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# Fatigue Failures in Industry and Their Repairs – Case Studies

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## Abstract

*In spite of numerous and expensive researches in the field of fatigue, cracks and failures caused by fatigue occur every day in all fields of human activity. The paper presents some typical fatigue damages in industry and transport. Fatigue failure of the main engine lateral support (at bulk carrier), fatigue cracks on the large portal crane, and fatigue cracks and failures of the large gear wheel of the cement mill are described. The complete fatigue damage analysis and repair procedures are presented, too.*

***Keywords**: fatigue cracks, fatigue damages, fatigue analysis and repair*

## 1. Fatigue failures on the main engine lateral supports

Fatigue failures of the main engine lateral supports appeared in series of new bulk carrier ships (38100 DWT, main engine power 7150 kW). These failures caused a significant financial impact to their owner, too. On all of these sister ships, supports cracked after approximately the same period of a few months of use.

### 1.1 Failure description

A consequence of the cracking of the supports, Fig. 1, is obligatory stopping of the main engine. After that had happened, the crew usually attached additional reinforcements until new supports were finished. Therefore, crack surfaces were not examined and only crack locations were known. The supports were cracked or failed on the location marked in Fig. 1.

Also, it was not known whether the crack started from the middle of the beam and spread towards the edges or vice versa. After cracking one of the supports, loads were probably redistributed, each time in a different manner. According to the description of cracks and failures, it was obviously that fatigue of material took place again, and its causes should be detected by detailed stress analysis.


**Fig. 1.** Bulk carrier "Don Frane Bulić"

### 1.2 Stress analysis

Due to the complicated shape of the crack area stress analysis was performed by means of strain gages. Strain gages were installed on all four beams (Fig. 2) in order to obtain operational loads (axial forces and bending moments).

The measurements took place during the sea trial of the new ship from the series. Measurement of local stresses was done at the locations of crack initiation spots, i.e. at the spot of the maximum stresses. As the observed bending moments were negligible, attention was put on the middle

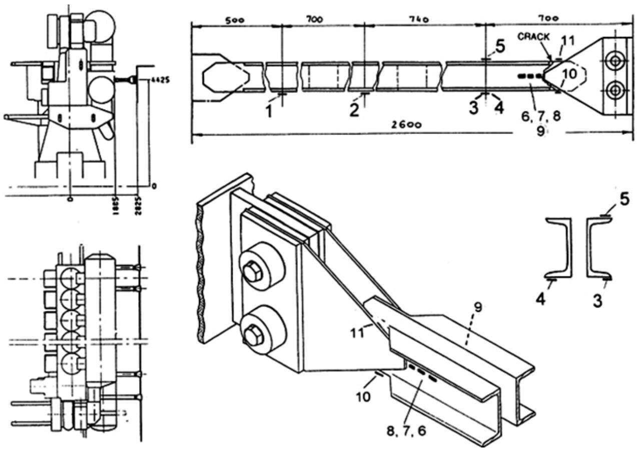



**Fig. 2.** Lateral engine support with observed failures and setup of the measurements for stress determination

of the joint. In order to obtain maximum stress, three strain gages were applied (15-17), Fig. 2. As all four supports were not manufactured geometrically identically, on the other side of support 3, strain gage 18 was applied as well as gages 21, 22, 23 on supports 1, 2, 4, respectively. A significant difference of the measured axial forces between the supports was detected. One of the beams was loaded with approx. 50% lower load. However, maximum axial force F = 20 kN (calculated from the nominal stresses) was within the range of design load values. Measurements gave no significant bending moments. The results of nominal stresses ($\sigma$ = 10¸15 MPa) could not be the reason for fatigue cracks, in spite of observed differences from one support to others. Stresses at the crack initiation points were measured to evaluate the quality of design. Three strain gages (15, 16 and 17) were used for extrapolation of maximal stresses. Maximum stresses at the welds toe are extrapolated. Their amplitudes vary depending on the weld design, but the measured values of 70 or even 80 MPa could easily cause the initiation and propagation of fatigue cracks.

