# Problems due to faulty design in welded steel structures in cranes

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**Abstract**

This paper deals with fundamental problems related to welded steel structures in cranes, and it is based on many years' experience of crane inspections and condition monitoring in Sweden. In general, failures in steel structures and machines occur due to faulty designs, poor material quality, bad manufacturing processes, handling faults, and a defective maintenance. Only the problems related to Faulty machine design are treated here. Welded joints, in particular, are very sensitive to fatigue loads, corrosion, low welding quality or a combination of these situations. Old cranes were designed according to standards with a limited fatigue analysis, which resulted in weak welded joints. Fortunately, newer standards include more detailed and precise calculation processes that usually lead to better results. Nowadays there exists a wide series of new high tensile weldable steels; however, although they show very high static yields and ultimate strength, the fatigue strength (endurance limit) is very far from 100% in relation with the static strength. One of the biggest difficulties for designers is placing the welds on suitable places, i.e. on places with low stress. These stresses, however, can be relieved by a heat treatment directly applied after welding, but this technique is expensive and difficult to accomplish. Multiple examples of crane failures and failure analysis are presented along the text. Some of them were discovered during the inspections and therefore fatalities were avoided; other failures, unfortunately, led to catastrophic crashes and death accidents.

## 1 Introduction

Cranes exist in an enormous variety of forms – each tailored to a specific use. Sometimes sizes range from the smallest jib cranes, used inside workshops, to the tallest tower cranes, used for constructing high buildings. We can even find large floating cranes generally used to build oil rigs and salvage sunken ships. Hence cranes are used in many different environments and are subjected to different loads. So, for example, a crane used in an industrial workshop where the ambient temperature is constant around the year will necessarily suffer less and last longer than a harbor crane working in a corrosive environment with changing temperatures, and, above the lifting loads, is subjected to wind, snow, and ice loads.

Since cranes are normally used for lifting loads, they must be light-weighted in order to maximize their load capacity at the same time that a reduction of weight results in material savings and a reduction of cost. For this purpose, carrying beams consist of steel bars and plates where welded joints make an important contribution to the strength and life length of cranes. The crane frames and other mechanical parts related to them are subjected to variable loads and must be dimensioned for fatigue failures. The welding technology of today provides an excellent joining capacity for the flexible fabrication of different machine parts and structures; however, welded joints may represent the weakest part of structures when improperly done. Modern advances in welding techniques and equipment have provided engineers with a range of attractive choices for fastening, as an alternative to bolts or rivets for fabricating parts. Furthermore, machine elements can often be manufactured at lower cost by welding than by casting or forging [1]. Figure 1 shows three examples of machine parts fabricated by welding. The majority of industrial welding is done by fusion, with the joining pieces melting at their common surfaces. The quality and strength of welded joints depends on the design, dimensioning, and manufacturing processes. Weak designs, wrong dimensioning, residual stresses in the joints or metallurgical changes in the base material will decrease the life of crane structures and may eventually lead to catastrophic failures involving severe injuries and even death. The right design of welded joints requires taking multiple aspects into consideration, such as the manner of loading the joints, the materials involved in the weld, and the geometry of each joint itself [2].

An incorrect material selection may result in brittle material as well as welding problems such as cracking. Welding procedures have to be correctly formulated and approved to avoid imperfections. Supervision needs to be implemented to insure that the quality specified in current standards will be achieved. To assure fabrication with effective welding, workshop managers need to be aware of the source of potential troubles and introduce appropriate quality procedures[3]. Since heat is used in welding operations, certain metallurgical changes take place in the parents (base) metals around the vicinity of the weld. When the reliability of the components is high, a testing program should be established to learn what changes or additions to the operations are necessary to ensure the best quality [4]. Breakdowns of welded structures are usually the consequence of fatigue loading. Fatigue fractures are commonly initiated in the region close to the weld toe but can also begin in the weld root and from discontinuities inside the weld [5]. In general, failures in steel structures and machines occur due to faulty designs, poor material quality, bad manufacturing processes, handling faults, and a defective maintenance. These different reasons for failure in cranes and lifting machines are discussed below, and the conclusions drawn from this analysis are based on a long experience over many decades of inspection of such devices and machines.

