



Review

# Structural durability validation of bearing girders in marine Diesel engines

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## Abstract

The aim is to present the state-of-the-art methodology for structural durability evaluation of marine Diesel engines bearing girders and to describe the responsibility of engine designers, manufacturers and system suppliers. A real example of several engines of the same type, where fatigue cracks arose in certain areas of their bearing girders, has been presented. The extensive investigation revealed the cause of the damage. The proper design was proved by properly implemented state-of-the-art design methods and by experimental verification of calculations in two ships. Quality and test specifications prescribed by the licensor have been found correct. It is concluded that the damage cause was the impermissible quality of worldwide manufacture and improper production repair welding during manufacture.

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*Keywords:* Marine Diesel engines; Bearing girders; Fatigue strength; Design; Manufacturing

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## Contents

1. Introduction . . . . .	248
2. Responsibilities of the engine designers and the manufacturers. . . . .	250
3. Design procedures for general machinery components. . . . .	251
4. A state-of-the art design procedure for the bearing girders . . . . .	252
4.1. Determination of the bearing loads . . . . .	252
4.2. Calculation of the stresses . . . . .	253
4.3. Assessment of the bearing girders fatigue strength . . . . .	254
5. Validation of bearing girders design by experiments . . . . .	255

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6. Manufacturing of bearing girders and production repair welding . . . . .	255
7. Example . . . . .	256
8. Discussion of the obtained results . . . . .	258
9. Conclusion . . . . .	259
References. . . . .	259

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## 1. Introduction

From the functional and the safety aspect, modern merchant ships are strongly dependent on the prime movers in their propulsion systems, regardless of their concept. The essential propulsion system concept may be based upon marine turbines, or a single- or multi-Diesel engines installation. Diesel engines are commonly used today. It is always important to understand their functional role (class related), as well as the safety aspects of their implementation.

From the designer's point of view it is necessary to consider the ship in exploitation, operating in heavy seas, rather than nothing more than the floating object during the outfitting phase in the shipyard. Functional problems related to the ship prime mover can usually be solved in the shipyard without further implications to the ship safety. However, any ship during operation may face an extremely difficult situation, when the proper functioning of the propulsion system may be the ship's crew only hope. Fig. 1 is to remind a designer of such a situation. So, the designer is to design marine Diesel engines, manufacturer is to manufacture, assemble and test them on the test bed, and finally the shipyard is to mount them and test them onboard during the sea trials. These engines shall be able to withstand all the hazardous situations that may arise later. An important part of the responsibility for the proper functioning of Diesel engines lies also on the ship's crew, especially the chief engineer, to follow the proper instructions prepared by the engine designers.

Engine designers have to properly deal with the engine as a whole, from its initial specification, to the feedback information obtained from the test bed or onboard, as well as the design of the engine essential parts. From the functional point of view, the most important engine parts are these that transform reciprocating movement of the piston mechanism into rotation of the output flange, such as crankshaft, as well as all the



Fig. 1. A tanker in operation at heavy seas.

parts taking part in transmission of generated forces to the engine foundation, e.g. the bed plate, the frame box, or the cylinder block. In modern large Diesel engines (Fig. 2) bedplates usually consist of their outer part made of steel plates, connected together by means of cast steel bearing girders. These bearing girders take over and distribute forces acting on the engine bedplate as a whole, originating from assembly pre-loading by tie rods, cylinder firing loads and bearing reactive loads. A typical bedplate of a modern large Diesel engine may be seen in Fig. 3 during the assembly process.

This paper is initiated as a consequence of cracks that developed in several Diesel engine bearing girders in newly built ships and the investigation of the problem cause. The basic aim of the paper is to describe the present state-of-the-art methodology, which has to be implemented in design and manufacturing of modern Diesel engine bearing girders. The design of these components shall be based upon a proper structural durability evaluation. The manufacture shall be based upon the proper implementation of quality assurance procedures (production and testing specifications) in general. The final goal of all the mentioned procedures is to avoid any undesirable effects and to prevent initial crack development in similar structures.

The design procedures based upon loading assumptions, selection of suitable materials and the manufacturing procedures, as well as the shaping and dimensioning procedures are described in details. The transition from cylinder loading and tie-rods pre-load to the existing stresses in critical parts of bearing girders is explained. On the other hand, evaluation of structural material properties for cast steel bearing girders in accordance with the international standards, such as ASTM, or FKM-Guideline, dependent also upon the initial and the in-service scope of inspections implemented. It is important to validate design premises and assumptions, as well as calculated results by measurements, even for only few measurement points and influence factor levels.

