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Stress analysis of the application of the diamond plate on the quad-joint connection: A case study on the flat plate hull of ships

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Abstract: The hull structure is a vital part of a ship that supports internal and external loads. Failure that often occurs in the hull structure is due to maximum stress at the meeting point of the hull plate arrangement. The purpose of this study is to analyse and optimize a certain design of the connection plate at the meeting point of the hull plate arrangement to reduce maximum stress. A diamond plate innovation was applied, which is a plate with a diamond shape that aims to reduce the maximum stress at a certain angle. The method of this study is finite element analysis modelling supported by metallographic data. As a comparison analysis, two external loading conditions were carried out, i.e., hogging and sagging conditions; furthermore, the variations of the diamond plate were also carried out to obtain the optimum dimensions. The results of this study show that the plate arrangement using a diamond plate can reduce the maximum stress under hogging and sagging conditions, reaching 37.2% and 33.1%, respectively.

Subjects: Structural Mechanical Engineering; Stress Analysis; Manufacturing Engineering Design

Keywords: Hull structure; maximum stress; diamond plate

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PUBLIC INTEREST STATEMENT

A flat plate hull ship is an alternative form of the ship since, in terms of construction, it can be mass-produced at a lower price because the production process does not require plate bending but is formed from a collection of plates that are put together to form a fairly simple ship. This study will compare the application of diamond plates at the connection of four plate meeting points using the FEM. The hull structure is an important part of a ship because it supports both internal and external loads. Maximum stress at the meeting point of the hull plate arrangement causes failure in the hull structure. By applying a diamond plate innovation which is a plate with a diamond shape at a certain angle, the maximum stress under hogging and sagging conditions can be reduced, reaching 37.2% and 33.1%, respectively.
1. Introduction

The shipyard industry is increasingly advanced and competitive to achieve optimum performance and cost. One of the most important parts of a ship is the hull structure (2008). The hull structure is mainly composed of plate arrangements and is supported by frames and stiffeners (Halikyard, 2005). Plate arrangement is also a critical part of an above-seawater building to support internal and external forces (2008). Internal forces consist of loads acting on the ship, namely hydrostatic loads and torsional loads (Eyres, 2007). External loads consist of wave loads and other loads (Guedes Soares & Duan, 2019). The hull structure is exposed to various forces when the hull is above the water, namely lateral pressure, transverse bending moment due to side forces and vertical shear forces in the cross-section (Jie Shi & Wei Gao, 2021). Due to the important role of the hull structure, there have been many studies related to the hull structure, including corrosion prevention (Zayed et al., 2018), fatigue avoidance (Gaidai et al., 2019), plate thickness and structure optimization, and shape enhancement (Putra & Kitamura, 2021; Putra et al., 2019).

Studies related to plate thickness have been carried out to optimize the number of stiffeners based on topological optimization (Jia et al., 2019; Zhang et al., 2021). Other researchers have previously optimized the amount of stiffener in slabs subjected to shear loads, which plays an important role in the design of the structure (Alinia, 2005). One researcher further presented an efficient and simple hybrid framework for buckling analysis and optimization of hierarchical rigid plates (Nonomi et al., 2014). The next researcher also optimized the stiffened plate using the calculation method to evaluate the strongest structure using the exact finite element method model (Ghasemzadeh & Kefai, 2022; Wang et al., 2015). More and more simulation studies using the finite element method (FEM) validated with experimental data are becoming increasingly popular to save time and costs (Paul, 2021).

From the existing literature, the research gap is related to the hull structure, especially regarding the emergence of maximum stress at the meeting point of the ship’s plate arrangement. However, there is still very little discussion about the structure of the hull, specifically the maximum stress at the plate meeting point. The purpose of this research is to analyse and optimize a certain design for the connection plate at the meeting point of the hull plate arrangement by applying diamond plate innovation to a certain angle plate arrangement. A case study used a ship with a hull arranged with flat plates, which is the result of previous research (Firdaus, 2013). This vessel is an alternative form of ship. This flat boat design, in terms of construction, can be mass-produced at a lower price because the production process does not require plate bending but is formed from a collection of data plates that are put together to form a fairly simple ship (Guswondo, 2009). This study will compare the application of diamond plates at the connection of four plate meeting points using the FEM. Two case studies of loading were carried out, namely, with hogging and sagging conditions, in addition to the estimation of diamond plate dimensions. The contribution of this research is the effectiveness of the use of diamond plates at the four meeting points of the hull plate arrangement. Also, the results of this study are useful as a study and reference material in the manufacturing of flat plate ships, especially regarding the problem of leaks and cracks in flat plate ship construction, and as a reference in the manufacture of flat plate ships with large dimensions.