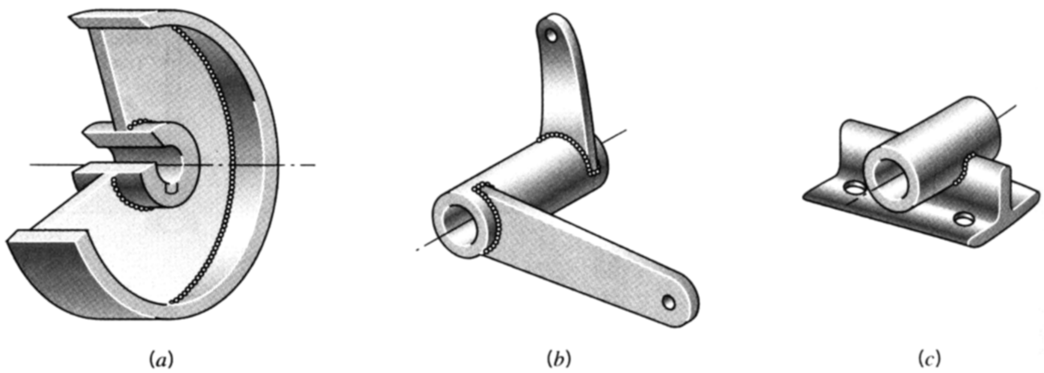



Figure 1: Examples of machine parts fabricated by welding

## 2 Problems due to Faulty Designs and Poor Material Quality

In mechanical engineering, the design stage is probably the most important stage for the life length of machine components. Piece dimensioning and design, material selection, manufacturing methods, quality control, safety, ergonomics, etc. will be decided in this stage. Also, the budget assigned to the project and its economical limitations are typically fixed under or before this stage, and must be taken into consideration. Gurney [6] stated that in the design of a component or structure the designer has to satisfy three conditions:

1. It must be able to perform its specified functions as efficiently as possible.
2. It must be capable of being fabricated economically.
3. It must be capable of providing an adequate service life.

As a direct result of the first and second of these conditions the modern trends in engineering design are to reduce factors of safety to a bare minimum, in order to reduce weights and costs, and to increase the speed of operations of machines and production processes, in order to make the most efficient use of the invested capital. Unfortunately both these trends tend to work against the designer in his efforts to obtain an adequate service life, particularly in cases where fatigue failure is likely to occur. Perhaps it is therefore not so surprising that it has been estimated that 90% of the failures which occur in engineering components can be attributed to fatigue [6]. A great number of evidences from machine inspections show that Gurney's statement is very true.

The strength of welded joints depends on many factors that must be properly controlled in order to obtain high quality welds. The heat of welding may cause metallurgical changes in the parent (base) metal in the vicinity of the weld. Residual stresses may be introduced through thermal gradients, which cause differential expansion and contraction patterns, the influence of clamping forces, and the changes in yield strength with temperature. Residual stress and wrapping problems are most pronounced when welding pieces of varying thickness and irregular shape, although these problems can be avoided by heating the parts to a uniform temperature before welding, following detailed "good-welding practice" for the application involved, giving the weldment a low-temperature stress-relieving anneal after welding, and shot-peening the weld area after cooling [2]. Some advantages of welded joints over threaded fasteners are that they are inexpensive and there is no danger of the joint loosening. Some disadvantages of welded joints over threaded fasteners are that they produce residual stresses; they distort the shape of the piece, metallurgical changes occur, and disassembly is usually a hard problem [7]. This statement fits very well with the experiences learned from inspecting cranes.

The essential points made by the authors in this article are the following:

1. Residual stress distortions can give tolerance failures in general purpose steel structures. Gearboxes with bad tolerances, due to welding problems like wrapping, when connected to motors and rope drums can result in dangerous failures and crashes. Figure 2 shows a gearbox case where the gear flank is loaded only on one side due to an incorrect shaft parallelism, what eventually resulted in pitting defects.

2. Residual stresses can also lead to stress relaxation and deformations, directly after welding or later in service, due to external loads. In general, steel structure tolerances are regulated in standards such as European Standards EN 1090-2 [8].

3. The residual stresses should be added to the load stresses in the fatigue-based calculation of total life time. This is a very common problem, especially for very high tensile steels, and its importance must be highlighted.

4. In the case of welded joints, the term "High quality" should be changed to "Right quality" in order to take economical considerations into account.

It is very important to pay extra attention to the dimensioning procedure of welded structures subjected to variable loads. Most of the cranes included in this research are quite old, and they were designed according to old standards. The handbook "Design with Weldox and Hardox" [9] which is based on the 1970's Swedish Standard for steel structures StBK-N2 greatly differs from current fatigue-based procedures for the estimations of

