INTERNATIONAL DESIGN CONFERENCE - DESIGN 2002
Dubrovnik, May 14 – 17, 2002

FATIGUE FAILURES IN INDUSTRY – CASE STUDIES

Ž. Domazet and T. Piršic

Keywords: Fatigue cracks and failures, repair welding, FEM

1. Introduction

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 at large portal crane, and the fatigue cracks and failures in large gear wheel of cement mill are described.

2. Fatigue failures on the main engine lateral supports

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

2.1 Failure description:

Consequence of the cracking of the supports, figure 1, is obligatory stopping of the main engine. After this had happened, the crew usually had attached additional reinforcements until new supports have been finished. Therefore crack surfaces were not examined and only crack locations were known. Supports have been cracked or failured on the location marked on figure 1.

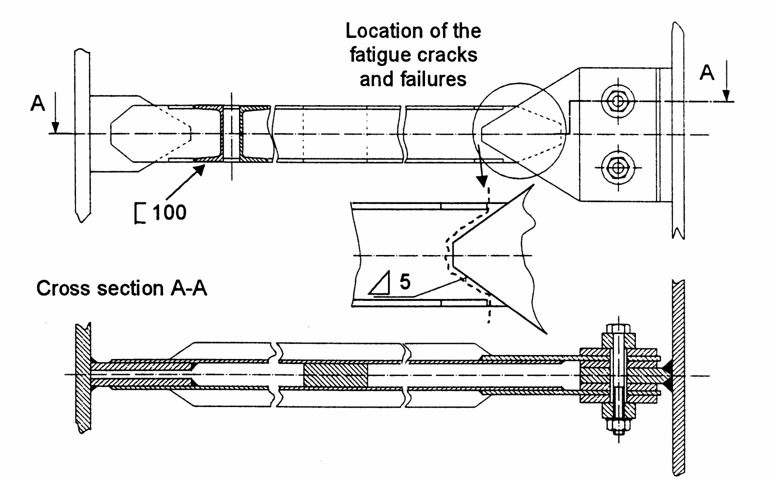

Figure 1. Lateral engine support with observed failures

Also it was not known whether crack started from the middle of the beam and spread towards 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 a place again, and its causes should be detected by detailed stress analysis.