2. Methodology

2.1. Research stages

The research was carried out in research stages, starting with literature studies, making flat plate ship models, data processing, and analysis and ending with drawing conclusions, as shown in Figure 1.

At the initial stage, data and sources were collected regarding flat plate ships and the main dimensions of the ship itself, as well as the characteristics of the materials used in the process of making flat plate ships. This literature study includes an explanation of the design of a flat plate
ship as a reference and explanations of the longitudinal strength of the ship, an explanation of the waves acting on the ship, FEM and the characteristics of the steel material used.

Material identification was also carried out to determine the characteristics of the materials used. In the process of making flat plate ships, the material used is ST 42 material, so all input materials used in the simulation process refer to that material. The modelling in this study was
carried out using commercial software. A flat plate ship model using CATIA V5R20 (yyyy, 2013) software was then imported into ANSYS student version (ANSYS Inc., Ansys Student Workbench-based Simulation Tools, n.d.) for calculations by entering material data from the results of material identification and testing, as well as existing literature data. The diamond plate model with variable dimensions and positions was carried out on flat plate ships with various dimensions and positions of diamond plates with the same loading so that the angle vs. stress graph was used as a benchmark. After obtaining the optimum dimensions and position, the diamond plate sample was applied to model a completely flat plate ship. Comparative analysis was carried out by comparing the results of modelling flat plate ships with and without diamond plates.

2.2. Prediction of the ship’s longitudinal strength

Many studies have been carried out to predict the longitudinal strength of steel vessels; some of these methods are based on different approaches, such as the Caldwell method (Caldwell, 1965), Smith method (Smith, 1977), FEM (Schellin & Perez de Lucas, 2004) and the structural unit idealisation method (Ueda & Roshed, 1984). For the structure of the flat plate ship made of ST 42 steel, an approach with the 3D structure method using the FEM was used. From the simulation results with the FEM method, the deformation and stress values that occur in the flat plate ship structure were obtained. To calculate the longitudinal strength of the ship, the ship’s data, especially the main dimensions, were used in making models and simulations, as well as the displacement or weight of the ship itself. Table 1 shows the ship’s particular data used in the case study.

The loading model used in this case is a primary hull girder load. This loading model assumes that the forces and moments originating from the effects of still water, waves and dynamic loads are considered local loads acting on the entire ship (Hirdaris et al., 2014). In these external loading models, loading is obtained from waves that produce buoyancy pressure on the hull of the ship. In addition to buoyancy, there are loadings due to the weight of the ship (displacement), which are in a state of full load or full capacity. The load conditions used in this process were sagging waves and hogging waves. In the sagging wave, the crest of the wave is at the ends of the ship, while in the hogging wave, the crest of the wave is in the middle of the ship (Watson, 2002).

2.3. Flat hull ship 3D models

Flat plate ship modelling and ship longitudinal strength calculations were carried out with the help of the ANSYS Workbench programme. For this purpose, the meshing process on the FEM is carried out to idealise the structure of the flat plate ship to be simulated. The flat plate ship model itself was made using CATIA V5R20 software with the Assembly Design model. The ship structure model consisted of 14 parts, all of which were divided into the ship’s frame. Each frame is 0.485 with the dimensions of the ship, as shown in Table 1.

Modelling of flat plate ships was carried out on all parts of flat plate ships by inputting the coordinates that were obtained into point form in CATIA V5R20 software. Then, a line was made to connect the points so that the shape of the ship was obtained. The X-coordinate axis in the model

| Ship Particulars | Plate hull ships |
|------------------|------------------|
| Ship Types       | Flat plate ships |
| Length overall (Loa) | 7.0 meter |
| Length perpendicular (Lpp) | 6.8 meter |
| Beam (B)         | 2.6 meter |
| Height (H)       | 1.2 meter |
| Draught (t)      | 0.8 meter |
Figure 2. Meshing result on entire flat plate ships.

was made in the direction of the ship's length, the Y-axis was the longitudinal direction of the ship, and the Z-axis was the horizontal direction of the ship.

After obtaining the shape of the ship, each area was given a surface and a thickness of 6 mm so that it became a completely flat plate ship. Then, the design that has been made is transferred to ANSYS 14 software. The meshing process uses solid elements of the hex-dominant type, but in some parts, the mesh forms tetrahedron solid elements. The meshing process was carried out by applying the fine type to the entire structure of the plating arrangement. The mesh is created with a node count of 265,945 and an element count of 132,379. Figure 2 shows the hull of the ship that has been meshed.

