which is influenced by several factors such as the degree
of pitting corrosion, the shape of pitting, the number of pitting, distribution, location of pitting, and depth of pitting [11–14].

Grounding calculation has been studied in several variables, such as initial velocity, impactor dimension, and material [15–19]. The effect of corrosion in the ship grounding was calculated in uniform corrosion cases that can reduce the crashworthiness and internal energy during grounding cases [20,21]. In this study, another type of corrosion, i.e., pitting corrosion in the plate of the ship, was evaluated in the grounding scenario.

In this study, the pitting corrosion effect on the bottom plate ship was calculated in the grounding phenomenon using 14 scenarios. A numerical method of explicit dynamic LS Dyna software was used to investigate the grounding case under different locations of pitting corrosion. The pitting corrosion was investigated by stress distribution, crack nucleation, and reaction force. Therefore, reaction force and plate deformation were assessed on time grounding simulation. The grounding simulation must be calculated until the bottom plate cracks, so distribution stress and crack nucleation were considered in this study.

2 Materials and methods

2.1 Grounding scenario

Figure 1 shows the assembling of two parts to simulate grounding phenomena: impactor and bottom plate, which is simplified from the Alsos and Amdahl’s model experiment [22] but has additional corrosion in the plate. Dimensions of the impactor and plate in this study follow Alsos and Amdahl’s experiment [18] using a bottom plate of S235 with a dimension of 1,200 mm × 7,200 mm.

Commonly grounding simulation uses shell elements because a solid element is more expensive in the calculation. In this study, the solid element was applied to accommodate the pitting corrosion model; therefore, simplification was necessary to run this problem. Alsos and Amdahl’s model was simplified to reduce the number of elements [22]. Figure 2b shows that the constraint in the edge of the plate in this simulation substitutes the hollow structure of the element in Alsos’ experiment (Figure 2a). Another setting of this study was that the impactor utilized rigid elements with declining deforming effects.

\[ x_i(x_d, t) = x_i(x_d(\xi, \eta, \zeta)t) = \sum_{k=0}^{n} \Phi_j(\xi, \eta, \zeta)x_i^j(t). \quad (1) \]

Solid elements with an eight-node hexahedron mesh type were applied to transform the pin in the plate into an element, as shown in Figure 3. In solid elements, the coordinate of nodal \( x_i \) is described in Eq. (1), which is dependent on the time \( t \) [23]. The initial position of the node in parametric coordinate \( (\xi, \eta, \zeta) \) is represented in \( x_d \). The nodal coordinate is represented on \( x_i^j \), on the \( j \)th node and the \( i \)th direction. The shape function of an eight-node hexahedron is represented on \( \Phi_j \).

A coupling method was used to evaluate ship groundings, such as experiments and numerical methods. In experimental methods, the scale of the ship’s bottom
structure is struck by a grounding object, which is represented as an impactor \[19,21,22\]. While in finite element methods, fracture simulation is a common method. In previous studies, numerical methods commercial software is commonly used for calculating ship groundings, such as LS Dyna, Abaqus, and other non-linear software \[24–27\]. In this study, explicit simulation in LS Dyna was used to evaluate the strength of the bottom plate on the ship.

Contact is an interaction between two bodies consisting of the slave (which is represented as the impactor) and the master body (which is represented by the plate), while the slave element cannot penetrate the master element. The touching moment between the slave elements and master elements will evoke the contact force \[28\]. Figure 4 describes the contact between the rigid impactor and the flat plate, which complies with this simulation. $\delta$ represents the distance of impactor translation, which can be seen in Eq. (2). $u_z$ and $h$ are measured in the observation point in $\lambda$. $\lambda$ represents the distance from the center of the impactor. $u_z$ is the depth of plate deformation, and $h$ is the distance between a point in the radius of the impactor to the surface of the plate.

\[
\delta = u_z + h. \tag{2}
\]

Figure 3: Finite element modeling on grounding scenario.

Figure 4: Simulation contact scenario.

Figure 5: Drawing of position pit corrosion: (a) scenario A, (b) scenario B, (c) scenario C1–C6, and (d) scenario D1–D6.
2.2 Scenario of pitting corrosion location

Based on the previous research on scanning techniques, pitting corrosion in nature has a random position, size, and geometry [29–32]. Corrosion in nature grows in a yearly phenomenon on an irregular pattern. Some researchers use artificial pitting corrosion to represent corrosion from actual conditions [33–43]. Different types of pitting corrosion in artificial are cylindrical, hemispherical, and cone. Cylindrical pitting corrosion was applied to this simulation using a 10 mm diameter and 2.5 mm depth. The position of the pitting corrosion in this study was on the inner side of the plate, which was exposed to the ballast tank water. Positions on pitting corrosion varied, while other properties and settings were constant. Figure 1 shows the corrosion position in the plate to the impactor in each condition. Based on Figure 1, condition A was a plain plate that was made to validate this simulation to previous research. Another condition was in different distances and patterns.