2.2 Stress analysis

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

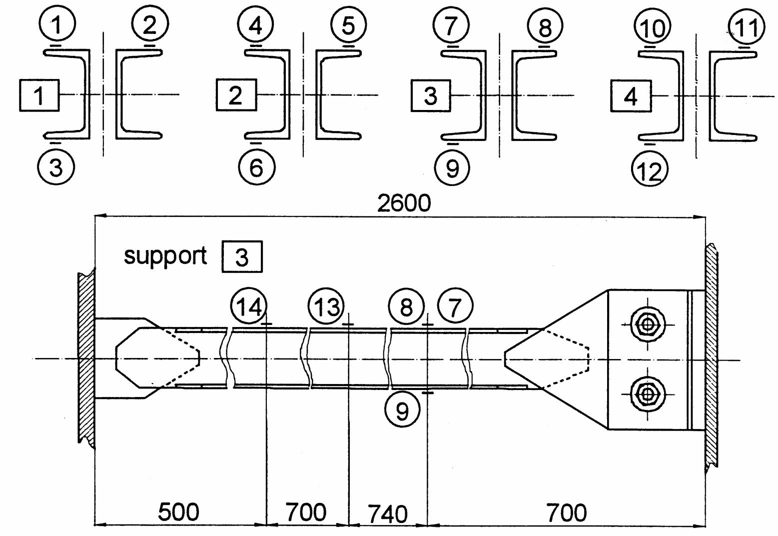

Figure 2. Setup of the measurements for nominal stresses determination

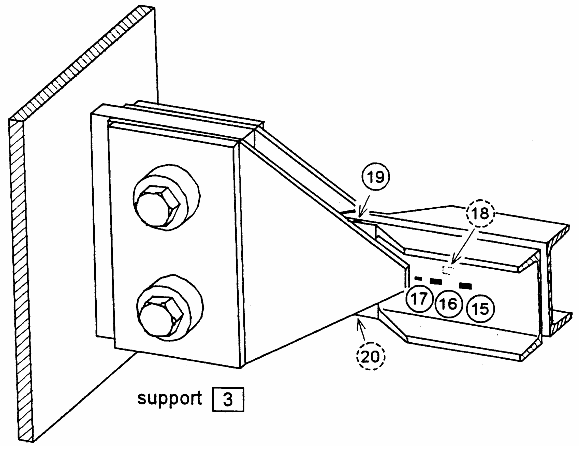

Figure 3. Strain gauges for local stres determination

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 maximal stresses. As the observed bending moments were negligible, attention was put on the middle of the joint. In order to obtain maximal stress, three strain gages were applied (15-17), figure 3. As all four supports were not manufactured geometrically identical, on the other side of support 3, strain gage 18 is applied as well as gages 21, 22, 23 on supports 1, 2, 4, respectively. The significant difference of measured axial forces between supports was discovered. One of the beams was loaded with approx. 50% lower load. However, maximal 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 ($\sigma = 10 \div 15$ 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. Maximal stresses at the welds toe are extrapolated. Their amplitudes vary depending on weld design but measured values of 70 or even 80 MPa could easily cause the initiation and propagation of fatigue cracks.

2.3 The first case study discussion

According to existing S-N curves for such weldments and determined maximal 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 is in good agreement with the time to failure observed on former ships. Failures are mainly caused by inadequate joint design, of the support and ship (hull) structure from one side, and insufficient weld quality. Namely, stress concentration factor at critical area $\sigma_{loc}/\sigma_{nom} \approx 5$ is quite unacceptable. It should be not more than 2 ÷ 2.5, and reconstruction of this important detail was necessary.

3. 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. After few years of crane service, fatigue cracks occurred at several critical points – bottom of the tower and both legs of 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.

3.1 Failure description

The cracks occurred at transition areas from vertical to horizontal supports on both legs, growing from the corners and bringing into danger the whole construction, figure 4. 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, 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 the simple beam elements, without taking into account the stress concentration, and the influences of inertial forces and wind were underestimated. Those facts led us to perform the complete static and fatigue analysis, to measure the real stresses during the typical manoeuvres and to redesign the critical places of the crane.

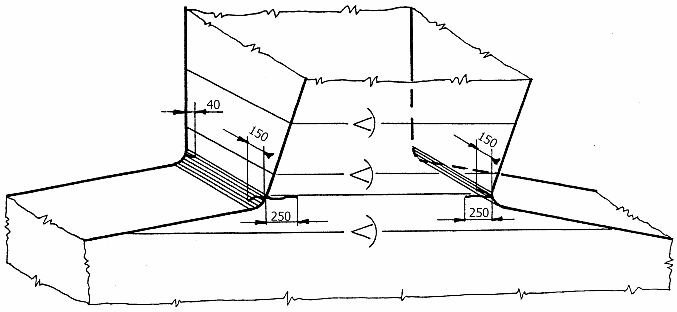

Figure 4. Detected cracks

3.2 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, and there were no wind during the measurement. All data were recorded during the typical working cycles of the crane and results were presented by great number of diagrams. Based on the analysis of these diagrams, some general conclusions can be set:

- the highest measure stress amplitude were about 150 MPa, but in practice stresses can be higher, because of several reasons: - strain gauges were not attached at the places of highest stress concentration (access is not possible because of cracks)
- stress concentration factor αk 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/s2, what is acceptable, but during the test the crane was driven very carefully – in every day’s use, with the influence of wind, these values can be higher.

- it is interesting to notice that the stresses were mostly caused by the manoeuvres of the crane – stresses caused by the loads were not significant.