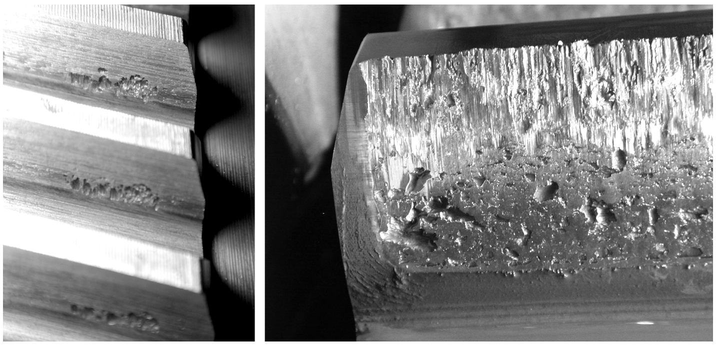


Figure 2: Pitting failure on one side of the gear due to the lack of parallelism of the shaft supports of a gearbox housing

allowable stresses, traditionally based on static models. The static strength for a Weldox 960, for example, is 960 MPa, and if we use the recommended safety factor of 1.5 the final allowable static yield strength is reduced to 640 MPa. On the other hand, the fatigue strength (endurance limit) for fully reversed loading using a probability of failure QB $<$ $10^{-5}$ (according to StBK-N2) with a fatigue stress concentration factor Kx = 5 (fillet welds in weld class WB), for infinite life (N = 2 x $10^6$), the resulting allowable fatigue strength is less than 39 MPa. As this comparison proves, the fatigue strength of 39 MPa is only 6 % of the initial static strength of 640 MPa. For $10^3$ cycles, which can be considered as a static load, the allowable fatigue strength is reduced to 491 MPa. It is worth mentioning that the standard StBK-N2 has been replaced by Euro Code 3 [10], which should give about the same result.

The following set of photos illustrates a variety of failure modes found in welded joints taken during the inspection of cranes. These problems were found to be more common than expected.

Figure 3 represents two images of a mobile crane boom. These photos clearly show the cracks initiated in fillet welds (between the boom and a secondary plate), and how they evolved through the weld material.

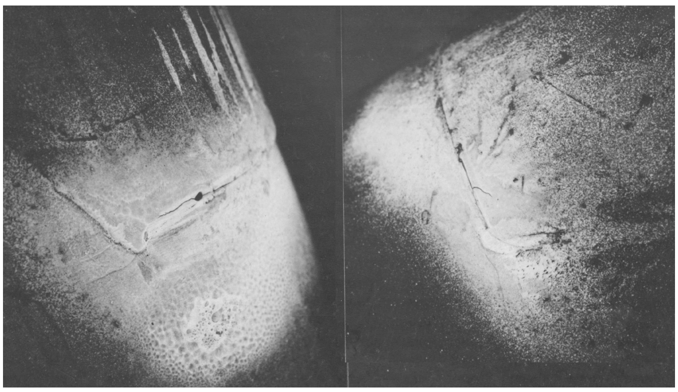


Figure 3: Cracks in fillet welds

Figure 4a shows the in-site inspection of a mobile crane boom. Figure 4b provides a close up of the crane boom welded with tubes used for protecting electrical cables. These tubes are fixed to the boom with a small weld. This arrangement produced an extra stress concentration in the weld, which initiated a crack on the boom at the area with the highest tension stress.

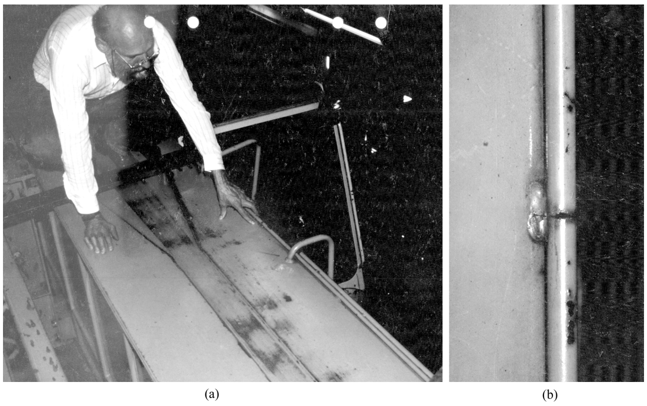



Figure 4: Inspection of a mobile crane (a) and crack in the weld joint (b)

Figure 5 provides typical examples of welded parts on booms. Figures 5a and 5c show a device for guiding steel ropes on the boom, which tends to be on the upper side of the boom. As seen in the schematic, the device is welded on the part of the boom with the highest tension stresses. It would be more effective to place the joints close to the neutral plane of the beam. Figure 5b depicts two L-shaped profiles introduced for reducing the clearance between telescoping booms at their most extended position. In this case, the welds are also placed on a high-stress area.