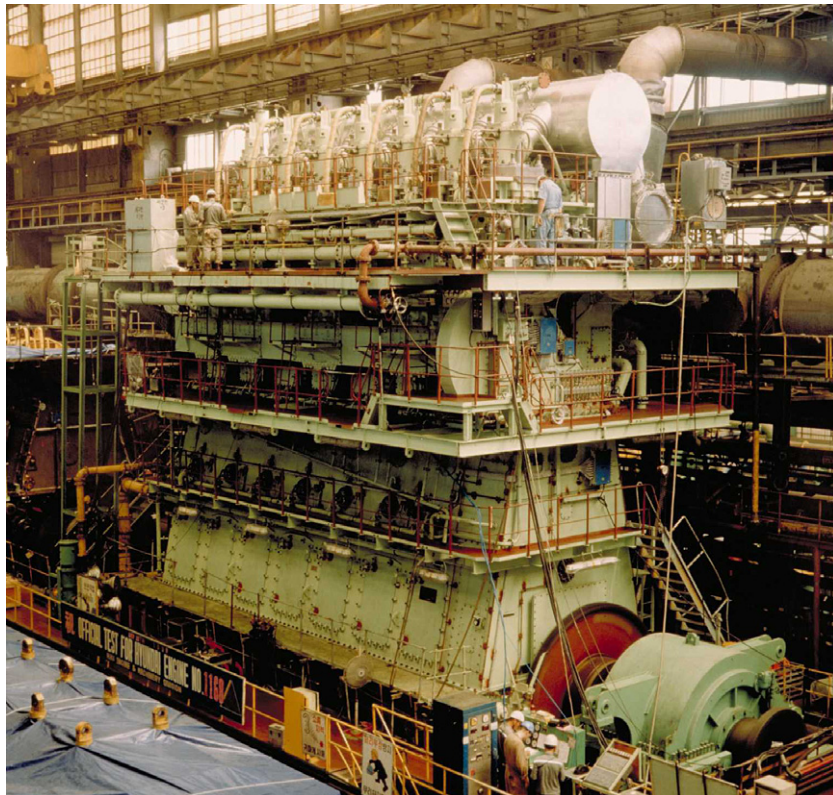


Fig. 2. A large two-stroke marine Diesel engine at test bed.

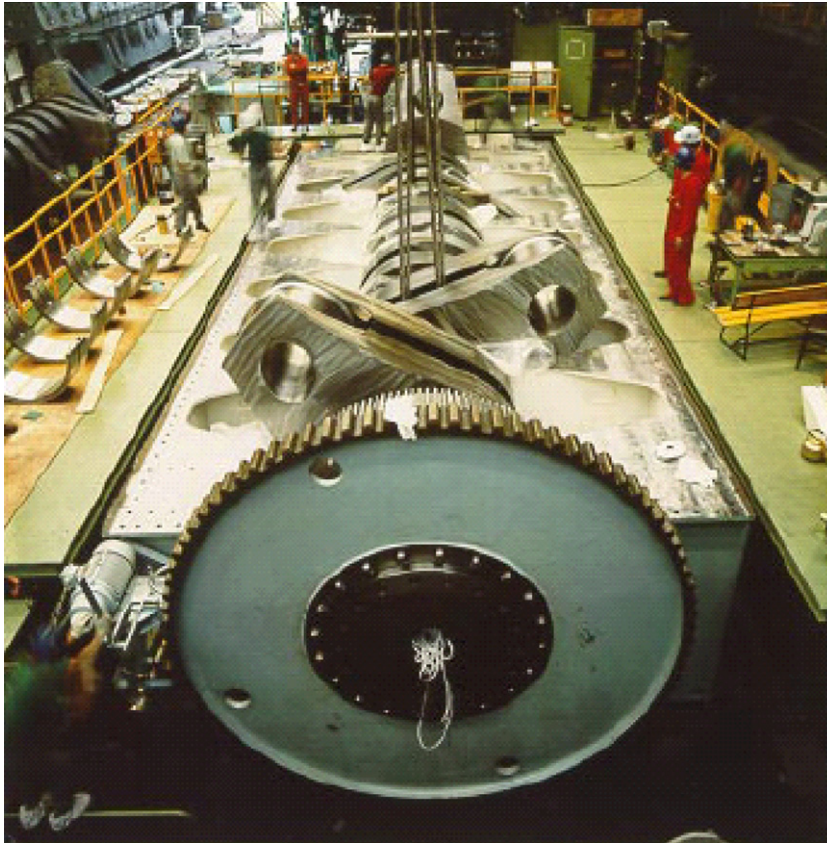


Fig. 3. Crankshaft installed in the bedplate of a seven-cylinder engine.

Manufacturer's responsibility is called for further on. The manufacturers have to keep up to the pre-defined specifications during manufacture of the components. They are responsible for, quality assurance, component testing, providing proof that the test requirements have been satisfied, as well as for assembly of components into a fully functional system. The point here is upon implementation of proper production repair welding procedures, regularly used to correct unavoidable casting defects, where their improper use may have detrimental consequences to the final behaviour of the bearing girders and engines as a whole.

The mentioned real practical case study example of several engines of the same type, where fatigue cracks arose in certain areas of their bearing girders is presented and analysed. This analysis had the scope to find out the cause of the damage, in order to solve the problems on existing, as well as on engines in future and treat the influence of the design and the manufacturing process to the cracks developed and found on existing engines.

