FAILURE ANALYSIS OF HIGH-PERFORMANCE SURFACES USED FOR TRANSVERSAL STABILITY OF SHIPS (BILGE KEELS)

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ABSTRACT

During a scheduled maintenance program of a ship, several cracks were detected in the internal structure of bilge keels, as well as on the connection of these to the hull. The cracks encountered compromised the watertight integrity of the hull and, in the long run, could jeopardize its integrity.
This paper presents a failure analysis of the structural damages detected, in order to identify the causes of failure and propose improvements that could avoid them. Several stress concentration areas were identified, which coincided with the critical areas where there have been found the structural failures. It was confirmed the reinforcements (stiffeners) influence in the increased levels of stress in the welded joints of the bilge keels to the hull.
Alternative design geometries for the bilge keel internal structure are presented as well as it is shown that the application of brackets or a bulb flat on the connection of the bilge keels to the hull can reduce the high level of tensile stresses that are induced in the structure.
The fatigue analysis according to the *Germanischer Lloyd* Classification Society is applied to the new structural internal geometry and is presented on this paper.

KEY WORDS: Bilge Keels, Structural Failures, Failure Analysis, Improved Design Arrangement, Finite Element Analysis.

1. INTRODUCTION

The hydrodynamic resistance of a ship to roll motion can be increased through passive and/or active stabilizers. Encased in the passive roll stabilizers are the bilge keels under study, which, in addition to attenuate the roll motion, present a low manufacturing cost, compared with the cost associated with the manufacture of active stability systems.

In essence, bilge keels are hull appendices, applied approximately at half length of the ship, on both sides of the hull, which transform the vessel's motion kinetic energy into fluid motion, especially under the form of vortex shedding [1]. Their efficiency depends on their location, size and shape [1]. The bilge keels studied and presented in this article have a triangular, or "V", arrangement as shown in Figure 1.

The bilge keel in study is built in D36 steel, characterized by the chemical composition and mechanical properties referred in Table 1 and 2 [2], respectively. The steel, furnished in the normalized condition, possesses good weldability and low harden effect after welding, due to the low probability of martensitic transformation during cooling [2].

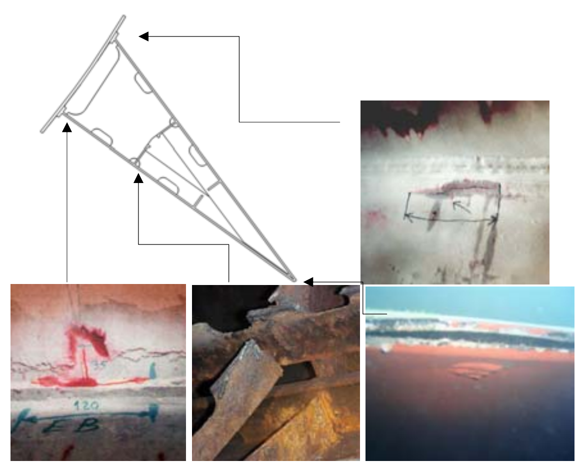


Figure 1. Cross section view of the bilge keel with a "V" arrangement studied. Examples of cracks detected.

.Table 1. Chemical composition of D36 naval steel grade type [2].

C [%]	Si[%]	Mn [%]	P [%]	S [%]	Al [%]
0.18	0.5	≥0.7	0.035	0.035	≥0.02

Table 2. Mechanical Properties of D36 naval steel grade type used in the bilge keels manufacture [2].

Yield Strength [MPa]	Tensile Strength [MPa]	Elongation [%]
≥355	490-620	≥21

The connection to the hull is performed through a doubler plate (Figure 2), where a full welding penetration without any intermittent fillet welds is imposed. The doubler plate connection to the hull is often encountered in marine structures, not only due to its easiness in production, because it provides a faster and easier way to perform the alignment of the bilge keel over the hull structure, but also represents an excellent configuration to avoid multi-axial stress states at the connection to the hull [1].

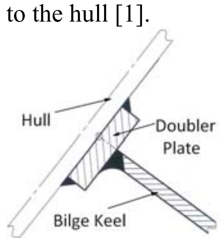


Figure 2. Doubler connection detail of the bilge keel to the hull.