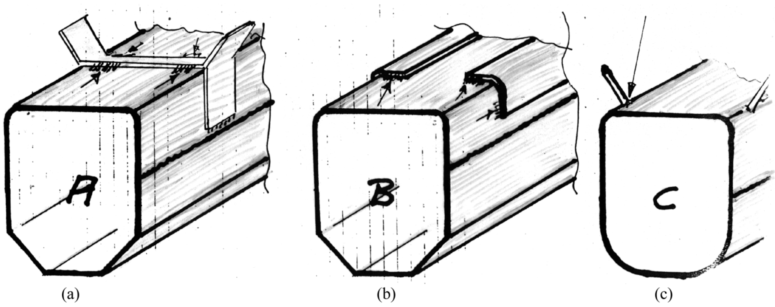



Figure 5: Examples of welded parts on booms

The summation of the different types of stress actuating on a beam must be calculated for the sections of the highest stress in order to calculate the total maximum stress. Figure 6 shows a diagram of how this addition can be carried out.

Figure 7a evidences how residual stresses can deform the upper flange of the head beam of an overhead traveling crane. Figure 7b is a close up of the crack of figure 7a, where it is shown that the crack goes through the whole flange used to support the crane rail. Similar problems have been reported in the crane runways, which imply that cracks may appear in both fillet welds and flanges. The round profile portrayed in the image is a backing support for the weld.

# 3 Conclusions

As shown along the text, the life of cranes is affected by many factors, from the dimensioning and design stage to crane handling and inspection. It is crucial to investigate type and magnitude of the loads affecting each part of the weld before conducting fatigue calculations. The quality of the material must match the minimum requirements set for a

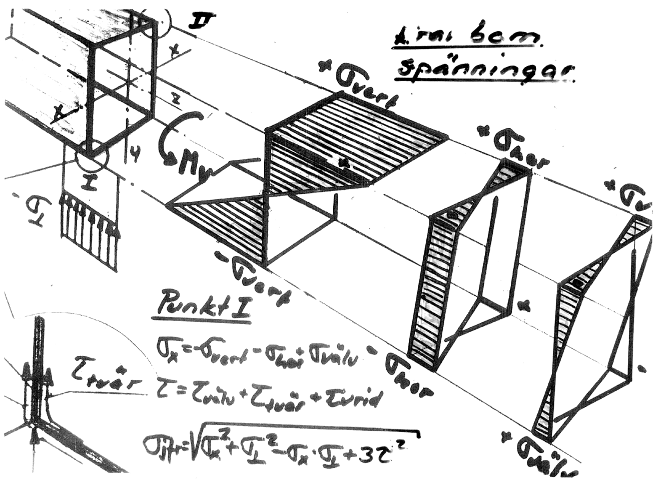
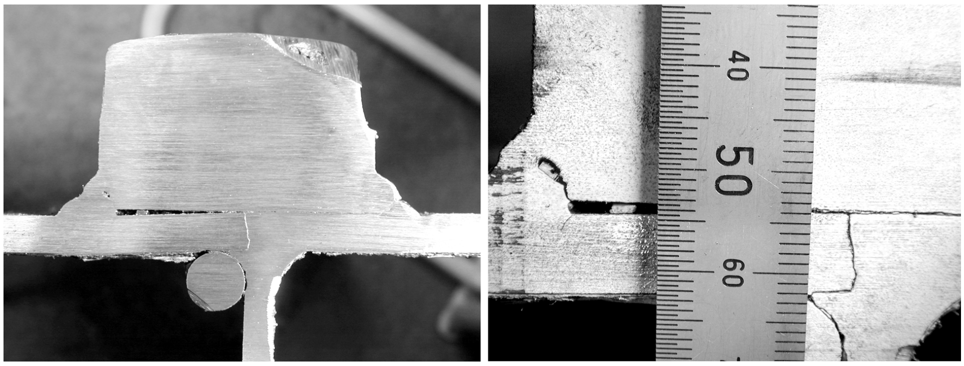



Figure 6: Calculation of stresses in beams




(a) (b)

Figure 7: Deformations and cracks provoked by residual stresses

reliable design. Although the negative effect of corrosion has not been covered in this work, it is important to keep in mind its consequences, as corrosion turns the ductile material into brittle, and destroying the material from the surface. As a matter of fact, welds are particularly sensitive to corrosion, especially when combined with fatigue loading; therefore, crane structures must be coated with paint or other protecting chemicals. Sometimes, a disadvantageous design induces water and dirt to come inside unprotected beams and structures. This detrimental situation facilitates corrosion in hidden spots not easy to detect with visual inspection. Failures in crane structures may lead to extremely dangerous situations for people in or around the cranes, and it normally leads to massive economical losses. Therefore, at the challenging dichotomy faced by the designer between cost and quality, the quality, the safety, and the future failure consequences of the crane must be given clear priority.

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