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The Collapse of a Crane on Site: A Case Study

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***Abstract*—**This paper discusses the causes of the structural failure in a tower crane. The structural collapse occurred at the upper joints of the extension element used to increase the height of the crane. The extension element consists of a steel lattice structure made with angular profiles and plates joined to the tower element by arc welding. Macroscopic inspection of the sections showed that the break was always observed on the angular profiles at the weld bead edge. The case study shows how, using mechanical characterization, chemical analysis of the steel and macroscopic and microscopic metallographic examinations, it was possible to obtain significant evidence that identified the mechanism causing the breakage. The analyses identified the causes of the structural failure as the use of materials that were not suitable for welding and poor performance in the welding joints.

***Keywords*—**Failure, weld, microstructure, microcracks.

I. Introduction

THE causes of breakage of a metal component can be investigated through non-destructive tests and destructive tests carried out on damaged elements. The results of the investigations are useful to avoid the repetition of harmful events. In the literature, the case studies of the possible causes of breakage of a welded component are extensive, damages can be determined by: design errors, non-compliant material, inadequate thermal treatments or poor conditions of use. The identification of the target can contribute to define the corrective measures to be adopted in the different phases of the production process of a metal product starting from the design, construction up to the operation [1].

The determination of the causes of failure/breakage related to the welded steel components, could be obtained by the identifying the mechanism causing the rupture.

II. Problem description

The problem addressed concerns on the analysis of the collapse of a tower crane used on a construction site. The structural collapse of the tower occurred at the upper joints of the extension element used to increase the height of the crane. This element consists of a steel lattice structure; the joints were prepared by arc welding of corner profiles with connecting plates to the adjacent tower element. The joints are of T-type. In the vicinity of the upper joints, the corner profiles have tapering which reduces the side from 140 to 90 mm (nominal dimensions). The breakage of the joints is always observed at the corner profiles at the height of the weld seam edge. Immediately after the collapse of the tower, the fracture surfaces were partially covered with rust (Fig. 1, joint 2). This may indicated that the opening of the joints did not occur instantly, but began before the accident. Furthermore, the detachment of the weld seam from the wall of the corner profiles is observed locally.

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Fig. 1 Joint n. 2. Fracture surfaces covered with rust

The metal joints were made with electric arc welding, so the union of two metal parts is achieved using electrodes that make up the filler material. The electric arc is combined with strong heat development (up to 4000° C), which quickly melts both the edges to be welded, and the filler metal.

III. Investigation Activities and Results

The main objective of the investigations carried out on the samples was to collect information useful for identifying the causes of the structural failure of the crane. For this purpose, mechanical characterization, chemical analysis of the steel as well as metallographic macroscopic and microscopic tests were performed.

A. Mechanical Characteristics of Corner Profiles

1. Tensile Strength of Steel

The specimens were obtained from the lower ends of the four corner profiles constituting the element of the tower which suffered the collapse. The test was performed according to the standard ISO 6892-1 [2].

TABLE I
Tensile Test Results

Specimens	Yeild strength [N/mm^2]	Tensile strength [N/mm^2]	Elongation [%]
1	377	573	21
2	377	572	21
3	377	568	21
4	378	573	21
average	**377 ± 0.5**	**572 ± 2.4**	**21 ± 0**

The results (Table I) show that the steel of the corner profiles have an average yielding point of 377 N/mm^2, an average breaking strength of 572 N/mm^2 and an elongation at rupture of 21%.

The mechanical characteristics of the steel of the corner profiles correspond to those of S355 type steel according to the standard EN 10025-1. It is therefore suitable for structural uses.

2. Brinell Hardness

The hardness of the components of the joints was determined by means of a durometer equipped with a Brinell-type indenter made of a 2.5 mm diameter steel ball and operating with a test load of 1,830 kN (HB30). The test was performed both on the components (corner profile, weld seam and plate) of the broken joints, from 1 to 4, and on the joints of the lower part of the tower element, from 5 to 8 (unbroken). As regards the corner profiles, the hardness was determined both in the unaltered area (base metal) and in heat affected zone (HAZ), during the welding process.

TABLE II
BRINELL HARDNESS TEST RESULTS: AVERAGE, MINIMUM AND MAXIMUM HARDNESS VALUES FOR EACH JOINT EXAMINED

Sample	Brinell hardness HB30											
	Weld seam			Plate			Corner profile			HAZ		
	X_m	X_{max}	X_{min}	X_m	X_{max}	X_{min}	X_m	X_{max}	X_{min}	X_m	X_{max}	X_{min}
Joint 1	196	220	175	158	165	148	190	200	185	212	218	205
Joint 2	204	235	175	159	170	145	186	195	180	216	228	190
Joint 3	193	212	170	154	160	148	190	196	185	225	250	200
Joint 4	198	212	180	159	170	152	192	200	185	220	238	200
Joint 5	---	---	---	---	---	---	---	---	---	---	---	---
Joint 6	190	210	172	139	148	125	185	192	178	220	240	205
Joint 7	182	190	172	139	145	135	183	190	175	209	215	205
Joint 8	188	210	175	140	148	132	189	200	180	207	220	170

The hardness measurements performed in correspondence with the unaltered area of the corner profiles have a statistically significant difference between the broken joints and the intact joints. The hardness in the intact joints is slightly lower. The average value of the profile hardness at joints 1-4 is 189 HB30, which corresponds to a breaking strength of about 640 N/mm^2 [4]. This resistance is approximately 12% higher compared to the traction tests.