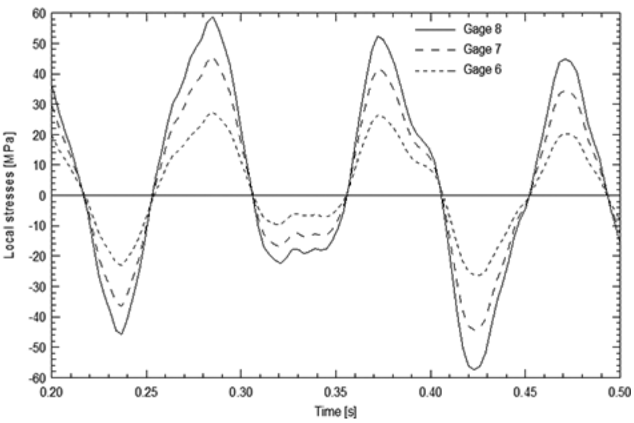



**Fig. 3.** Local stress determination

### 1.3 The first case study discussion

According to the existing S-N curves for such weldments and determined maximum stresses, it is possible to predict the fatigue life of approx. 5 x 10 6 cycles, or a few weeks of service. This service life is too short, compared with expected 20 years. This prediction had good agreement with the time to failure observed on the former ships. Failures are mainly caused by the inadequate joint design, the support and ship (hull) structure from one side, and insufficient weld quality. Namely, stress concentration factor in the critical area $\mathbf{s}_{loc}/\mathbf{s}_{nom}$ ~5 was quite unacceptable. It should be not more than 2 – 2.5, and **a** complete reconstruction of this important detail was necessary.

## 2. Fatigue cracks at large portal crane

This case study presents fatigue damage analysis and repair procedure that was carried out after the cracks at 250 kN portal crane were detected, Fig. 4. After a few years of crane service, fatigue cracks occurred at several critical points – bottom of the tower and both legs of the portal. Previous attempts of repair by simple welding of cracks were not successful, because new cracks were detected soon after the repair. When cracks reached the critical length, the exploitation of the crane was stopped and detailed analysis was carried out.

**Fig. 4.** Portal crane in Shipyard Split

### 2.1 Failure description

Cracks occurred at transition areas from vertical to horizontal supports on both legs, growing from the corners and bringing into danger the whole construction, Fig. 4. The first cracks were detected soon after the crane was placed in the shipyard, so the allowed carrying capacity was reduced from 250 kN to 50 kN, figure 4, but the cracks continued to grow. In order to find the source of crack initiation and growth, the complete documentation and calculations were checked. It was found that calculations were performed by using simple beam elements, without taking into account stress concentration, and influences of inertial forces and wind were underestimated. Those facts led us to perform complete static and fatigue analysis, to measure real stresses during typical manoeuvres and to redesign the critical places of the crane.

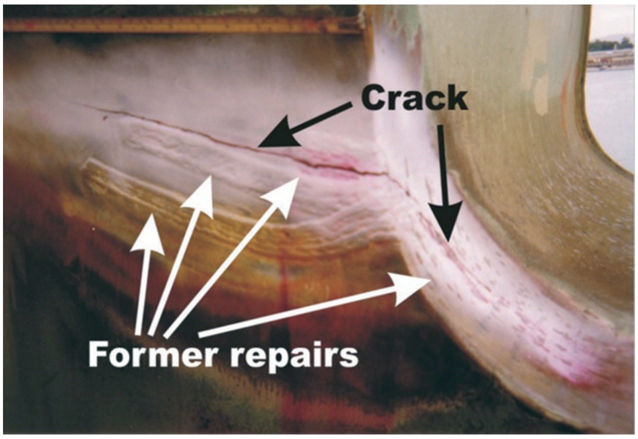



**Fig. 5.** Detected cracks

## 2.2 Measurement of stresses, COD and acceleration

To determine the dynamic behaviour of the construction strain gauges, two induction transducers for displacement and capacitive transducer for acceleration were applied. Test load was 50 kN, without wind during the measurement. All data were recorded during the typical working cycles of the crane and results were presented by a great number of diagrams. Based on the analysis of these diagrams, some general conclusions can be set out:

- the highest measure of stress amplitude was about 150 MPa, but in practice stresses can be higher, due to several reasons: – strain gauges were not attached at the places of highest stress concentration (access is not possible because of cracks)
- stress concentration factor ak is about 2, what is not theoretical maximum
- crack opening displacements reached 1.5 mm, what according to the Fracture Mechanics COD – concept indicates the stress of about 200-300 MPa
- measured values of acceleration were up to 0.2 m/s$^2$, what is acceptable, but during the test the crane was driven very carefully – in every day's use, and under the influence of wind, these values can be higher.