3.3 FEM Analysis

Finite Elements Method was used to determine the global stress distribution and to find out the weak points of construction. Linear elastic model and 3D- Plate elements with four or three nodes and six degrees of freedom was 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 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 crane branch and including the weight of construction. Typical results of FEM analysis are shown on figure 5.

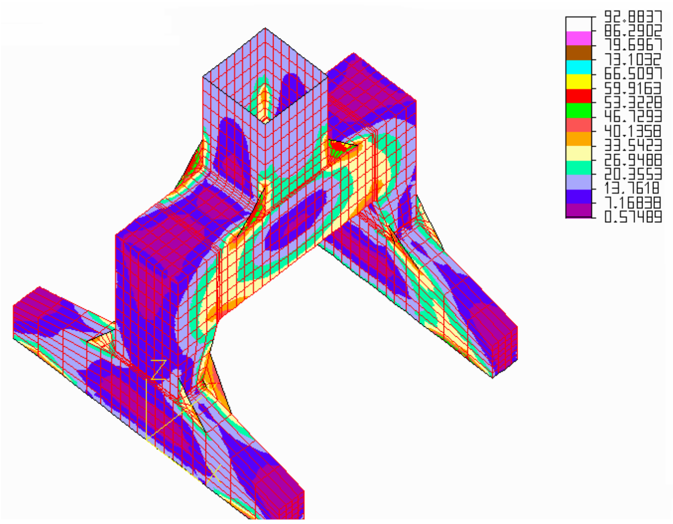

Figure 5. Typical stress distribution

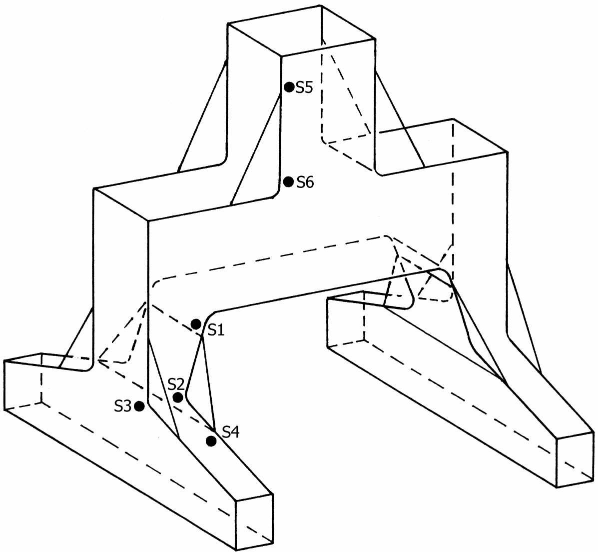

Figure 6. Positions of attached strain gauges

3.4 Repair procedure

Strain gauge measurement and FEM analysis showed the source of crack initiation – high stress concentration in the transition areas from vertical to horizontal part of the supports. At critical points those stresses exceeded the fatigue strength of 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 the local stresses. FEM analysis also showed the best way for redistribution of high stresses: application of triangle stiffeners that fit the existing construction (figure 5). Those stiffeners were welded by using MAG process. The heat treatment was used to minimize the residual stresses and fatigue limit of welds was 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. Places where strain gauges were attached are shown on figure 6, and the results are shown in Table 1. Presented results are approximate, because the strain gauges cannot be attached perfectly at the same positions. According to data from Table 1., it is clear that the stresses at critical points are significantly lowered, especially in critical areas. All the stresses are under the fatigue limit, so the main source for crack growth is removed.