It resulted in conclusion that the cause of the cracks found lies in impermissible quality of world-wide manufacture and improper production repair welding during manufacture. As a consequence of this conclusion, it is recommended that a special attention is to be given by the engine licensors to their manufacture and the implementation of their quality assurance procedures by their licensees world-wide. The proposed approach may, at least in the analysed examples, prevent further problems with cracks in cast steel components exposed to production repair welding.

## 2. Responsibilities of the engine designers and the manufacturers

One of the most common definitions of quality, applied to a machine system component, relies upon its suitability for use. It is not easy to see or determine how many parties took place in its creation, from the

design to the final testing prior to delivery. In modern industrial society the parties that may be recognised at a first glance are the designer, the manufacturer and the system supplier [1].

Design of the component always defines the direction of all further steps to be made in its manufacture and behaviour in exploitation. The designer is responsible for the following [1]:

- full description of the requirements which the components are to satisfy with specified conditions for their use;
- evaluation or estimation of operating loads and component strength;
- constructional shaping and dimensioning;
- selection of suitable materials appropriate to the loading; and
- selection of the manufacturing methods.

On the other hand, the responsibilities of the manufactures are basically related to the fabrication of the component itself. These consist of the following [1]:

- manufacture of the components in accordance with clear and complete specifications for the design and in accordance with standard engineering practice;
- assurance of component quality in accordance with the use-related specifications;
- examination of the components in accordance with prescribed and agreed testing methods;
- proof that the test requirements have been satisfied; and
- assembly with other parts to form a unit.

System suppliers are responsible for [1]:

- assembly of all the necessary units and equipment to form plants capable of operation;
- adjusting of plant adjustable parameters if necessary;
- final testing of assembled and built-in plants in accordance with the test specifications;
- proof that all the prescribed and agreed tests have been performed with the results that satisfy the requirements, prior to the delivery of the whole plant.

In modern shipping business all this applies to the bearing girders as the components, marine Diesel engine as the unit and, finally, to the whole ship as a unit. Designers of the two-stroke slow speed large marine Diesel engines, together with all the engine components such as bearing girders, are usually licensors themselves (presently, there remain only three significant international companies in large two-stroke marine Diesel engines business). Manufacturers are their world-wide licensees, i.e., Diesel engine factories around the world. System suppliers are, in this context, the shipyards.

One of the important aspects of a component/unit/plant operational behaviour in practical exploitation further on lies upon the ship operators. These are the shipping companies (ship owners or management companies). Their responsibilities are to always keep up to the operating instructions prescribed by the designers and to avoid any misuse or abuse.

In investigations of any failure, if it happens, independent experts are usually engaged to determine its root cause. Upon the above-defined responsibilities once uncovered cause usually leads to an answer who is responsible for the failure. This is one of the basic reasons for writing of this paper: to write down a procedure, based upon objective evidence and own experience, to be used by these experts in future, so as to exclude the influence of any party interest.

### **3. Design procedures for general machinery components**

In general, design of a component involves the following activities: load assumption, selection of suitable materials and manufacturing procedures, shaping and dimensioning [1]. The design is dependent on the acting loads and the stresses caused by these loads in individual areas of the component, as well as the allowable stresses, influenced by the material and the manufacture. Dimensioning of components is always dependent

on the relation between the stresses that arise and the stresses that can be tolerated. Designer's task is to determine the stresses that arise through the calculation and, starting from the material characteristics and the expected manufacturing quality, to determine the allowable stresses.

Designers shall take into account all the stresses that are brought about by various causes, in order to determine the strength behaviour of the designed components. These are the stresses produced by assembly and operation:

- static or quasi-static pre-stresses during assembly and or warming up of the unit;
- static pre-stresses, called residual stresses, that can arise during component manufacture;
- dynamic time-dependent stresses superimposed to the pre-stresses in operation.

In addition to these it is important that the designer determines all additional influences relevant to the component strength behaviour with respect to the permissible stresses, such as material inhomogeneities, surface roughness, etc.

#### 4. A state-of-the art design procedure for the bearing girders

The above-described general methodology is valid for two-stroke slow-speed marine Diesel engine bearing girders and is to be applied to their design. Each step, together with all the influencing parameters will be described in detail hereafter. The essential steps are determination of the bearing loads, calculation of the stresses, and, finally the assessment of the bearing girder fatigue strength [2].

##### 4.1. Determination of the bearing loads

Bearing forces are to be determined as a first stage in the computational analysis of the stresses in bearing girders. Mapping of the bearing housing deformation during installation and operation load, that point both to a displacement and also to redistribution of the forces in the bearing girders is of a particular interest. This is also significant for the load distribution in the bearing girder, since the force flow from the bearing is not only lead away via the wall of the bearing girder. Asymmetrical distribution of the load brought about by deformation of the crankshaft along the bearing shell shall also be taken into account in the calculation.

So, the decisive loads to be taken into account are defined in [Table 1](#).