In case of an accident or catastrophic failure, the bilge keel will partly, or entirely, detach from the ship's hull structure without causing structural damages that could compromise the hull plating water tightness.

2. FAILURE REGISTER

2.1. Cracks in the Bilge Keel Connection to Hull

Several cracks were detected by visual and dye penetrant inspection up to 150mm long, mainly in the welded connection between the bilge keel plating and the doubler plate (Fig.1), but also in much smaller number and size, on the doubler connection to the ships' hull plating.

2.2. Fractures in the Internal Structure of Bilge Keel

After a close inspection at the internal structure of the bilge keel, multiple fractures, originated from fatigue cracks, were recorded. These occurred at the intersection between the longitudinal and transverse reinforcements of the bilge keels, leading to the complete separation of the link between them (Fig.1).

2.3. Fractures in the Bilge Keels Plating Edge

At the bilge keels plating edge multiple fractures were recorded, resulting in the loss of the bilge keel watertightness and the separation of the welded connection/joint between the two plates that define the external surface used for the transversal stability of ships (Fig.1).

2.4. Structural Failures Location

Both the cracks in the bilge keel internal reinforcements and the cracks at the plating edge occurred along the entire length of the bilge keel.
The remaining cracks (Figure 3, points marked) were located in the middle plane of the internal reinforcements of the hull (bulkheads /frames) and, in some cases, also in the alignment with the middle plane of the bilge keel internal reinforcements (Figure 3).

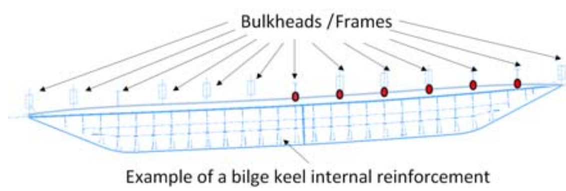


Figure 3. External overview of the bilge keel. Recorded location of cracks (marked points).

3. DESIGN LOAD, P_{BK}

While one can often adequately predict heave, pitch, sway, yaw and even surge, roll motions of a ship are still remarkably difficult to predict, since roll is the motion that is very dependent upon viscous effects of the fluid on the surfaces used for transversal stability of a ship [3]. Nevertheless, design principles from the *Germanischer Lloyd* Classification Society were used [4], in order to determine the maximum load applied on the bilge keels, P_{BK} (fig.4) (1)

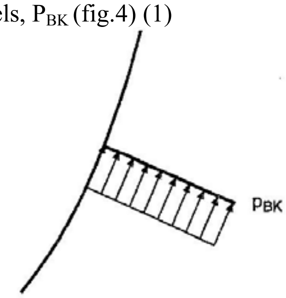


Figure 4. Design load, uniformly distributed across the bilge keel span.

Equation 1 is valid for ships with a length ***L*** between 50m and 200 m, measured in the corresponding waterline and for bilge keels located between 0.4***L*** and 0.6***L***.

$$P_{BK} = \frac{52000 \times d}{(L+240)^{1.1}} \times \gamma_{fdyn} \left[kN/m^2\right] \quad (1)$$

Where, d, represents the density fluid value, involving the bilge keels (of 1.025, for saltwater at 25ºC), ***L*** the distance measured from bow to stern, on the waterline

(109m, for the case in study), and γ_{fdyn} the partial safety factor representative of permanent and cyclic loads acting on the undamaged structure in normal operational conditions (considered a value of 2). Accordingly, a design load (P_{BK}) of approximately 170kPa, was calculated.

Since the waterline length of the ship, where the bilge keels under study are installed, is 109m, the domain of validity for the design load is satisfied; regarding the second parameter on the range of validity of the equation, between 0.4$\boldsymbol{L}$ and 0.6$\boldsymbol{L}$, the design load is only valid for approximately 70% of the length of the bilge keels under study, as shown in Figure 5. Although the region where the application of the design load is valid does not include the entire length of the bilge keel, it covers some of the registered structural failures (Fig. 5), not invalidating the calculated value of the design load and its implementation in subsequent studies.