The boundary conditions used in the simulation of flat plate ships inhibit the movement of several nodes of the ship. To perform the simulation, the settings refer to the DNV classification regulations (GL, 2014). The node on the centerline located on frame 0 is fixed (GL, 2014). On the ship’s deck, the node on the centerline located on frame 0 was restrained from horizontal movement and in the front keel, the node on the centerline located on frame 13 was restrained from vertical movement. The other nodes were left free to move. The working load consists of the weight of the ship and the pressure caused by buoyancy. The distribution of ship weight and water pressure due to waves was applied to the ship’s frame as a line force.

2.4. Diamond plate models
In the design of a flat plate ship, a minimum of three coordinate points and one remaining coordinate point were determined to form a straight plane with the help of linear algebraic calculation methods.

The calculation of the straight plane plate produced five plane equations, and then one point was taken so that three coordinate points were obtained and the initial coordinates of the diamond plate were obtained. The coordinates were then made into an equation of the diamond plate plane and produced a point of intersection with the other planes. Thus, when the coordinates of the diamond plate were connected to the point of intersection, we obtained a diamond plate plane. Figure 3 shows the plane of the diamond plate. Where the value of a is part of the plane of plate 2, the value of b is part of the plane of plate 3, and the value of c is part of plate 4, provided that the values of a, b and c have been predetermined. The equation used to determine these points was a straight plane equation in linear algebra shown in equations 1 and 2.

\[
\mathbf{u} = \begin{pmatrix} i & j & k \\ a & b & c \\ a & b & c \end{pmatrix}
\]
The diamond plate was obtained from linear algebraic calculations that were done previously. The modelling was carried out several times by varying the internal angle formed between the intersection of the plate and the diamond plate. First, we hoped to find the interior angles in the sample to be as symmetrical as possible and then to vary the angle on the shortest axis of the diamond so that several different samples were obtained, which would then be analysed using ANSYS to get the stress value at the angle. There are four variations of the angle of the diamond plate used, namely $\alpha$, $\beta$, $\gamma$, $\theta$. An illustration of the four angles is shown in Figure 4, where ten angle parameters are used, ranging from 140–180 degrees.

After obtaining the optimum value, the angle on the long axis was then revariabled and analysed using ANSYS, so that later the optimum diamond plate position and dimensions were obtained on the flat plate vessel sample. All angles were variables and then analysed so that a table of analysis results could be obtained. From the table, a comparison graph was made. After obtaining the optimal dimensions and position estimates, the results obtained were then applied to flat plate ships.

The element used was a solid element with a hex-dominant type, but it formed a tetrahedron in some parts of the mesh. The meshing process was carried out by applying the fine type to the entire structure of the simulated flat plate ship. Meshing was performed in nodal counts between 17011 and 19166 and element counts between 9012 and 10348, depending on the model used and the angle in which the diamond plate was formed. The boundary conditions used in the simulation of the diamond plate sample were by inhibiting movement on all sides of the diamond plate. The load or force applied to this diamond plate sample used the load obtained from the calculation of the load distribution of the flat plate ship when the full load condition was on frame.

\[ \vec{v} = (x - a, y - b, z - c) \]
Figure 5. Variation of loading on diamond plates.

12, which was where the diamond plate was located. The load used was 15119.85 N. This load assumption was based on empirical calculations that consider the calculation of the weight of the empty ship and the calculation of the weight of the ship’s cargo being transported. This approach is realistic under standard ship loading analysis (Okumoto et al., n.d.). The sample diamond plate was given two different treatments by concentrating the load only on the diamond plate and by distributing the load throughout the plate around the diamond. The variation in the loading on the diamond plate is shown in Figure 5.

2.5. Boundary condition setting of the simulation models

The FEM simulation model in this study used the commercial software ANSYS 14. The purpose of this simulation is to analyse stress concentration or stress distribution and displacement in a certain shape and geometry. The FEM process consists of several stages, namely object modelling and meshing and determining element type, material properties, initial conditions and boundary conditions. From this, modelling can be carried out by analysing the type of loading and the results. The object modelling and meshing process consists of two parts: the ship model and the diamond plate model, as shown in Figure 6. The mesh of ship model was created with a node count of 265,945 and an element count of 132,379. Meshing of the diamond plate was performed in nodal counts between 17011 and 19166 and element counts between 9012 and 10348, depending on the model used and the angle in which the diamond plate is formed.