## 2.3 FEM Analysis

Finite Elements Method was used to determine the global stress distribution and to find out the weak points of the construction. Linear elastic model and 3D- Plate elements with four or three nodes and six degrees of freedom were used. The geometry of the lower part of the crane was defined by 2191 elements (2327 elements in variants with stiffeners). Boundary conditions were defined as follows:

– all six degrees of freedom on the nodes at the bottom contour of model were constrained,
– concentrated forces and bending moments are distributed along the nodes on the top of the model, representing the own weight of the upper part of the crane and particular load case. The complete analysis included 17 variants, with various loads, with or without stiffeners, with different orientation of the crane branch and including the construction weight. The mesh and typical results of FEM analysis are shown in Fig. 6.

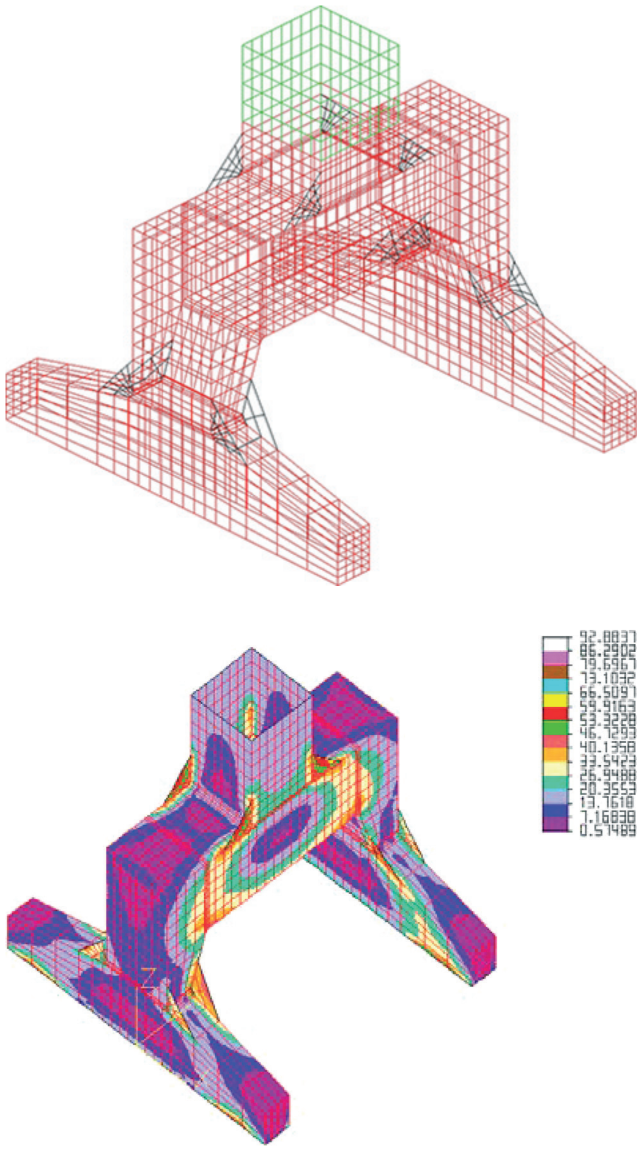


**Fig. 6.** FEM mesh and some results

## 2.4 Repair procedure

Strain gauge measurement and FEM analysis showed the source of the crack initiation – high stress concentration in the transition areas from the vertical to horizontal part of the supports. At critical points those stresses exceeded the fatigue strength of the material and caused the crack initiation and growth. Variable loads cannot be avoided, so the only solution was to redesign the critical areas in order to redistribute local stresses. FEM analysis also showed the best way for redistribution of high stresses: application of triangle stiffeners that fit the existing construction (Fig. 7). Those stiffeners were welded by using the MAG process. Heat treatment was used to minimize residual stresses, and fatigue limit of welds increased by grinding the weld toes and roots. After the repair was completed, stresses at critical points were measured once again and compared to the values predicted by FEM. According to the data obtained from FEM and strain gauges measurements, it is clear that stresses at critical points were significantly lowered, especially in critical areas. All the stresses were under the fatigue limit, so the main source of crack growth was removed.

