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П. ФРАНКОВСКИ, К. МАСЛАКОВА

ПРИНЦИП И ПРИМЕНЕНИЕ МЕТОДА PHOTOSTRESS ®

Цель работы – ознакомление с оптическим методом PhotoStress® и его использованием при экспериментальном анализе главных относительных деформаций и главных напряжений с помощью покрытия фотоупругим слоем структурных элементов и их систем. Этот метод может быть также применен для анализа статических и динамических напряжений в деталях механических систем, имеющих различную форму и материал. В дополнение к основным теоретическим аспектам этого метода, в работе приведены также примеры практического применения.

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PROBLEMS RELATED TO WELDED STEEL STRUCTURES IN CRANES

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. Considered diagnostic methods that reveal cracks occur and prevent the destruction of structures during their operation.

1 Introduction. 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. In fact, current standards are significantly demanding on material excellence, weld quality, and calculation processes. 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. As a result, welding specialists must cooperate with machine designers to achieve the necessary welding quality, and Welding Procedure Specifications (WPS) should be applied to the high tensile loaded areas of steel structures. 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 WPS, as the process of welding often induces residual stresses in the structures. These stresses, however, can be relieved by a heat treatment directly applied after welding, but this technique is expensive and difficult to accomplish.

The influence of operators when handling cranes is also significant for the proper duration of cranes. This study proved that identical cranes used in the same environmental conditions, for identical loads, and driven by different people resulted in notable differences with regards to mechanical failures. 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.

A crane is a machine generally equipped with a hoist, wire ropes or chains, and sheaves that can be used for both lifting and lowering industrial materials and moving them horizontally. It is mainly used for lifting heavy things and transporting them from one place to another. Cranes use simple mechanisms to create mechanical advantages and thus move loads far beyond the normal capability of a man. They are commonly employed in the transport industry for the loading and unloading of freight, in the construction industry for the movement of materials and in the manufacturing industry for the assembling of heavy equipment [1].

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 [2]. 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 [3].

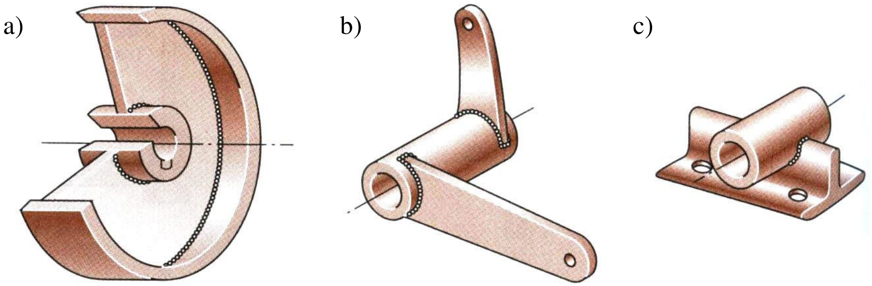


Figure 1 – Examples of machine parts fabricated by welding.

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. 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 [4]. 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 [5].

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 [6]. 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.

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 [7] 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 [7]. 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 is in reality lower than what is recommended in the Welding Procedure Specifications (WPS). In addition, cheating with the Non Destructive Testing (NDT) has also been detected.

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 [3]. The main purpose of the shot-peening operation is the removal of dirt to clean the surface before painting, but it also gives an extra bonus of longer life. The shot-peening technique builds up surface compression stresses which decrease the risk of surface crack occurrence, at the same time corrosion resistance is improved [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 [8]. 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.

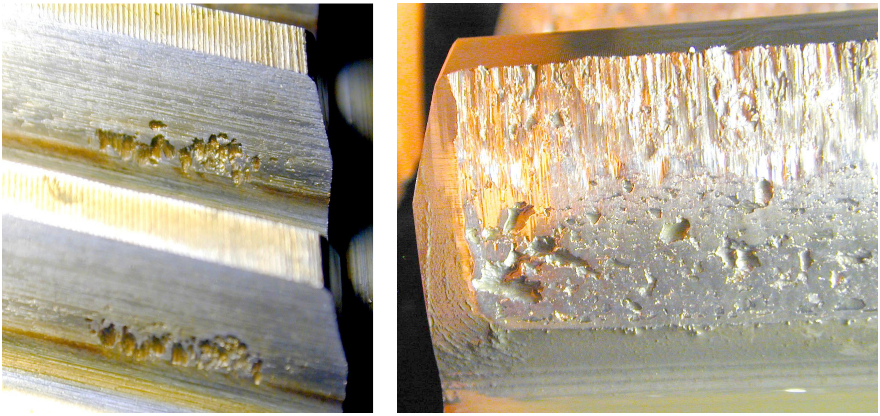


Figure 2 – Pitting failure on one side of the gear due to the lack of parallelism of the shaft supports of a gearbox housing

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 [9].