Table 1

Determination of bearing girders loading

Internal engine forces	Ignition forces	Caused by firing process in engine cylinder Obtained from the cylinder pressure versus crank angle curve
	Guide shoe forces	Obtained from ignition and reciprocating mechanism inertial forces
	Forces acting on main bearings	Consequence of forces acting on crank journals Elastic system response to the active forces (bearing reactions) Require crankshaft modelling Require taking at least three cylinders into account
Loads originating from assembly forces	Pre-tensioning of tie-rods	
	Pre-tensioning of bearing cover bolts	
	Assembly stresses to be added to other calculated stresses	
Dynamic loads	Crankshaft vibration forces (coupled vibrations)	
	Hydrodynamic loading by the oil-film in the bearings (dynamic alignment)	

#### 4.2. Calculation of the stresses

The engine structural modelling, utilising the finite element method for the deformation analysis is to start from the whole engine to the section with the three cylinders. In fact, the two complete cylinders, and the two halves of the neighbouring ones disposed around the bearing girder are to be evaluated [3]. The last step is to evaluate the bearing girder itself. Selection of the finite elements and numerical calculation procedure is to be in accordance with the state-of-the-art, meaning 3D finite elements and a non-linear calculation procedure. A typical part of the engine single bearing girder to be numerically modelled is shown in Fig. 4 [3].

The structural finite element model of the bearing girder shown in Fig. 5 [3] lies between the two “whole” cylinders within the model. The influence of bearing forces out of the modelling scope (two complete cylinders and two halves) on the forces acting on the considered bearing girder may be neglected [3].

The whole calculation procedure is implemented to determine stresses in the considered (model mid-section) bearing girder. Iterative calculations are necessary. Namely, the crank journals at a certain rpm do not lie directly on the bearing, but on a lubricating oil-film between the journal and the bearing. Crankshaft is to be modelled as a whole, together with the remaining parts of the propulsion system (intermediate shaft, propeller shaft and the propeller). Elasto-hydrodynamic properties of oil-film are to be taken into account [2].

Finite element mesh refinement in the model is necessary in order to prove the convergence of numerical calculations, as well as because the tilt of crankshaft journals in both radial and tangential direction has a significant influence. This gives a very extensive and complex numerical model used to determine acting stresses in bearing girders.

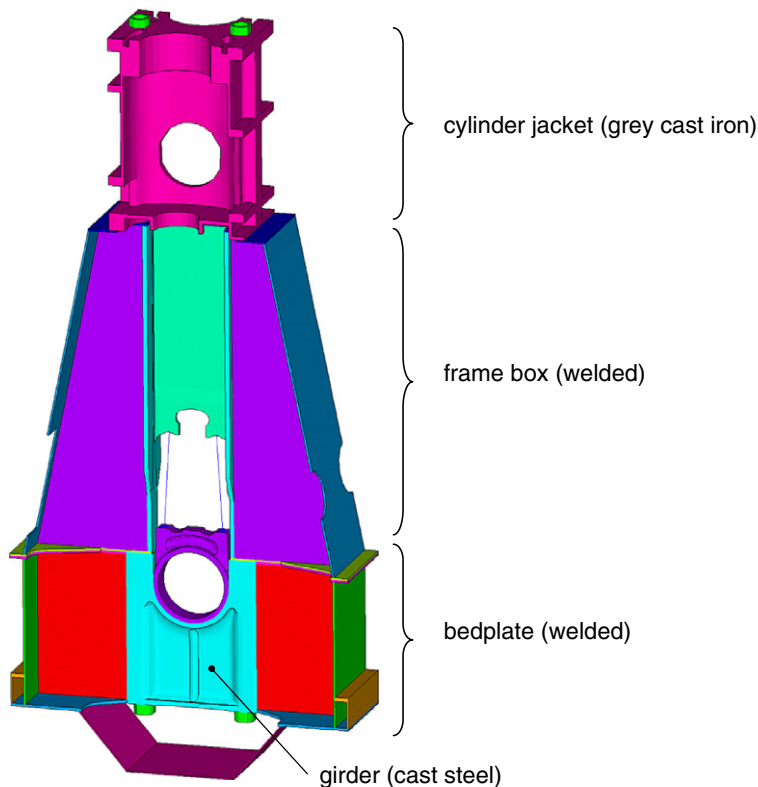


Fig. 4. A typical cross-section at engine bearing girder with parts.