The center of the plate was the grounding point in this study, so every pit referred to the center of the plate. In Figure 5, the distance is represented in mm. The scenario was grouped into four categories, scenario A was a plain plate, scenario B was a plate with a pit in the center, scenario C was a plate with four pits around the center of the plate, and scenario D was a plate with five pits, with four pits around the pit at the center of the plate. In Figure 5, every point represents the pit corrosion. In this study, distance pit corrosion spacing (s) in scenarios C and D consisted of 80–380 mm, which is described in Table 1.

This simulation has identical dimensions and geometry, while the pit scatters using a rectangular pattern that rotates

<table>
<thead>
<tr>
<th>Scenario code</th>
<th>Pit corrosion spacing (S), mm</th>
<th>Scenario code</th>
<th>Pit corrosion spacing (S), mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>—</td>
<td>C6</td>
<td>380</td>
</tr>
<tr>
<td>B</td>
<td>—</td>
<td>D1</td>
<td>80</td>
</tr>
<tr>
<td>C1</td>
<td>80</td>
<td>D2</td>
<td>140</td>
</tr>
<tr>
<td>C2</td>
<td>160</td>
<td>D3</td>
<td>200</td>
</tr>
<tr>
<td>C3</td>
<td>200</td>
<td>D4</td>
<td>260</td>
</tr>
<tr>
<td>C4</td>
<td>260</td>
<td>D5</td>
<td>320</td>
</tr>
<tr>
<td>C5</td>
<td>320</td>
<td>D6</td>
<td>380</td>
</tr>
</tbody>
</table>

**Table 1: Pit spacing description**

**Table 2: Material Properties of S235**

<table>
<thead>
<tr>
<th>Material property</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
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<td>kg/m³</td>
</tr>
<tr>
<td>Young’s modulus</td>
<td>210</td>
<td>GPa</td>
</tr>
<tr>
<td>Poisson ratio</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>Yield stress</td>
<td>235</td>
<td>MPa</td>
</tr>
<tr>
<td>Tan modulus</td>
<td>672</td>
<td>MPa</td>
</tr>
<tr>
<td>Beta</td>
<td>0.225</td>
<td></td>
</tr>
<tr>
<td>Strain rate C</td>
<td>500</td>
<td>s⁻¹</td>
</tr>
</tbody>
</table>

**Figure 6:** Comparison of reaction force between simulation and experiment.

**Figure 7:** Plate deformation comparison: (a) Alsos and Amdahl’s experiment and (b) scenario A (present study).
Figure 8: (Continued)
45 degrees are variable in this study. Although Alsos and Amdahl’s experiment [22] center of the plate is not at high risk of failure, several studies show that the center of the plate is the location of crack initiation [15]. So, an additional variable was added where pitting corrosion in the center of the plate was placed to evaluate the strength in the center of the plate.

2.3 Research variable

Table 2 describes the material properties of the bottom plate in this study [22,44–46]. Material of kinematic hardening was used to calculate this simulation which utilized Cowper–Symonds equation to calculate the dynamic non-linear effect [47]. To find the dynamic stress \(\sigma_d\) on the plastic kinematic, hardening is used in Eq. (3), while strain rate dependent is applied as \(\dot{\varepsilon}\), \(C\) and \(P\) are Cowper–Symonds strain rate parameters, and \(\sigma_s\) is static stress.

\[
\frac{\sigma_d}{\sigma_s} = 1 + \left(\frac{\dot{\varepsilon}}{C}\right)^p.
\]  

3 Benchmark test with experimental data

Currently, finite element analysis is more popular than experimental because it have more data capturing and requires lower costs. In the previous research on finite
Figure 9: (Continued)
element analysis of ship grounding, validation is needed to prove the simulation result [15,46,48,49]. The previous research by Alsos and Amdahl was used as a comparison to find the optimum analytical setting to validate this simulation [18]. The present study used scenario 1, which was a plain plate. Figure 6 shows that this study’s reaction force complies with the experiment.

The finite element method and experiment had different patterns in the 140 mm penetration. The finite element at 140 mm of penetration did not have any dip in the curve of reaction force. This situation was similar to that of the previous study, which used a numerical method that did not have a dip phenomenon [48].