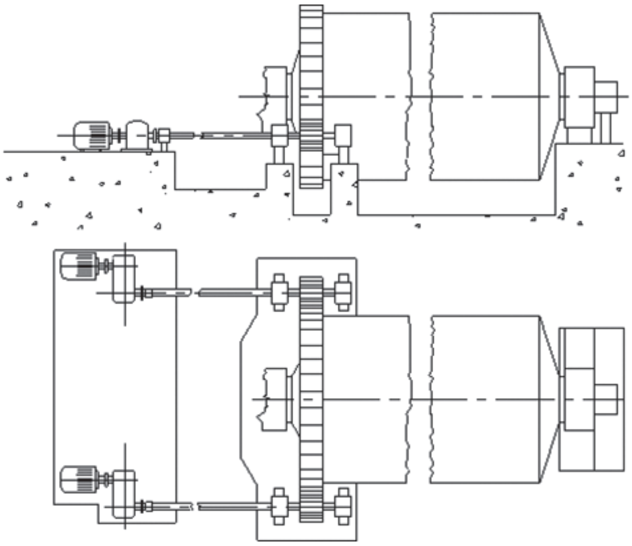
**Fig. 7.** Positions of attached strain gauges

## 2.5 The second case study discussion

The sharp transition from vertical to horizontal plates at the crane leg caused the initiation and growth of fatigue cracks that endangered the whole construction. By replacing the plates with cracks and applying the stiffeners at the places of the crack initiation, the sources of fatigue damages were removed and the maximum stresses at the redesigned construction were lowered to approximately one half of the previous values. Later examinations of the crane construction confirmed the success of this repair – two years after repair no new cracks were detected.

## 3. Fatigue cracks at cement mill gear

After 20 years in service, the great gear wheel of cement mill, Fig. 7, failed due to fatigue. When the whole mill plant was stopped and inspected, additional seventeen fatigue cracks were found at the tooth fillets. The gear wheel was fabricated of cast steel and mounted in two ring parts at the front side of the cement mill, Fig. 8.

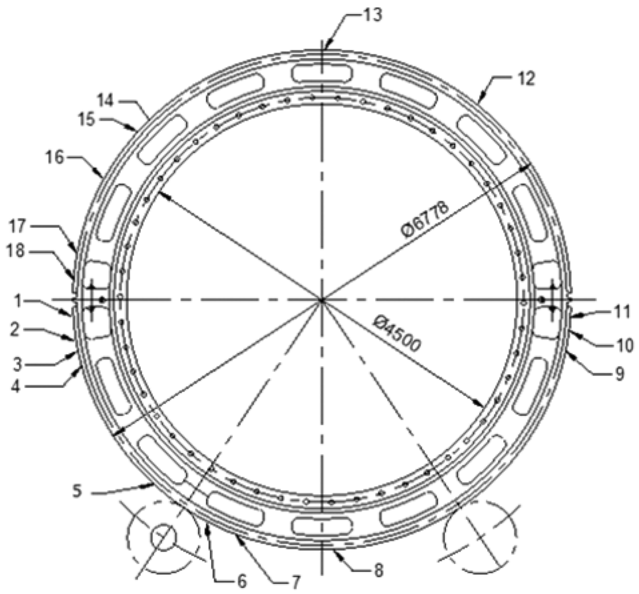


| | Large gear | Small gears |
|---|---|---|
| Med. diameter | 6778 mm | 960 mm |
| Teeth width | 600 mm | 600 mm |
| Tooth number | 230 | 32 |
| Module | 30 mm | 30 mm |
| Gear rim thick. | 80 mm | 160 mm |
| Gear mass | 25000 kg | 2815 kg |