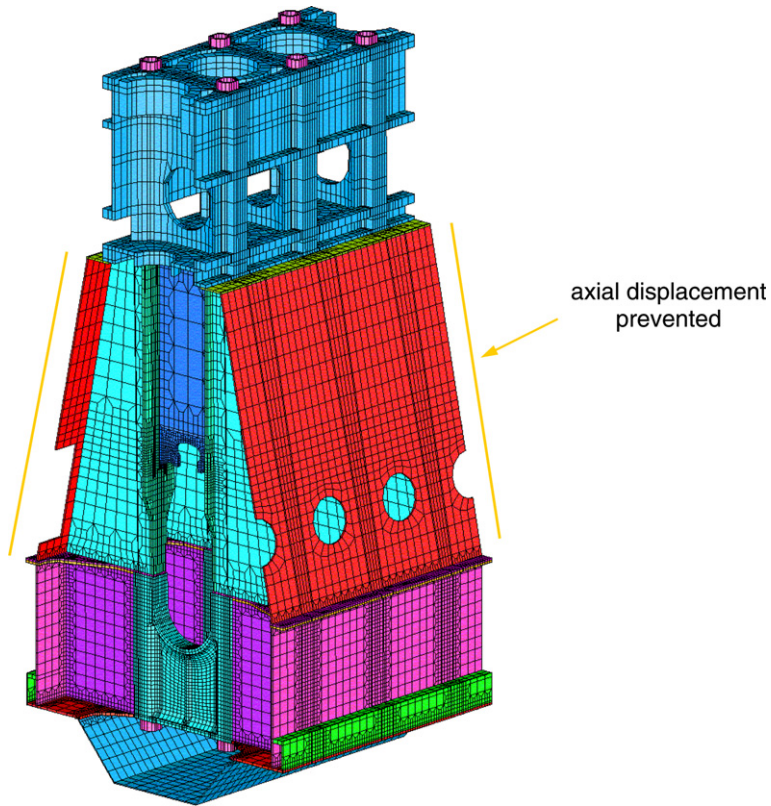


Fig. 5. Finite element model of the engine bearing girder.

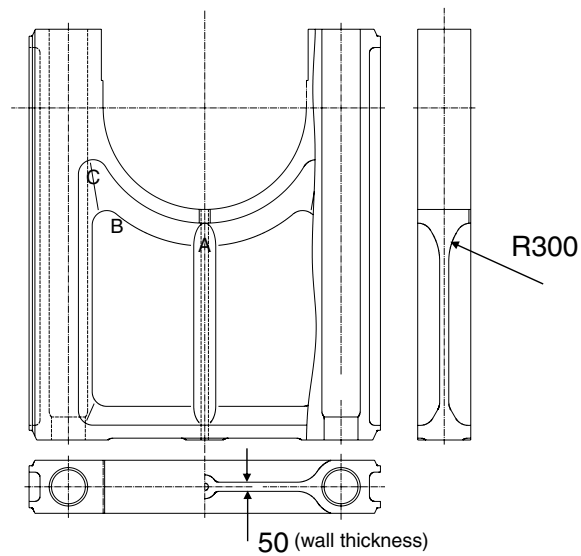


Fig. 6. Zones of strength validation based on FEM model.

#### 4.3. Assessment of the bearing girders fatigue strength

Consequently, the multi-axial stresses in the highly loaded points of the bearing girder analysed are presumed to be the critical ones. These are composed of static pre-stresses (preferably arising during installation



as a consequence of tightening torque in the tie-rods and bearing cover bolts) and the variable (dynamic) stresses, which are superimposed on these during operation. During a single rotation of the crankshaft these stresses change both their value and the direction. Zones of strength validation, based on finite element analysis, for a particular case (see Example) are shown in Fig. 6 [3].

Based upon the calculated stresses, the equivalent stresses are to be determined in accordance with the material dependent fracture hypothesis. These equivalent stresses are then compared with the allowable stresses determined from samples with uni-axial stresses. In the case of cast steel bearing girders the normal stress hypothesis is to be implemented. Determined allowable stresses shall also take into account material type, as well as the initial and periodical regime of inspections implemented (annual and/or class surveys) [4]. International standards and guidelines such as FKM-Guideline [5] and ASTM [6] are to be implemented.

The way to compare these stresses in a particular analysed case is shown in the forthcoming Example.

## 5. Validation of bearing girders design by experiments

It is important to prove and evaluate how accurately do the computationally determined stresses in individual areas of the bearing girders correspond with the stresses arising in operation. This can only be supplied by the corresponding operational measurement.

The experiments are to shed enough light to the parameters taken into account in the numerical calculations, especially if all these parameters have had been necessary to deal with or not. Experimental validation of the numerical model at only few (to reduce costs) levels of parameters is necessary. A similar approach is quite common in marine engineering and is, in certain cases, even the requirement of classification societies [4]. Fig. 7 [3], referred to in the Example, shows comparison of calculated stresses to the measured ones.

## 6. Manufacturing of bearing girders and production repair welding

The bearing girders are predominantly manufactured from cast steel. For cast components of the size of bearing girders it is assumed, on the one hand, that an appropriate casting quality is guaranteed, and on the other hand that if casting quality is inadequate, a repair can be effected. Usually, the so-called production repair welding improves the components with casting failures. The requirements for the quality of bearing girders, as well as the procedure for repair welding, must be described in the quality assurance specifications.