Figure 7 shows that the crack and deformation of the ship’s bottom plate are validated in the previous experiment [22]. In this study, the ratio between the narrow and wide plates was 3–5. The simulation showed that the crack was in a similar position in the narrow area of the plate. This study proved that a simplified simulation model had less effect on the simulation result. Based on this condition, another variable was used in the analytical setting.

4 Results and discussion

Structure failure in the grounding was described on the crack of the plates. Analysis of the stress concentration and crack initiation described the grounding phenomenon. The stress of the bottom plate based on stress concentration

![Stress distribution after crack initiation:](image-url)
before crack nucleation (Figure 8) and locates of the crack initiate (Figure 9) was classified into four different types. This classification was based on the effect of the pit on stress concentration. Stress concentration was a method to predict the failure location of the structure where the location of stress concentration had a high probability of failure.

First, pit corrosion was not the location of the stress concentration factor. Based on Figure 8, the plain plate and the corrosion near the center of plates (scenarios A, B, C1, and D1) showed stress concentration before the crack nucleation created a ring. Scenarios A, B, C1, and D1 had a similar pattern of the ring stress concentration, which in the narrow plate has dominance compared to the wider side.

The next type is stress concentration in the pit corrosion, located in the inner ring of stress concentrations. Figure 8 shows this condition in scenarios C2 and D2, where the stress was concentrated in the four outer pit corrosion. In scenarios C2 and D2, stress concentration transformed from the ring of stress concentration into the pit. Although the stress concentration was depicted in the four pits corrosion, Figure 9 shows crack initiating only in a couple of the pits on the narrow side. Stress contour in conditions C3 and D3 showed pitting corrosion precisely in the ring of stress concentration. The four pits had stress concentration; therefore, nucleation started only in a couple of pits in the narrow plate.

In the last six scenarios (scenarios C4, D4, C5, D5, C6, and D6), the stress concentration expanded to the pit location up to 380 mm of the pit distance. In this situation, the stress concentration transformed only into a couple of pits on the narrow side. In this situation, the
stress concentration transformed into the pit, although it had a distant location of the pit into the ring of stress concentration.

All scenarios in this study described that plate’s strain caused the ship bottom plate’s failure. A pit in the center of the plate (scenarios B, D1, D2, D3, D4, D5, and D6) caused stress concentration, and a crack was initiated. This condition does not align with the previous research, in which the center of impact is the starting of crack nucleation [15]. This situation is caused by the round of the impactor, making stress concentration distribute to the area in the center of the plates.

The reaction force is commonly used to evaluate the effect of ship collision and grounding. Integrating the lower area of the reaction force to displacement is energy internal to the plate. Lower energy absorption indicates that the bottom ship plate is weaker on the grounding accident. Figure 10 shows that every scenario has an identical graph in the rising reaction force. However, they have a different location on a dip. An early reaction force dip indicates that lower energy is needed to break the bottom plate. This situation shows that the internal energy to deform the bottom plate is the same until before it cracks.

Based on the reaction force graph, the crack initiated by the reaction force started to decrease. Scenarios C3 and D3 were the weakest condition, which initiated a crack at 130 mm of penetration. Scenarios C3 and D3 had 200 mm of pit spacing. These scenarios indicate that the pit on the narrow side is the critical point in pitting corrosion. In another scenario, avoiding the critical point in pitting corrosion can increase the plate strength under collision load.

Figure 11 describes that pitting corrosion in the center of the plate has a small effect on reaction force, where a plate on a plate with pitting corrosion in the center of the plate earlier broke without pitting corrosion in the center. Pitting corrosion on the center of the plate made the plate slightly weaker on the grounding phenomenon. The simulation results comply with a study by Cerit that describes the pit as only sometimes a critical point in the structure [50].

5 Conclusion

The pitting corrosion location effect on the strength of the plate under the grounding effect was calculated in this study. Based on finite element methods, the grounding effect evaluated stress concentration, crack nucleation, reaction force graph, and penetration depth in crack nucleation. The stress concentration factor leads crack nucleation; this study has found that crack initiates on the narrow side of the plate although stress concentration is captured in both the narrow and wider sides of the plate.

A plain plate scenario created a ring of stress concentration under grounding simulation, leading to crack nucleation located about 100 mm from the center of the plates. In this study, the nearer location of the pitting to the ring of stress concentration in the plain plate weakened the plate in the grounding phenomenon, measured by stress concentration in crack nucleation, reaction force, and depth of penetration in the crack initiation. The nearest and farthest of the pit showed an insignificant effect.

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References