The boundary conditions used in the simulation of flat plate ships are by inhibiting the movement of several nodes of the ship. The following settings are used to perform the simulation: the settings use the reference to the DNV Classification Notes regulation No. 34.1 Section 6 (DNV, 2018). The boundary condition setting is shown in Figure 7 and Table 2. The node on the centre line located at frame 0 is fixed; on the ship’s deck, the node on the centre line located on frame 0 is restrained from horizontal movement; in the front keel, the node on the centre line located on
Frame 13 is restrained from vertical movement. The other nodes are left free to move. The working load consists of the ship’s weight and the pressure caused by buoyancy. The distribution of ship weight and water pressure due to waves is applied to the ship’s frame as a line force.

The material used in the flat plate ship simulation model is Steel ST 42 which refers to ASTM A572 Steel grade 42 (MatWeb, n.d.). The mechanical properties of the materials used as input parameters in the FEM simulation process refer to the material properties shown in Table 3.

The simulation was carried out under static conditions. However, the loading given to the ship is considered static and dynamic. The static load is the weight of the ship’s construction and the upward force of the water. Meanwhile, the dynamic loads used were the sagging load and the hogging condition.

### 2.6. Verification and Validation

To ensure that the simulation results provided valid results, two stages were carried out, namely by verifying and validating the FEM simulation results. The first stage was verification of the simulation model using the grid independence test to ensure that the number of meshes used gave consistent results. The results of the grid independence test in this FEM simulation are shown in Figure 8. From these results, the mesh used in this simulation was a fine mesh with a mesh count of 17,011, where the independence test graph shows that the maximum stress result was
constant and that there was no significant change. Based on these results, it can be ascertained that the number of meshes used was appropriate.

To validate the result of the simulation models, experimentation was carried using the tensile test methods, in detail, the experimental setup is not described in this paper. The tensile test method has been carried out on the cut section of the diamond plate with the same material and geometry as the simulation conditions. The results of the validation between the FEM simulation and the experiment are shown in Figure 9. From the comparison results, it can be said that the simulation results are in good agreement with the experimental results. Although the FEM simulation results could not capture the yield strength value in the simulation results, the trendline simulation results showed appropriate results.

3. Results and discussion

3.1. Longitudinal strength analysis

The distribution of the longitudinal strength of the ship’s weight and buoyancy originating from the sagging and hogging waves results in the distribution of vertical shear forces and vertical bending moments. The longitudinal strength curve for the hogging condition is shown in Figure 10, while the longitudinal strength curve for the slack condition is shown in Figure 11. The hogging wave coordinates used the Hanske wave coefficient. The wave worked on a full load of 10,871 tonnes so
that the hogging wave was at a water level of 0.70 m, while the sagging wave was at a water level of 0.59 m. The biggest bending moment in the hogging condition was at frame 7, with a value of 1.11 tonne.m or 10.95 kN.m. Meanwhile, in the sagging condition, the largest moment value was in frame 9, with a value of −2.90 tonne.m or −28.42 kN.m.

From the FEM simulation process carried out, the simulation using the hogging wave produced a higher stress concentration than that produced by the sagging wave. This was caused by the difference in the received force and the vertical bending moment between the sagging and hogging conditions, especially in frame 6, where the diamond plate was located. These results are consistent with several other studies, which state that sagging and hogging moments cause the midship portion of spanning ships to experience structural failure (Ardianti et al., 2021; Jafaryeganeh et al., 2021; Windyandari et al., 2022).

The maximum stress that occurs on flat plate ships when hogging conditions occur at the meeting of four plates on frame 9 is shown in Figure 12; this indicates the occurrence of stress
concentration in that area. As for the stress concentration point, the sample was the meeting of four plates that occurred at frame 12. From the results of the meeting of the four plates, it is known that the stress value that occurred on the outside was 215.61 MPa, while for the inside it was 115.55 MPa.

3.2. Estimation result of dimension variation of the diamond plate

The load was given to the sample diamond plate on a flat plate ship by varying the angles in the diamond plate. The simulation results obtained a comparison graph between angle stress. Figure 13 shows the angle sizes in the alpha-beta and gamma-theta used, along with the stresses that occur in the first case. In the first case, it was done by giving a concentrated load only on the diamond plate, which was applied to several diamond plate samples with different interior angles. From the graph, the optimum alpha-beta angle was around 150.8° for alpha and 149.4° for beta. From the graph, the optimum gamma-theta angle was around 169.1° for gamma and 167.9° for theta.