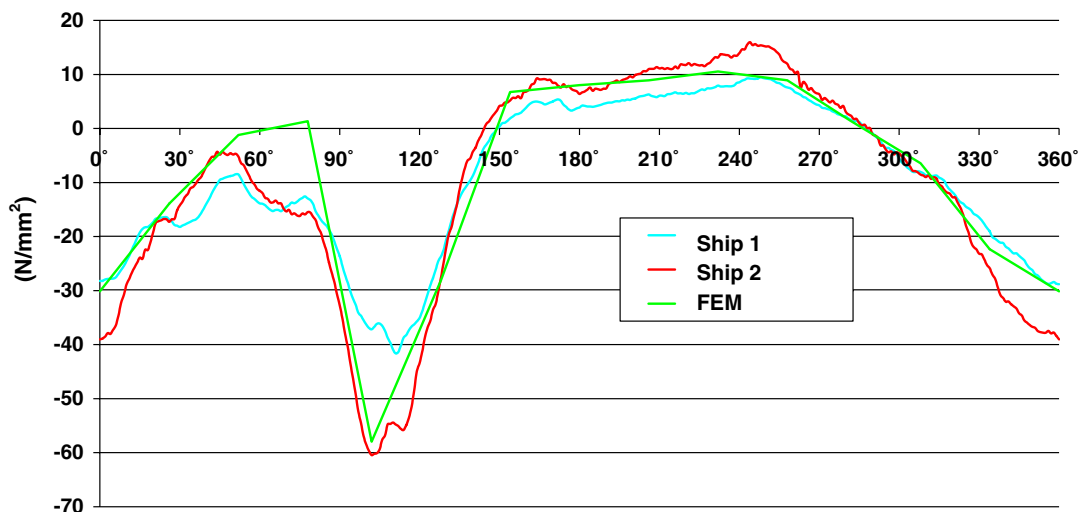


Fig. 7. Comparison of FEM calculations with measurements.

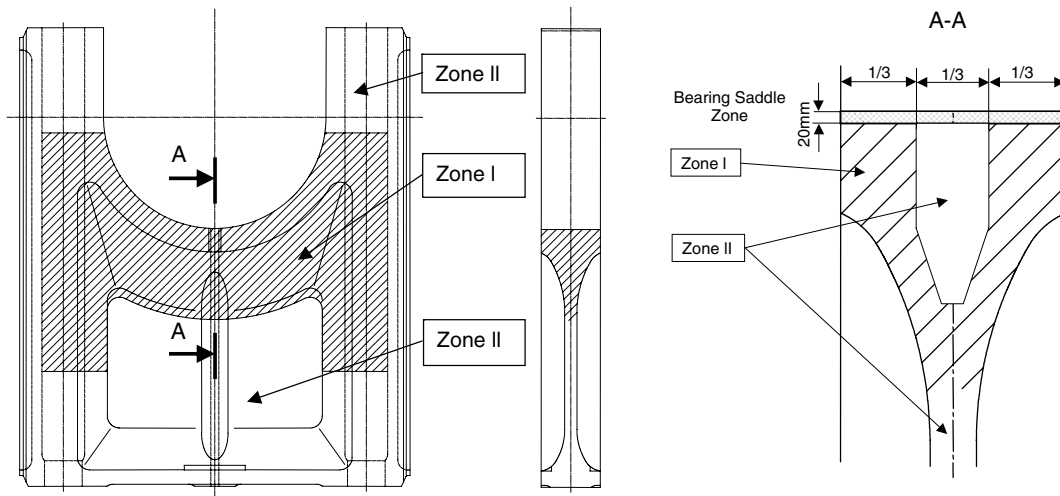


Fig. 8. Zones of specified material defects.

With the production repair welding the faults caused in production should be removed and the required nature of the casting [5,6] should be ensured, which should have the characteristics similar to the basic material.

To assure a reliable and economical repair the bearing girder is, depending on the stress distribution (results of FE-stress analysis), divided into individual zones (shown for example in Fig. 8) on which the specified casting failures can be accepted or, depending on their shape and position, repaired. These requirements should be specified at the design stage in a close cooperation with the engineers being responsible for the manufacturing. If the casting faults are higher than allowable, but possible to improve by repair welding, this could be made if the specified conditions are fulfilled. Depending on the size of the component to be repaired it is necessary to decrease the residual stresses generated by the repair welding. In such a case the American Society for Testing and Materials [6] requires that a residual stress treatment by annealing must take place if the extent in depth amounts to more than 20% of the wall thickness, or more than 1 in. (25.4 mm), with the respectively lower value being decisive.

## 7. Example

Implementation of the described procedure for the structural strength calculation and validation of obtained results is presented below in a real case study example. These analyses refer to several engines of the same type, where fatigue cracks arose in certain areas of their bearing girders. The basic goal of these calculations was to investigate and find out the cause of the damage [1,2].

The first step in the analyses performed was modelling of the engine structure. This was done by means of finite element methods analysis for linear elastic behaviour of material of engine components and a very complex non-linear behaviour of oil-film in the bearings in operation. The analysis was performed in three steps: from the whole engine, through the section with three cylinders disposed around the bearing girder to be evaluated, to the bearing girder itself.

Once stresses in isolated bearing girder have been obtained, the calculated local stresses become the basis for further evaluation of bearing girder strength. As has already been pointed out, the multi-axial stresses, present in highly loaded points of the bearing girder are presumed to be critical. So, it is essential to properly recognise position of these points and to analyse stresses in them. Zones of interest, where these points may lie are shown in Fig. 8.

