Problems with Welded joints in Steel Structures

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Problems with Welded joints in Steel Structures: *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. Welded joints, in particular, are very sensitive to fatigue loads, corrosion, low welding quality or a combination of these situations. This analysis shows that failures due to poor designs are most significant for highly fatigue-loaded structures. 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. One of the biggest difficulties for designers is placing the welds on suitable places, i.e. on places with low stress. Welded joints must be executed by professionals who follow the Welding Procedure Specifications (WPS), as the process of welding often induces residual stresses in the structures. The influence of operators when handling cranes is also significant for the proper duration of cranes. 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.*

Key words: *failures and problems with welded joints; steel structures; cranes, failure analysis.*

INTRODUCTION

Steel structure is a structure which is made from organized combination of structural steel members designed to carry loads and provide adequate rigidity. Structural member is physically distinguishable part of structure with independent structural function, e.g. member, element, cable and their combination [1]. The steel members are joint to each other by screw joints, welded joints or rivet joints, but this paper is dealing only with welded joints in steel structure with experiences from cranes.

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. 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].

For welded constructions to be effective and free from serious problems in production and service, it is necessary to provide a regular controlling strategy, from the design phase through material selection, into fabrication and subsequent inspection. For example, a poor welding design may create serious and costly difficulties in the workshop, on site, or in service. 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. 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 [3]. 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 [4]. 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 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.

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. Gurney [5] 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 factors of safety must be reduced to a bare minimum, in order to reduce weights and costs, and to increase the speed of operations of machines and production processes. Unfortunately this result tends 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 [5]. A great number of evidences from machine inspections show that Gurney's statement is very true. On top of that, it happens very often that the welding quality in reality is lower than what is recommended in the WPS.

The strength of welded joints depends on many factors that must be properly controlled in order to obtain high quality welds. 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. 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 [6]. 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 steel structures.*
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 [7].*
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 economic considerations into account.*

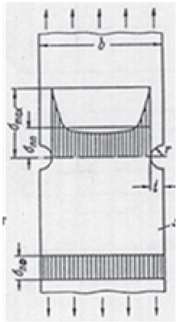
The residual stresses in many steel materials can be relived through a heat treatment process, but this process is quite costly and unfeasible for huge structures. An alternative way of relieving residual stress is by subjecting the structure to tension stress up to the yield strength limit and then reloading it [8]. 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 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 106), 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.

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.

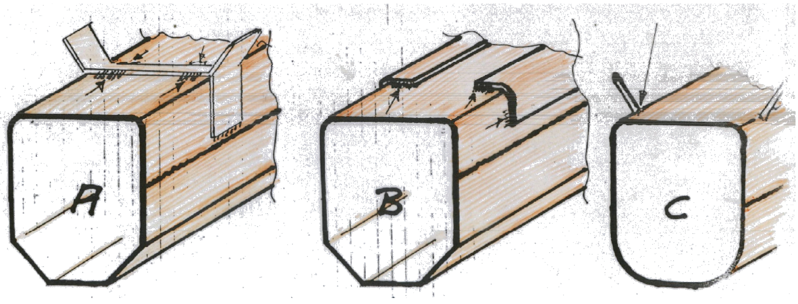
- Figure 1 represents an image of a mobile crane boom. These photos clearly show the cracks initiated in fillet welds (between the boom and a secondary plate), and how they evolved through the weld material.
- Figure 2a provides a close up of the crane boom welded with tubes used for protecting electrical cables. These tubes are fixed to the boom with a small weld. This arrangement produced an extra stress concentration in the weld (see figure 2b), which initiated a crack on the boom at the area with the highest tension stress.
- Figure 3 provides typical examples of welded parts on booms. Figures 3a and 3c 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 3b 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.

Fig. 1. Cracks in fillet welds

Fig. 2. a. Crack in the weld joint



b. Stress raiser



(a) (b) (c)

Fig. 3. Examples of welded parts on booms

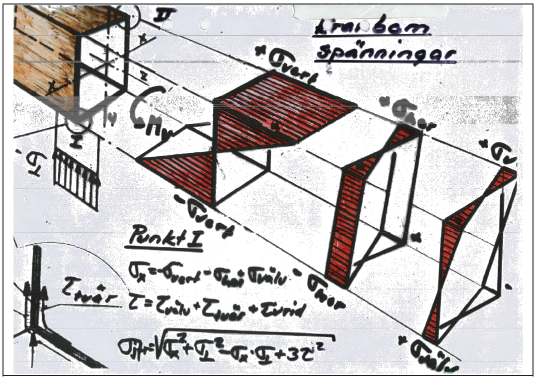
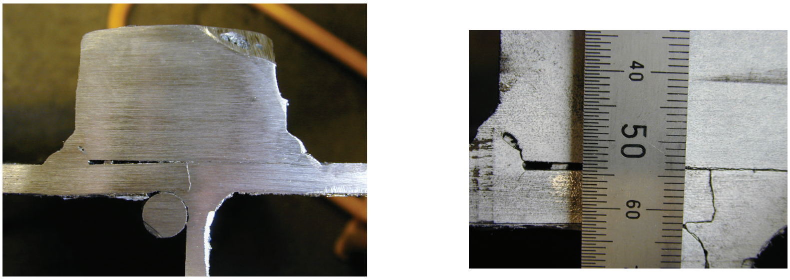


Fig. 4. Calculation of stresses in beams

- 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 4 shows a diagram of how this addition can be carried out.



a b

Fig. 5. Deformations and cracks provoked by residual stresses

- Figure 5a evidences how residual stresses can deform the upper flange of the head beam of an overhead traveling crane. Figure 5b is a close up of the crack of figure 8a, 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.