Figure 5. Valid domain for the design load, overlapped with the location of the recorded cracks.

4. BILGE KEEL GEOMETRY MODELING AND ANALYSIS BY FINITE ELEMENT METHOD (FEM)

4.1. Nonlinear FEM Analysis of a Bilge Keel Section

A bilge keel section with 200 mm long was modeled, in order to perform an analysis of the induced stress and deflection on the structure due to the design load. The model shown in Figure 6 includes the internal structural arrangement of the bilge keel and a hull section of 400x500mm length with a 3m curvature radius.

The three-dimensional model was uniformly loaded with 170kPa in the upper face of the bilge keel plating, corresponding to the design load (P_{BK}). The edges of the hull were fixed, in order to simulate the boundary conditions present in the real structure (Figure 6).

Figure 6. Three-dimensional model of the bilge keel section modeled, which includes the internal structural arrangement, the finite element mesh, the design load and the boundary conditions.

When submitted to an uniaxial tensile test, some mechanical properties of the D36 steel used in the bilge keel construction (Table 1 and 2) are characterised by its true Stress–Strain curve, as shown in Figure 7 [5]. The calculated coefficient and exponent of the Ramberg-Osgood Law, K and n, were 879.2 MPa and 0.1634, respectively, and the stress-strain curve was considered in the definition of the FE material model.

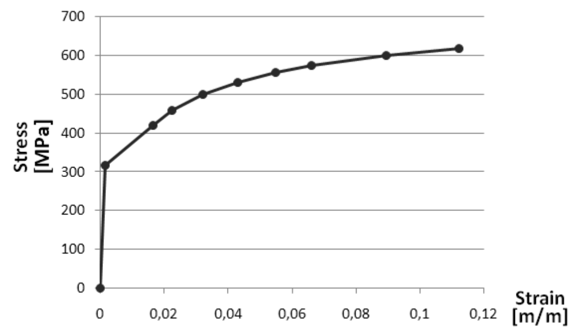


Figure 7. True Stress-Strain curve for the D36 naval steel [5].

The regions identified as hot spots were numbered (Figure 8), having been registered their corresponding *Von Mises* stress values (Table 3).

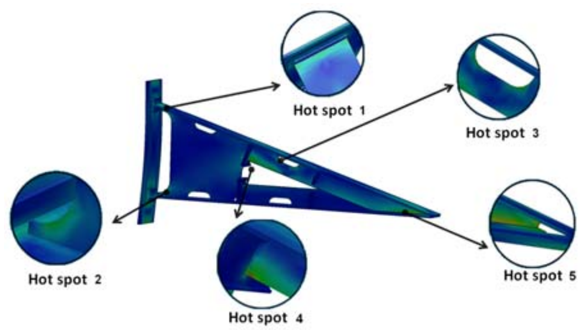


Figure 8. Bilge keel hot spots location.

Table 3. Maximum Von Mises stress values located in the hot spots for the nonlinear Finite Element Analysis (FEA) performed.

Total of Nodes	Total of elements	Hot Spot 1	Hot Spot 2	Hot Spot 3	Hot Spot 4	Hot Spot 5
50680	24702	229 MPa	317 MPa	336 MPa	364 MPa	359 MPa

The data presented in Table 3 shows high levels of stress concentration located in the hot spots, inducing local plastic deformations, but also yield strength safety factors close to one, which leads to the nucleation and propagation of low-cyclic fatigue cracks.

With reference to the yield strength value of the structural steel in which the bilge keel is made of (355MPa), the hot spots numbers 4 and 5 entered the plastic regime, concurring with the location of the register structural failures (Figure 1).

4.2. Study of the Influence of the Hull Reinforcements' Alignment with the Internal Structure of the Bilge Keel

Having been identified as hot spot 1, the stress concentration at the bilge keel to the hull connection (Figure 8), and having been detected a pattern in the location of the structural failures, namely the registration of cracks in the alignment of the hull internal reinforcements, an analysis of the position influence of the bulkhead/frames in the induced stress values in the connection between the bilge keel and the hull was carried out.