A case study was also conducted for the second case. The treatment in this second case was carried out by placing the same load on the diamond plate and all the plates around the diamond plate and applying it to several diamond plates samples with different interior angles. For this second treatment, the shape of the sample generated from the angle variable itself influenced the results. Because the load is given to the entire plate, the slightest change in the shape of the sample in any area will affect the results. The simulation results obtained are shown in Figure 14. From the graph, the optimum alpha-beta angle was around 151.5° for alpha and 149.5° for beta. From the graph, the optimum gamma-theta angle was around 168.6° for gamma and 168.2° for theta.

3.3. Analysis result of the application of the diamond plate

From the overall simulation results in determining the dimensions and position of the diamond plate, the position of the diamond plate was placed at each meeting of the four plates, which was...
a stress concentration with dimensions between 8 and 10 cm, depending on the angle in which the diamond plate was formed. In this simulation, almost the same results were obtained for both the first and second treatments, where the optimum angles formed were nearly symmetrical. This confirms that the diamond plate can be formed at the junction of four plates with as symmetrical inner angles as possible so that its use is optimal.

The maximum stress occurs on the flat plate ship when the hogging condition occurs at the meeting of the four plates in frame 12. From the simulation results above, it is known that the stress value that occurs on the diamond plate in the hogging condition was 72.52 MPa for the alpha angle, 62.70 MPa for the beta angle, 65.44 MPa for the gamma angle, and 66.93 MPa for the theta angle. The maximum stress that occurs on the flat plate ship when in the sagging condition occurs at the meeting of the four plates in frame 4. From the simulation results, it is known that the stress value that occurs on the diamond plate in the sagging condition was 55.01 MPa for the alpha angle, 42.39 MPa for the beta angle, 45.28 MPa for the gamma angle, and 62.88 MPa for the theta angle. The results of the von Mises stress simulation from the application of a diamond plate on a flat plate ship can be seen in Figure 15.

Table 4 shows the comparison of the maximum stress on a flat plate ship with the application of a diamond plate and without a diamond plate. The stress value on the diamond plate for both sagging and hogging wave conditions was smaller than the stress value on a flat plate ship without a diamond.
plate. The maximum stress value obtained at the angle of the flat plate vessel at the sample point for the sagging wave was 94.084 MPa and 115.55 MPa for the hogging wave, while for the flat plate vessel with diamond plate, the maximum stress value for the sagging wave was 62.88 MPa and for the hogging wave was 62.88 MPa. The 72.52 MPa. The decrease in the maximum stress value due to the application of the diamond plate can reach 37.24% in the hogging condition and 36.38% in the sagging condition. This is because the stress caused by the gravity of the ship and the sagging waves on flat plate ships are distributed over the entire surface of the diamond plate, in contrast to flat plate ships, where the stress is concentrated at one point. One of the implications of this finding is that to avoid structural failures on ships, especially ships with flat plate hulls such as on barges, diamond plates can be applied to quad joint connections. During sagging and hogging conditions, the maximum stress in the midship section can decrease up to 36.4% (Salazar-Dominguez et al., 2021); by applying a diamond plate, these stress values can prevent overcoming the yield strength of the hull material.

4. Conclusion
Analysis of the maximum stress reduction at the junction of the four points of the flat plate was carried out using FEM modelling. From the results, it can be concluded that the dimensions and optimum position of the diamond plate are obtained by making the inner corner of the diamond plate as symmetrical as possible, with a diameter ranging from 6 cm to 10 cm, depending on the angle in the shape of the diamond plate itself. The maximum stress value obtained at the angle of the flat plate vessel at the sample point for the sagging wave was 94.084 MPa and for the hogging wave was 115.55 MPa, while for the flat plate vessel with a diamond plate, the maximum stress value for the sagging wave was 62.88 MPa and for the hogging wave was 62.88 MPa. 72.52 MPa diamond plates can reduce the stress value at the meeting of four plates by 33.17% in the sagging wave and 36.38% in the hogging wave.

The maximum normal stresses and von Mises stress of the application of diamond plate on the flat hull ship might be ascertained using the approach suggested for structural analysis. Future research projects can simulate a flat hull ship applied with a diamond plate using non-linear FEM techniques. From this research, future research directions in this field include the analysis of the use of homogeneous materials due to the welding process, as well as the value of the strength of the ship at the four connection points.

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Table 4. Comparison results of the von Mises stress

| Load Conditions       | Hogging   | Sagging   |
|-----------------------|-----------|-----------|
| Without Diamond Plate | 115.55 MPa| 98.84 MPa |
| Using Diamond Plate   | 72.52 MPa | 62.88 MPa |

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