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.

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 [10]. 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” [11] 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 $Q_B < 10^{-5}$ (according to StBK-N2) with a fatigue stress concentration factor $K_x = 5$ (fillet welds in weld class WB), for infinite life ($N = 2 \cdot 10^6$), the resulting allowable fatigue strength is less than 39 MPa (Table 1). As this comparison proves, the fatigue strength of 39 MPa is only 6 % of the initial static strength of 640 MPa. Table 1 also shows that 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 [12], which should give about the same result.

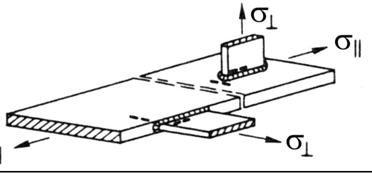
No	Constructional detail	Weld class	$K_{x\parallel}$	$K_{x\perp}$	Remarks
35	Fillet weld at edge of, or parallel to, stressed plate	Sv1 Sv2 Sv3	– 5.0 4.0	– 5.0 4.0	Stated K_x values also apply to section through the weld metal
					

Figure 3 – Fatigue stress concentration factors [11]

Table 1 – **Fatigue strength dimensioning procedure** [11]

N	Permissible stress range σ_r, N/mm^2 at probability of failure $Q_B = 10^{-5}$									
	K_X									
	1.3	1.5	1.7	2.0	2.3	2.6	3.0	3.5	4.0	5.0
10^3	900	900	900	900	781	692	642	592	554	491
10^4	557	514	481	450	363	322	298	275	257	228
10^5	312	276	249	219	168	149	138	128	119	106
$6\cdot10^5$	199	170	150	125	93	82	76	70	66	58
10^6	176	148	129	107	78	69	64	59	55	49
$2\cdot10^6$	148	123	106	86	62	55	51	47	44	39

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 4 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.

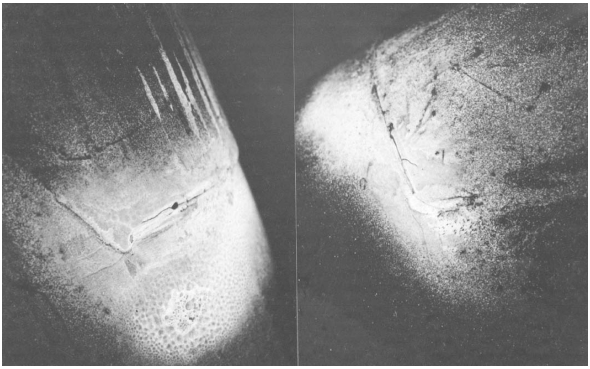


Figure 4 – Cracks in fillet welds

Figure 5, *a* shows the in-site inspection of a mobile crane boom. Figure 5, *b* 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 6 provides typical examples of welded parts on booms. Figures 6, *a* and 6, *c* 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 6, *b* 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.

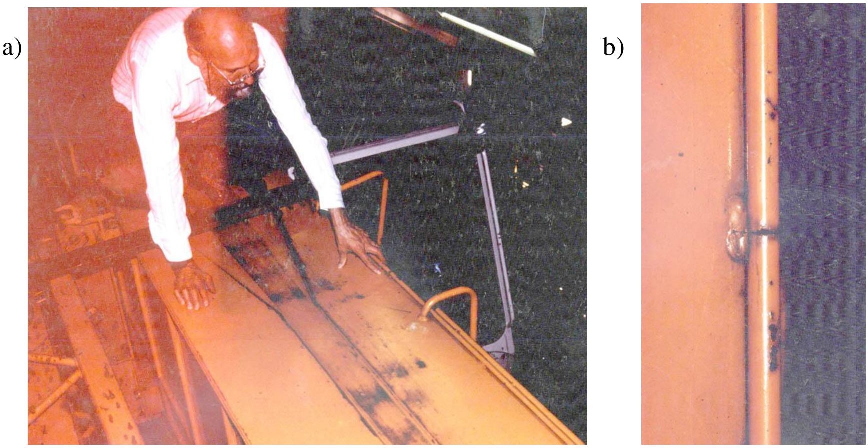


Figure 5 – Inspection of a mobile crane (a) and crack in the weld joint (b)