As shown in Figure 9, it was found that the presence of the hull's internal reinforcements (bulkheads or frames) resulted in an increase of the maximum stress value present in the connection between the bilge keel and the hull, since the maximum induced stress of 230 MPa increased to approximately 260 MPa (+13%). In addition, there was also a maximum stress concentration in the region closest to the alignment of the reinforcements.

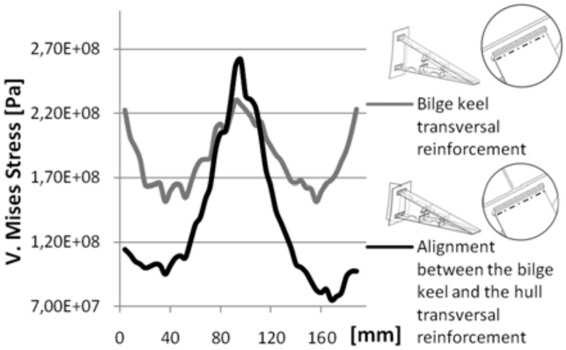


Figure 9. Influence of the alignment between the bilge keel and the hull transversal reinforcement.

5. ALTERNATIVE GEOMETRIES

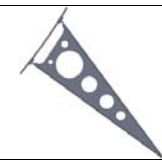
Taking into account the results from the FEM analyses, new geometries were designed and analysed in order to propose a viable substitute for the bilge keel internal structure and its connection to the hull.

5.1. New Internal Bilge Keel Geometry

With the objective of maintaining unchanged, as much as possible, the hydrodynamic characteristics of the bilge keel, in particular those related to its energy dissipation and drag coefficient, only the internal geometry of the bilge keel was redesigned, maintaining the thicknesses of the components, so that the rigidity of the structure was kept unchanged. The new developed internal geometries are shown in Table 4.

Several details were included in the new internal arrangements in order to minimize the stress concentrations (Figure 9) and, concomitantly, facilitate its production. An example representative of these details is the application of a steel bulb with 15mm in diameter in the bilge keel plating edge (Figure 10).

Table 4. Alternative internal geometries

Reference	Description	Illustration
Geometry nr: 1	Model containing only one solid and continuous transversal stiffener.	
Geometry nr: 2	Model containing one transversal and longitudinal stiffener, with smooth cuts in the intersection between them.	
Geometry nr: 3	Model containing only one transversal stiffener with two sections, with soft cut contours.	
Geometry nr: 4	Model containing one transversal and longitudinal stiffener, with smooth cuts in the intersection between them and with two sections with soft cut contours	
Geometry nr: 5	Model containing only one transversal stiffener, with multiple circular cuts sections and stress concentration reliever holes.	
Geometry nr: 6	Model containing one transversal and longitudinal stiffener, with smooth cuts in the intersection between them, and with multiple circular cuts sections and stress concentration relievers holes.	

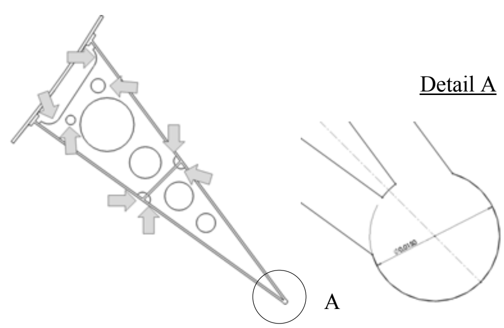


Figure 10. Stress concentration relievers.

All the tridimensional models of the new bilge keel internal arrangements were uniformly loaded with 170kPa, corresponding to the design load. Also the same boundary conditions as shown in Fig.6 were applied, in order to compare the results with those obtained for the current model.

Table 5 presents a summary of the results obtained from the FEA, pointing out the main features of the new geometries regarding the maximum *Von Mises* stresses induced in the structure, the number of existing hot spots, the maximum deflection value obtained and the mass of the new bilge keel's internal geometries developed.

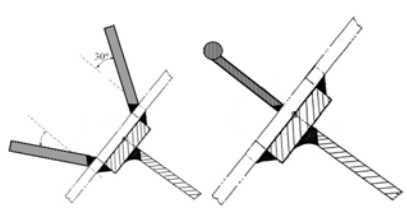
Table 5. Results obtained from the FEA of the new internal bilge keel geometries.