**Fig. 8.** Cement mill and its characteristics

### 3.1 Failure description

At several positions, very close to the surface, a lot of casting errors (pores, slag inclusions, etc.) were found, Fig. 8. Joint efforts of alternating stresses, casting errors (sized several millimeters to several centimeters) and most likely existence of residual tensile stresses caused fatigue cracks initiation and propagation at the critical positions. The cross section of the gear rim, where complete fatigue failure occurred (fatigue crack No. 2), was additionally weakened by decreasing the rim thickness due to connecting bolts. The position of the cracks is shown in Fig. 7. The surface crack length varied from 20 mm to 600 mm (total failure). The position and size (surface length) of each discovered crack were estimated by means of non-destructive testing (magneto-flux method). In order to determine the complete data on crack shape and size (depth), and to perform repair welding, voluminous work (cracks removal by arc-air grooving) was undertaken.




| Fatigue crack number | Crack position (teeth number) | Crack surface length (mm) |
|---|---|---|
| 1 | 2-3 | 200 |
| 2 | 3-4 | 600, failure |
| 3 | 16-17 | 290 |
| 4 | 19-20 | 330 |
| 5 | 24-25 | 20 |
| 6 | 26-27 | 315 |
| 7 | 32-33 | 50 |
| 8 | 63-64 | 320 |
| 9 | 112-113 | 250 |
| 10 | 113-114 | 180 |
| 11 | 114-115 | 200 |
| 12 | 158-159 | 100 |
| 13 | 168-169 | 400 |
| 14 | 209-210 | 160 |
| 15 | 210-211 | 60 |
| 16 | 216-217 | 120 |
| 17 | 229-230 | 200 |
| 18 | 230-231 | 90 |

**Fig. 9.** Detected cracks on the cement mill

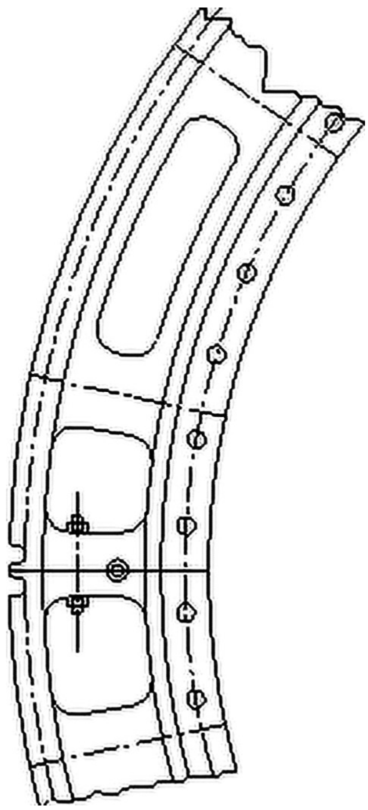


**Fig. 10.** Additionally weakened gear by decreasing the rim thickness due to connecting bolts (position 2 from Fig. 7)

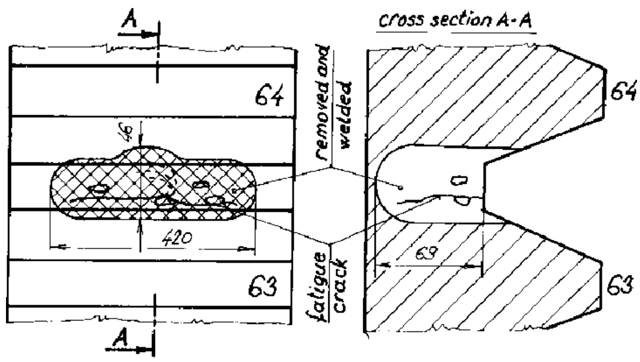



**Fig. 11.** Typical fatigue crack on the cement mill

### 3.2 Stress analysis and fatigue cracks repair

During each revolution of the cement mill and large gear, every tooth was loaded twice (two small gears) by tooth force alternating from zero to the maximum value. Numerical method (FEM) was used to determine the stress distribution at the gear rim. Calculated maximum stress amplitudes were found at the tooth fillet, approximately 50 – 115 MPa, depending on their positions on the surface. Stress intensity decreased very fast in the depth of the gear rim.

These stress values could not be the only reason for cracks initiation and propagation. In spite of a great number of cracks and one complete failure of the gear ring, repair welding was performed. All necessary steps for the best quality insurance (best welders, best welding rods, pre-heating, very slow cooling conditions, NDT inspection following every layer, hammering of all layers, etc.) were respected and documented.