In determination of these points it is important to understand the basic function of the bearing girders. They are incorporated into the complete engine structure in such a way that the bearing forces are transmitted into the foundation both through the bearing girder itself and also through the lateral plates. Consequently,

loading at individual positions of the bearing girder is not determined only by the bearing girder wall thickness. On the other hand, within a cracked bearing girder a redirection of the force takes place, leading to a delay of the crack propagation.

Three characteristic points have been chosen for further detailed fatigue strength analyses, as shown in Fig. 6:

- Point A, located centrally below the lower bearing half (radius 30 mm).
- Point B, located in the area of central web (thickness 50 mm).
- Point C, transition to the tie-rod bore (radius 80 mm).

Variation of thickness has also been taken into account. This is important because of the manufacturing tolerances for cast steel bearing girders.

The specially evaluated areas, with the characteristic points A, B and C denoted have been shown in Fig. 9 [1]. Pre-stresses exist in points A, B and C as a consequence of assembly. They amount to +30/−40 MPa (tensile/compressive stress) in the presumed critical points B and C, and to only +4/−3 MPa (main compressive stress) in point A. The oscillating operating stresses are superimposed to these pre-stresses.

The wall thickness variation of 50–45 mm (where the nominal value is 50 mm) has a notable influence only in the area of the point B (increase of approximately 10%). However, reduction of the web thickness in the area of points A and C does not have any notable influence to the stresses.

Finally, the resultant stress (pre-stress with the superimposed dynamic alternating stress) achieves the following values:

- Point A:  $-40 \pm 45$  MPa
- Point B:  $-36 \pm 37$  MPa
- Point C:  $-26 \pm 50$  MPa

Assessment of strength is based upon comparison of the acting stresses with the allowable stresses. The latter were determined on the basis of the available data for the fatigue strength of cast steel GS 38.

The following influences effecting fatigue strength have been considered:

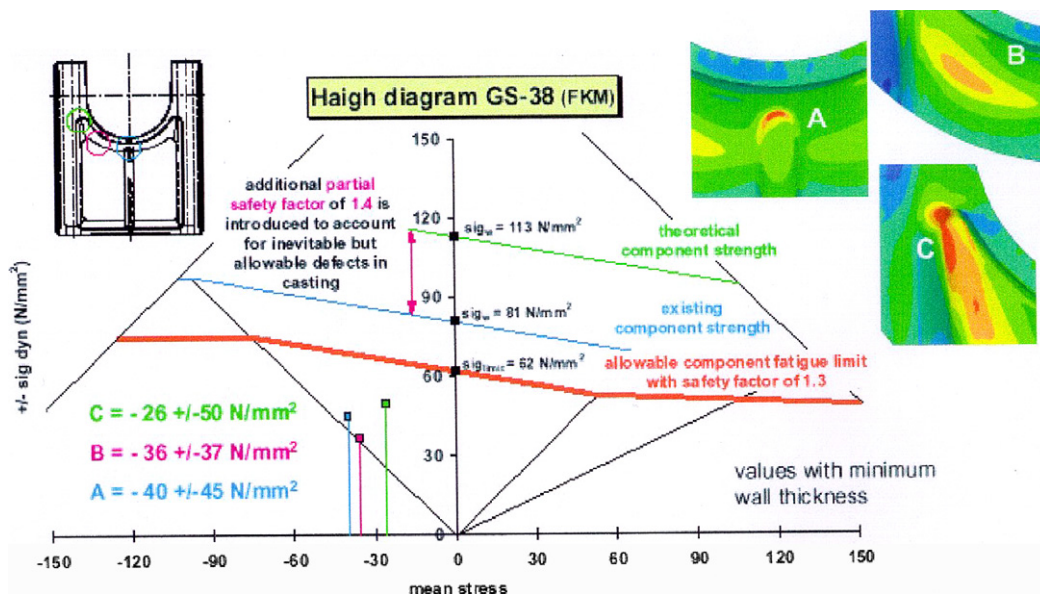


Fig. 9. Fatigue assessment in characteristic points.

- Engine operation of 6000–7000 h per year, with the total service life of 20 yr at nominal engine speed of 70 rpm gives a total of 580 million load reversals. Although the loading for the load reversals does not always correspond to 100% a fatigue strength at which no fatigue damage would have arisen for the allowable component stress has been selected.
- This allowable component stress is derived from fatigue strength tests with corresponding material samples, with the aid of safety factors. The starting basis is the fatigue strength found for 2–10 million load reversals, called the endurance limit. Natural scattering of the material characteristics calls for introduction of safety factors for determination of the allowable stresses.
- ASME code [6] determines allowable stresses by dividing average fatigue strength (at 50% probability of survival) with the safety factor of 2.
- FKM-Guideline [5] determines allowable stresses by dividing fatigue strength (at 97.5% probability of survival) with the safety factor of 1.3–1.5.
- Both standards lead finally to almost the same value of allowable stress, so the use of only FKM-Guideline in further considerations is thus found acceptable.