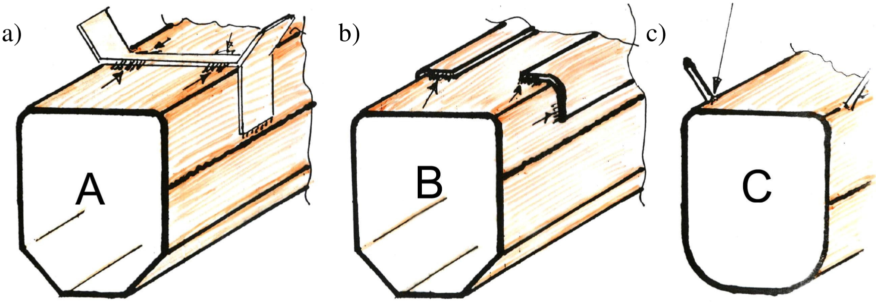


Figure 6 – Examples of welded parts on booms

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

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

Figure 9, *a* provides a different view (top) of the cracks shown in the runaway of Figure 8. To access to this view, the clamped rail was dismounted. The detailed design of this beam is shown in figure 9, *b*.

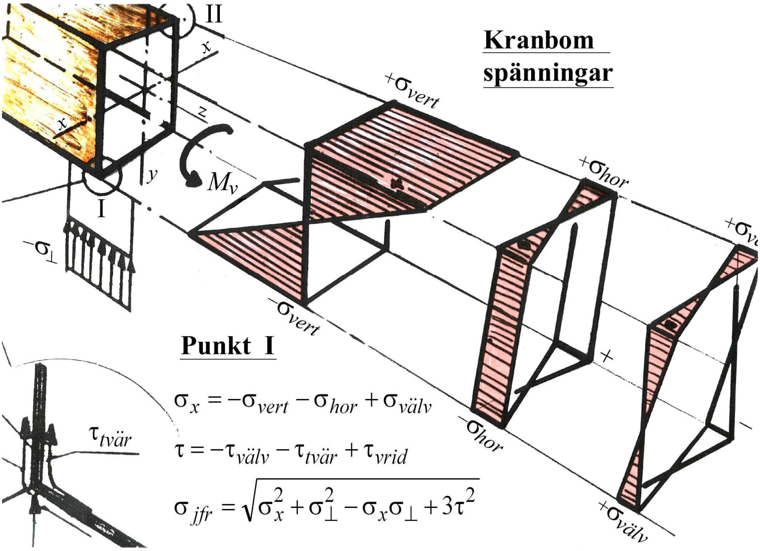


Figure 7 – Calculation of stresses in beams

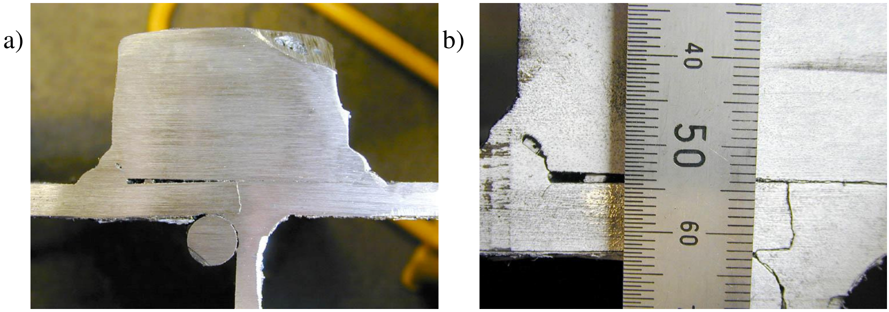


Figure 8 – Deformations and cracks provoked by residual stresses

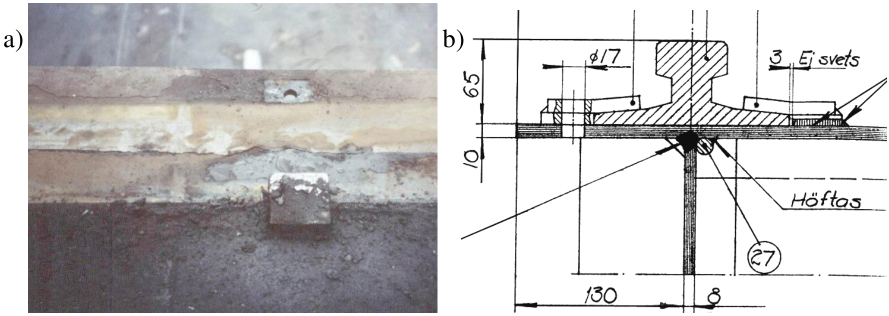


Figure 9 – Cracks in a runway (a), and drawing of the beam design (b)

3. 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 above, 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. The manufacturing cost is a key factor to be taken into consideration. It is important to ensure that welding is carried out in the most effective way, and that appropriate control is exercised over all aspects of the operation [4].