	Mass (kg)	Nr.of hot spots	Maximum Deflection (mm)	Von Mises Stress (MPa)
Current Geometry	41,34	5	3.8	364 MPa
Geometry 1	39,44	3	≈3.3	249 MPa
Geometry 2	40,90	3		255 MPa
Geometry 3	37,77	6		246 MPa
Geometry 4	39,27	6		260 MPa
Geometry 5	37,84	3		230 MPa
Geometry 6	39,33	3		248 MPa

The analysis showed a significant reduction in the stress level (a minimum reduction of 28% and a maximum reduction of 37%). Of all the analysed geometries, geometry number 5 presents the best alternative to the existing geometry, because it's definitely the geometry that showed the lowest level of maximum induced stress, 230MPa, together with the smallest number of hot spots and a lower mass. Notwithstanding, alternative geometries which include longitudinal reinforcements, namely geometries number 6, 2 and 4 (Table 4), in this order, should be considered in case bilge keel longitudinal strength needs to be enhanced. These solutions also revealed a lower maximum induced stress than the current geometry (Table 5).

5.2. Improved Design to Reduce the Stress in the Bilge Keel Connection to the Hull

Having been registered several cracks in the bilge keel connection to the hull, two alternative solutions have been designed, so as to reduce the maximum induced stress value to the connections under study (Figure 11), in order to eliminate the structural failures found.



a) b)

Figure 11. Cross section view of the bilge keel connection to the hull with a) brackets. b) bulb flat

The proposed solutions consisted in the application of brackets inside the hull (Figure 11a), or a bulb flat along the bilge keel connection (Figure 11b). A two-dimensional FEA was performed simulating the doubler plate discontinuity and the presence of the brackets (Figure 12) or the bulb flat. Accordingly with Figure 12 and with the data presented in Table 6, both proposed solutions could be considered to reduce the stresses induced in the doubler plate connection to the ship's hull, ensuring the water tightness of the hull.

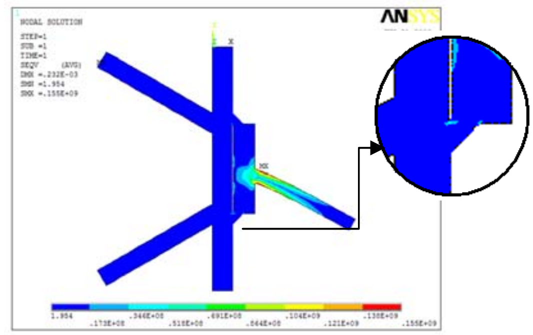
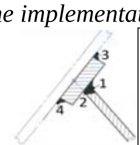


Figure 12. Two-dimensional FEA of the bilge keel connection to the brackets

Table 6. Stresses present in the bilge keel upper plating, with the implementation of brackets and bulb flat.

	Stress in Point 1 [MPa]	Stress in Point 2 [MPa]	Stress in Point 3 [MPa]	Stress in Point 4 [MPa]
Current model	157	149	29	50,6
Application of brackets	155	154	4,8	3,9
Application of bulb plate	122	134	29,7	27,3

6. FATIGUE ANALYSIS

A fatigue strength assessment of the redesigned doubler plate connection to the ship's hull (Figure 13) has been made assuming the inexistence of the doubler plate and in accordance with the fatigue design curves included in *Germanischer Lloyd* Rules [4], which state that for structures submitted to cyclic loads resulting from waves or engines [4] and for infinite life, eq.2 must be fulfilled.

$$\Delta\sigma_{Rc} \cdot f_n \geq \Delta\sigma \cdot \left(fa \cdot F_{dyn}\right) \qquad (2)$$

where $\Delta\sigma_{Rc}$ is the corrected fatigue strength reference value, f_n is the correction factor considering the allowable number of load cycles and the type of spectrum applied and $\Delta\sigma(f_a.F_{dyn})$ is the stress range due to the dynamic loads applied in the assessed structure.