The allowable stress  $\sigma_{\text{all}}$  is determined by taking into account the material properties  $\sigma_{\text{M}}$ , the expected fatigue strength of the components (factor  $K_1 < 1$ ), the fatigue decrease factor for  $10^9$  cycles (factor  $K_2 < 1$  related to fatigue strength, usually determined for  $2 \times 10^6$  cycles, known as the *endurance limit*), as well as the safety factor  $S_o$  specified for given usage conditions:

$$\sigma_{\text{all}} = \sigma_{\text{M},97.5\%} \cdot K_1 \cdot K_2 / S_o \quad (1)$$

where:

$S_o$  safety factor,  $S_o = 1.3$  in accordance with FKM;

$\sigma_{\text{M},97.5\%}$  material fatigue strength for 97.5% probability of survival;

$K_1 = 0.7$  factor related to the components fatigue strength for cast girder material GS 38 with thickness of 50–70 mm and quality assurance implemented for areas with high stresses;

$K_2 = 0.9$  factor taking into account the decrease of the fatigue strength for 20 yr of usage, equivalent to  $\approx 10^9$  cycles in relation to the fatigue strength at  $2 \times 10^6$  cycles for cast girders.

Allowable stress for the cast steel girders may be calculated as presented in the formula (2), where  $\sigma_{\text{M},97.5\%} \approx \pm 110$  MPa ( $R = -1$ ) based on the data in the relevant standards (for the castings of GS 38 with  $R_{\text{m}} = 380$  MPa):

$$\sigma_{\text{all}} = \sigma_{\text{M},97.5\%} \cdot 0.7 \cdot 0.9 / 1.3 = 0.49 \cdot \sigma_{\text{M},97.5\%} = 0.49 \cdot 110 = \pm 53 \text{ MPa } (R = -1) \quad (2)$$

Fig. 9 [1] shows the corresponding Haigh diagram for the fatigue assessment, i.e., the assessment of the fatigue strength in characteristic bearing girder points based upon Haigh diagram from FKM-Guideline [5]. The finally obtained safety values lie between 2.4 and 3.4. This is higher than the maximum safety factor of 1.8 required by the FKM-Guideline, taking into account cast components have not been initially tested, that contain permissible errors, where no regular inspections are foreseen and the consequences of possible damage are severe.

## 8. Discussion of the obtained results

The obtained results prove that the bearing girders of the engine in question, with a nominal web thickness of 50 mm have been designed properly and in accordance with the state-of-the-art. Consequently, the reason for cracks, which have been detected in bearing girders, is to be looked for elsewhere, but not in the design of bearing girders [1,2].

The forensic damage analyses show that the operational cracks are fatigue failures, early started in the zones (see Fig. 10) in which, owing to the production repair welding, the components fatigue strength is lower than the acting operational stress. It is obvious that the operational cracks did not start in the areas of highest

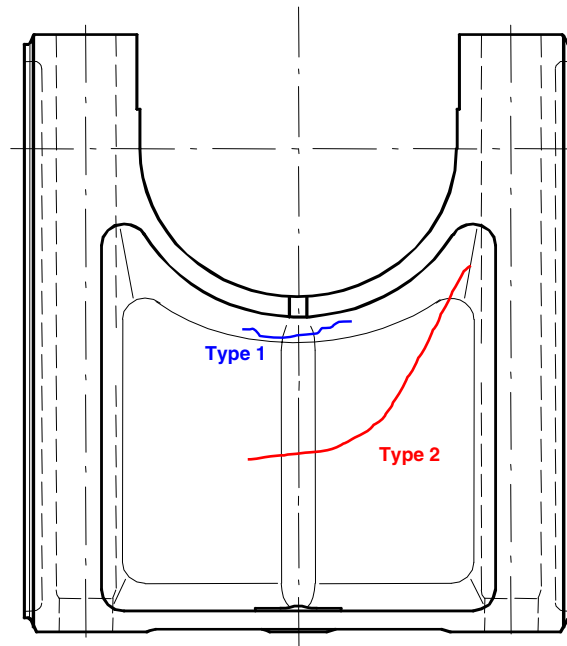


Fig. 10. Operational cracks in bearing girders.

stresses but in the areas in which the components fatigue strength was decreased by the poor production repair welding.

The operational stress level in the bearing girder is low and this was confirmed by a very slow crack propagation. After a crack has arisen, a continuous redistribution of the effective load takes place with its propagation, which can lead to a delay of the crack propagation up to a temporarily crack stopping. Regardless of this, a repair of the bearing girder is required because of the possible serious damages to the main bearing shell with a potential impact to the crankshaft in case of uncontrolled crack propagation.

## 9. Conclusion

The procedure of structural durability validation of bearing girders in large two-stroke marine Diesel engines, as shown in this paper, is a basis for a reliable lightweight design of modern engines. It is also necessary to prove the cause and the responsibility in the case that the damages (failures) occur at operational usage.

The presented and analysed example proves the necessity of the presented procedure also to determine the quality assurance specifications and the requirements for the production repair welding.

Production repair welding in cast components is a normal practice. This kind of repair of casting defects can not be avoided for economical and practical reasons. Production repair welding is to be performed in accordance with the prescribed quality procedures, based on standards and correctly supervised accordingly by independent bodies.

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