All described activities took two months and cost approx. $50 000 instead of $300 000 for a new gear ring and four months for its delivery and assembly. Three years after repair and frequent controls during the service, no further cracks were reported.

## 4. Conclusion

The case studies presented in this paper illustrate the circumstances of an inappropriate design, from the fatigue point of view. It is obvious that in the case of variable

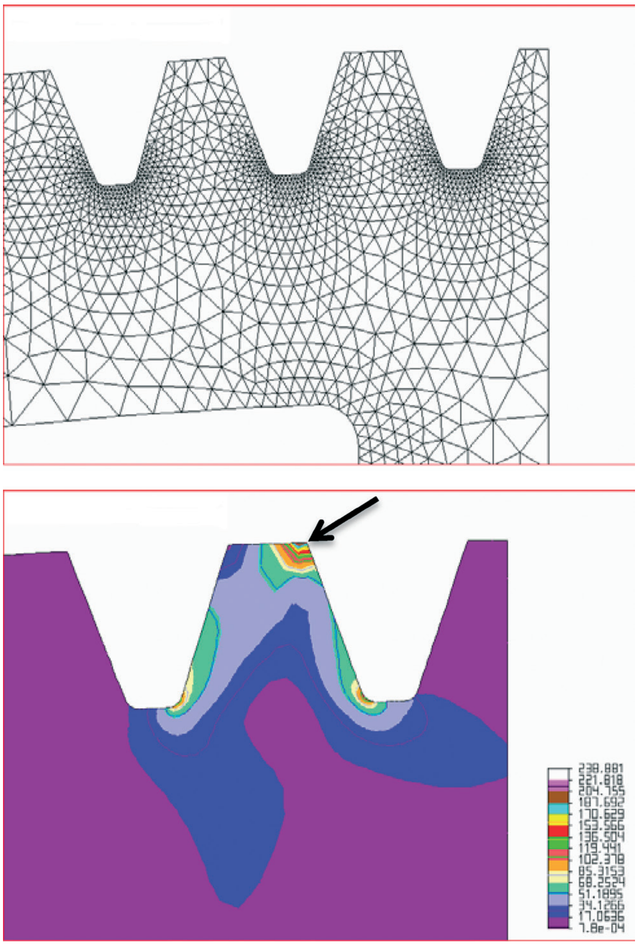


**Fig. 12.** Stress distribution and stress concentration

**Fig. 13.** Cracks removal by arc-air grooving before repair welding and subsequent slow cooling

loads, special attention should be paid to fatigue crack avoidance and fatigue crack repairs as well. A lucky circumstance with many fatigue failures is a relatively long crack propagation period from its origin to the final failure and a crack can be detected easily. What to do with detected fatigue cracks is a well-known question in such situations. The usual answer is one of the following actions:

- instantaneous unloading of the entire system and replacing the cracked component
- reducing the external loads and continuing careful crack growth control, and
- retarding, stopping or even eliminating the crack (crack repair) in a very short time.

As the complete replacement can be time consuming and expensive, and the reduction of service loads with existing fatigue crack is very dangerous and mostly unacceptable, fatigue crack repairs seem to be the best solution. The necessary steps for a successful repair of fatigue cracked component should be [Domazet 1996]:

a) Damage analysis: the first step with any damage and its possible repair should be damage analysis. It should give answers to some important questions, such as: what is the reason for the fatigue crack, how dangerous is the existing fatigue crack, how long is the remaining component life, etc.

b) Damage repair: the most frequent fatigue crack repair methods are: repair welding, metal reinforcements, CFRP patches, arrest holes, etc. The final choice of the adequate method and its parameters depend on all data obtained by damage analysis and knowledge of repair methods. The role of experience and case studies from literature should not be avoided either.

c) Reliability of repaired component: reliability of remaining life estimation of repaired components in accordance with new stress distribution and possible improvements of fatigue strength. For this reason, the S-N curve of the base component should be known. At this stage control interval and control type (some of non-destructive test methods) should be defined.

d) Documentation: correct and complete documentation of all undertaken activities, as well as quality insurance, represent the evidence of good work and valuable source of future repair jobs.

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