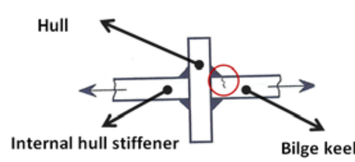


Figure 13. Simplification of bilge keel to the hull connection with internal stiffeners (bulb flat).

The S-N curves (Figure 14) for the welded detail represented in Figure 13, relative to two standard classes of Spectra A and B [4], were corrected through the application of a factor, f_n, [4], where Spectrum A represents the denominated straight-line spectrum, which is a typical stress range spectrum of seaway-induced stress ranges [4] and Spectrum B represents a parabolic spectrum, which represents a Normal function density of probability type of stress range. The fatigue curves presented in Figure 14 are representative of the fatigue resistance of medium/high strength structural steels used in shipbuilding [4].

Once known the maximum stress value present at the cruciform joint (155 MPa, Table 6) it was assumed a local stress of 170 MPa (Figure 14) due to the weld toe stress concentration factor (Figure 13) for the stress variation present in structure due to dynamic loads, $\Delta\sigma$ ($f_a.F_{dyn}$). The fatigue life prediction can be observed in Figure 14. For the spectra B or A, which reflect the service conditions of the ship, the estimated lifetime is approximately 16 years and infinite lifetime, respectively. The cycle conversion was carried out once known that $5x10^7$ fatigue life cycles in a class A spectrum, is equivalent to a lifetime of 25 years with 230 days per year of service at sea [4].

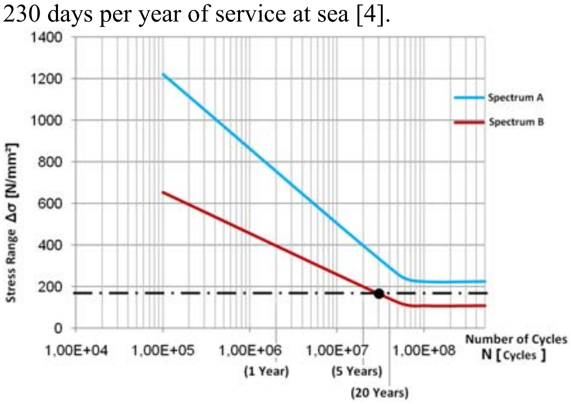


Figure 14. Fatigue life prediction for spectra A and B

7. CONCLUSIONS

This paper refers to an analysis performed to the structural failures found in bilge keels, with the objective of presenting structural solutions to solve them.

It was confirmed, through the analyses carried out by FEM that the location of the internal failures in the bilge keels coincides with high stress concentration regions. It was verified the existence of stress levels close to the material yield strength and, consequently, some areas were identified where local plasticity can occur.

The alignment between the bilge keel's internal structure and the hull transversal reinforcements results in an increased and more concentrated stress level along the hull-bilge keel connection, when compared to the stress level induced by the presence of the bilge keel transversal reinforcement only.

A 2D FEA performed to the doubler plate and the bilge keel, and between the doubler plate and the hull allowed to determine the maximum *Von Mises* stress present in the welded joint due to the stress concentration introduced by the welded detail, fact which is in accordance with the failure observed. The application of brackets or a bulb flat allowed to reduce the maximum stress induced to 155MPa between the doubler plate and the bilge keel.

In order to propose a new solution capable of preventing the structural failures identified in the internal bilge keel structure, six alternatives geometries to the internal structure of bilge keel were designed and analysed, maintaining unchanged the hydrodynamic characteristics of the bilge keel. The best solution found (geometry nr.5, Table 4) contains 3 hot spots regions and a maximum *Von Mises* stress of 230MPa, corresponding to a reduction of 37% in the stress induced levels when compared to the current geometry. Notwithstanding alternative geometries which include longitudinal reinforcements, namely geometries number 6, 2 and 4 (Table 4), in this order, should be considered in case bilge keel longitudinal strength needs to be enhanced. These solutions also revealed a lower maximum induced stress than the current geometry (Table 5).

Finally, a fatigue life assessment analysis to the bilge keel welded connection to the hull resulted in an infinite lifetime for a Spectrum A type. Adopting a more conservative approach, the fatigue lifetime for a class B spectrum estimated a fatigue lifetime of 16 years.

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