Table 1. Comparison of stresses before and after repair

Strain gauge	S1	S2	S3	S4	S5	S6
Max. stress without stiffeners (MPa)						
Measured	Not measured	Not measured (crack)	50-100	30	50	150
FEM	100	360	110	60	50-60	300
Max. stress with stiffeners (MPa)						
Measured	100	120	20	30	70	50-70
FEM	100	180	15-20	60	60-80	100

3.5 The second case study discussion

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

4. Fatigue cracks at cement mill gear

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

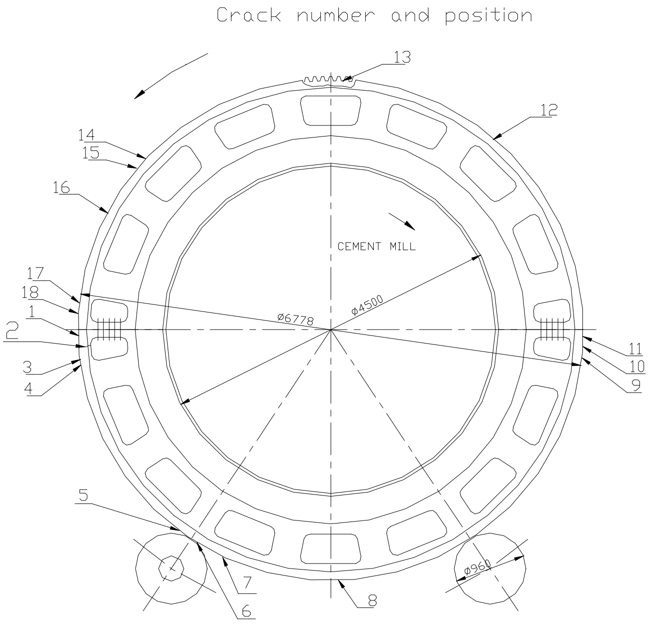

Figure 7. Detected cracks on cement mill

4.1 Failure description

At several positions, very close to the surface, a lots of casting errors (pores, slag inclusions, etc.) have been found, figure 7. Joint efforts of alternating stresses, casting errors (sized several millimetres to several centimetres) and most likely existence of tensile residual 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 showed on figure 7. The surface crack length varied from 20 mm to 600 mm (total failure). 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 has been undertaken.

4.2 Stress analysis and fatigue cracks repair

During every revolution of cement mill and large gear, every tooth has been 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 have been found at the tooth fillet, approximately 50 - 115 MPa, depending on their positions at the surface. Stress intensity decreases 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 great number of cracks and one complete failure of 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.) have been respected and documented. All described activities took two months and cost approx. $50 000, instead of $300 000 for new gear ring and four months for its delivery and montage. Three years after repair and frequent controls during the service, no further cracks have been reported.

5. Conclusion

The case studies presented in this paper illustrate the circumstances of inappropriate design, from fatigue point of view. It is obvious that in the case of variable 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 crack can be discovered easily. What to do with discovered 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 reduction of service loads with existing fatigue crack is very dangerous and mostly unacceptable, fatigue crack repairs seem to be 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 adequate method and its parameters depends 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 repaired components estimation of components remaining life in accordance with new stress distribution and possible improvements of fatigue strength. For this reason, the S-N curve of base component should be known. In this stage control interval and control type (some of non-destructive testing methods) should be defined.
d) Documentation: correct and complete documentation of all undertaken activities, as well as quality insurance, represents evidence of good work and valuable source for future repair jobs.

References

Domazet, Ž., Engineering Failure Analysis, Vol. 3, No. 2, 1996., pp. 137-147.
Domazet, Ž., Lozina, Z., Piršic, T., Mišina, N., Đukic, P., FESB Report No. 01/99, Split, 1999.
Domazet, Ž., Barlè, J., Đukic, P., FESB Report No. 14/01, Split, 2001.

Prof. dr. Željko Domazet
Faculty of Electrical Engineering, Mechanical Engineering
and Naval Architecture, University of Split
Mechanical Engineering Department
R. Boškovica bb, 21000 Split, Croatia
Telephone (021) 305-770, Telefax (021) 463-877
Email: zeljko.domazet@fesb.hr