PROBLEMS DUE TO POOR MANUFACTURING PROCESSES, HANDLING FAULTS, AND IMPROPER MAINTENANCE

Many problems found in welding joints have been related to manufacturing processes. Crane welds must be accomplished by highly skilled professionals who comply with quality procedures and industry standards. As mentioned before, some of the problems detected in the inspections are caused by residual stresses, but the welding process itself and weld bead shapes have a significant impact on the quality of the welds. According to the James F. Lincoln Arc Welding Foundation [10], several types of discontinuities may occur in welds on heat-affected zones. Welds may contain porosity, slag inclusions or cracks. Of the three, cracks are by far the most detrimental and are never acceptable, whereas there are acceptable limits for slag inclusions and porosity in welds. The cracking discussed here is the result of solidification, cooling, and the stresses that develop due to weld shrinkage. Weld cracking occurs close to the time of fabrication (hot and cold cracks). The different types of weld cracking are discussed below:

Centerline Cracking (Figure 6a): Centerline cracking is characterized by the separation of the center of a given weld bead. Centerline cracking is the result of one of the following phenomena: *Segregation-induced cracking:* segregation-induced cracking occurs when low melting point constituents (phosphorous, zinc, copper, etc.) compounds in the mixture separate during the weld solidification process. *Bead shape cracking:* bead shape cracking is associated with deep penetrating processes. When a weld bead is of a shape where there is more depth than width to the cross section, the solidifying grains growing perpendicular to the steel surface intersect in the middle, but do not gain fusion across the joint. See figure 6b. *Surface profile induced cracking* (Figure 6c): when concave weld surfaces are created, internal shrinkage stresses will place the weld metal on the surface into tension. Conversely, when convex weld surfaces are created, the internal shrinkage forces will pull the surface into compression.

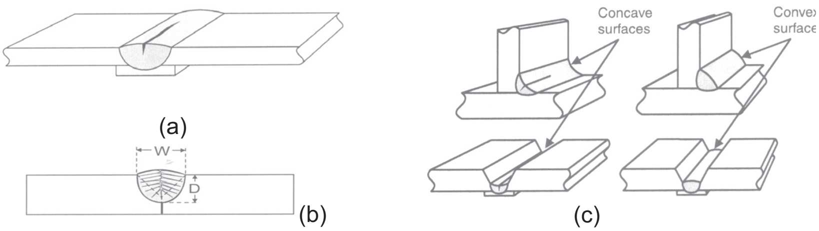


Fig. 6. Centerline cracking: definition (a); bead shape cracking (b); and surface profile induce cracking (c)

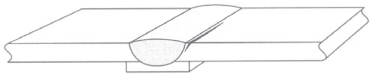


Fig. 7. Heat affected zone cracking

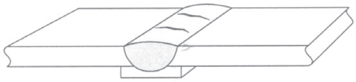


Fig. 8. Transverse cracking

Heat Affected Zone Cracking: heat affected zone cracking (Figure 7) is characterized by the separation that occurs immediately adjacent to the weld bead. Although is related to the welding process, the crack occurs in the base material. The conditions for heat affected zone cracks are: sufficient level of hydrogen, too-sensitive material involved, and sufficiently high level of residual or applied stress.

Transverse Cracking: transverse cracking, also called “cross cracking,” is characterized by a crack within the weld metal perpendicular to the direction of travel (Figure 8). This is the least frequent type of cracking.

According to inspection experiences carried out by Inspecta engineers, delayed cracking can manifest as late as 48 hours after welding. That means, in order to insure reliable inspection results, the inspection sessions must be done at least 48 hours after welding. As a result, it is not allowed to weld cold drawn plates to bearing parts; if done so, it will surely result in cracks which propagate through the weld material down to the parent material.

Many examples taken from real situations show, that certain failures in cranes are caused by inappropriate handling. Cranes with similar specifications and installed in the same environment but operated by different people often show different faults. Generally speaking, those cranes gently handled with care have fewer failures and less wear than the same type of cranes handled roughly and subjected to unnecessary shocks and impacts. According to Swedish authorities, cranes must be inspected every year by a third party organization. Repairing and/or strengthening of the detected failures must follow the applicable standard. An efficient way of identifying potential problems with all types of cranes is by following the guidelines laid down in the international standard ISO 12482-1, which covers crane condition monitoring (CM). The purpose of this standard is to define the limits of the crane design and to point out the necessary steps to keep the crane in safe working conditions. The CM procedure must include all parts of the crane in which deterioration can affect safe handling [11].

CONCLUSIONS

As shown along the text, the life of welded structures “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 reliable design; at the same time that manufacturing must be done according to current regulations and standards. Additionally, clear instructions for driving and handling cranes must be easily accessible, and the requirements for periodic inspections must be always respected. 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, destroying the material from the surface. As a matter of fact, welds are particularly sensitive to corrosion, especially when combined with fatigue loading. Failures in crane structures may lead to extremely dangerous situations for people in or around the cranes, and it normally leads to massive economic 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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