According to the James F. Lincoln Arc Welding Foundation [13], 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:

1 *Centerline cracking* (Figure 10, *a*) 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* occurs when low melting point constituents (phosphorous, zinc, copper, etc.) compounds in the mixture separate during the weld solidification process. This type of cracking can be prevented with several solutions; one of them is limitation of the amount of contaminant pick-up from the base material.

– *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. To prevent this problem, the weld bead width must be at least as large as the depth (the actual recommendations are Width/Depth 1:1 to 1.4:1). See figure 10, *b*.

– *Surface profile induced cracking* (Figure 10, *c*): 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. Concave weld surface are the result of high arc voltages, or high traveling speeds.

2 *Heat Affected Zone Cracking* (Figure 11) is characterized by the separation that occurs immediately adjacent to the weld bead. Although related to the welding process, the crack occurs in the base material. This cracking type is also known as “underbead cracking”, “toe cracking”, or “delayed cracking.” Because it

occurs after the steel has cooled below about 200 ºC (400 ºF), it is also called "cold cracking." 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. The adequate reduction -or elimination- of one of the three variables will generally eliminate heat affected zone cracking. In welding applications, the typical approach is to limit two of the three variables, namely the level of hydrogen and the sensitivity of the material.

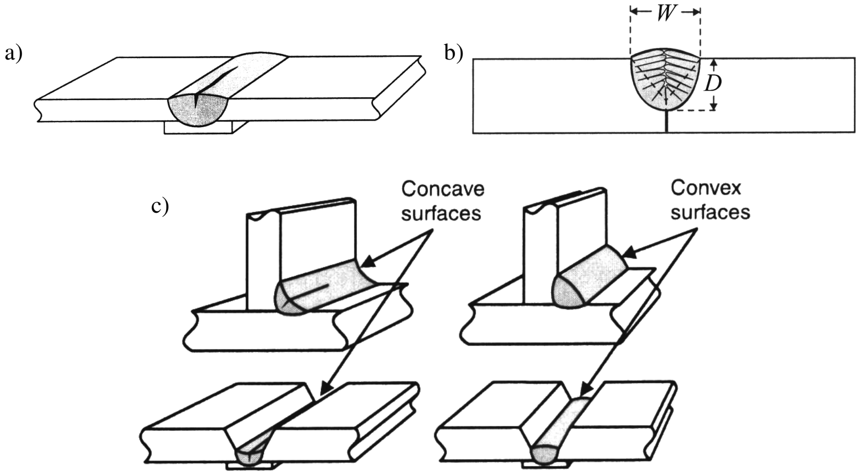


Figure 10 – Centerline cracking: definition (a); bead shape cracking (b); and surface profile induce cracking (c)

3 *Transverse Cracking*, also called "cross cracking," is characterized by a crack within the weld metal perpendicular to the direction of travel (Figure 12). This is the least frequent type of cracking, and is generally associated with high-strength weld metals that may significantly overmatch the base material.

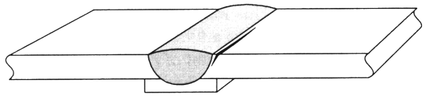


Figure 11 – Heat affected zone cracking

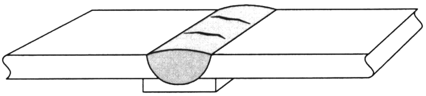


Figure 12 – Transverse cracking

According to inspection experiences carried out by Inspecta (Stockholm, Sweden) engineers, delayed cracking can manifest as late as 48 hours after welding. That means that 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, although there are manufacturers who are not aware of this; 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. Figures 13 and 14 show poor designs of fillet welded joints executed on different parts of steel structures. If the maintenance operations had been properly done, the crack in figure 14 would have been avoided. When the monitoring of crane conditions is accomplished according to ISO standards, it is easy for skilled inspection engineers to detect the location of dangerous spots. Figure 13 shows the use of permanent magnets and magneto powder to reveal cracks in magnetic steel structures. 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 [14].

Figure 13 – Inspection of a weld in steel structure

Figure 14 – Development of a weld crack

4 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 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; 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 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. Hopefully, all the experiences presented in this manuscript will contribute to improve the current situation in terms of safety and use of cranes, and will eventually help crane manufacturers to design and manufacture safer and more reliable cranes.

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ПРОБЛЕМЫ, СВЯЗАННЫЕ С НАЛИЧИЕМ СВАРНЫХ СТАЛЬНЫХ СОЕДИНЕНИЙ В КРАНАХ

На основе многолетнего опыта инспекции кранов и условий их мониторинга в Швеции рассмотрены основные проблемы, связанные с наличием сварных соединений в кранах. Приведены методы диагностики, позволяющие выявить возникающие трещины и не допустить разрушения конструкций при их эксплуатации.

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