In the HAZ of the corner profiles, the average hardness at the broken joints was found to be between 212 and 225 HB30. The HAZ is distinguished by greater hardness (approx. greater than 15%) compared to other areas (base metal and molten area).

The weld seams show statistically significant differences between the hardness measured in the broken joints and that measured in the intact joints. In the upper joints, the average hardness is approximately 7% higher than the average hardness measured on the seams of the lower joints.

The lower plates exhibit much lower hardness than the upper plates. Therefore it is realistic to assume that the steel used for their construction is not of the same type.

B. Elemental Chemical Analysis of the Joint Components

The elemental chemical analysis of the materials making up the connections was performed with a portable XRF analyzer. The chemical analysis was carried out both on the components of the broken joints and on the intact joints of the tower element.

The sum of the contents of the alloying elements in the corner profiles indicates an unalloyed steel. The carbon, silicon and manganese contents are compatible with the typical values of S355 construction type steel [3]. The results of the elemental chemical analysis are therefore consistent with those of the mechanical tensile tests. The chemical composition of the corner profiles is homogeneous, only at joints 1 and 3; the chemical composition of the profiles differs from that of the others by a clearly higher silicon content (0.51% versus 0.28%). The Carbon Equivalent (C_{ev}) is equal to 0,54%.

TABLE III
ELEMENTAL CHEMICAL ANALYSIS: CHEMICAL COMPOSITION OF THE STEEL OF THE DIFFERENT PARTS, EXPRESSED BY THE MASS PERCENTAGE OF THE ALLOY ELEMENTS DETECTED

Components	Chemical composition: average concentration [% in mass]								
	C	Si	Mn	P	S	Cr	Ni	Mo	Cu
Corner profiles	0.25	0.28	1.30	-.--	-.--	0.15	0.20	0.05	0.37
Superior plates	0.25	0.25	1.42	-.--	-.--	0.19	-.--	-.--	0.29
Inferior plates	n.d.	0.35	0.92	-.--	-.--	0.02	-.--	-.--	-.-
Weld seams	n.d.	0.79	1.27	-.--	-.--	0.04	-.--	0.01	0.10

The plates are made of an unalloyed steel. Except for the absence of nickel, the chemical composition of the upper plates is similar to that of the corner profiles. The steel of the plates is to be considered construction steel. On the other hand, the steel composition of the lower plates is different. Here, in fact, the manganese concentration is lower. These data confirm that the upper plates were made using steel different to that of the lower plates. The C_{ev} of the upper plates is 0,54%.

The weld seams are made of unalloyed steel. The main alloying elements are Manganese And Silicon. The material can be considered suitable for welding.

C. Macroscopic Visual Examination

The macroscopic examination was with a visual inspection, the naked eye or with observation means self-illuminating lenses and microscopes with optical magnification not exceeding 30/40 times. Figs. 2-4 show the glossy sections of the samples prepared for macroscopic analysis. This analysis, performed on the four broken joints, allowed observing that the fracture is practically always cohesive and that this occurred in the corner profiles in correspondence with the upper edge of the weld seam.

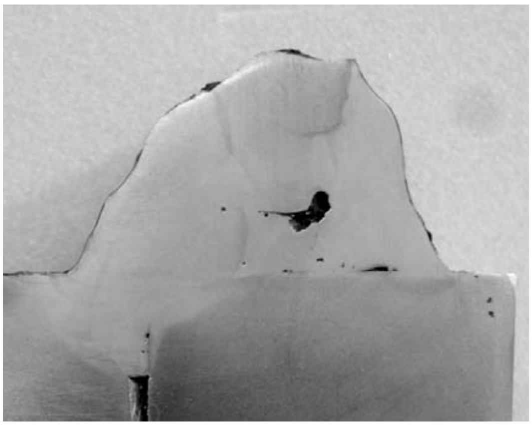

Fig. 2 Joint n. 1, Lack of penetration of the filler metal and pores

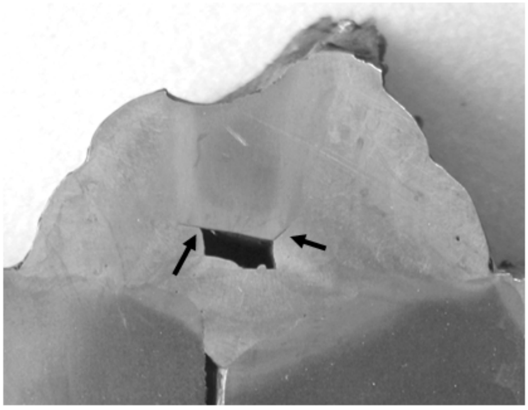

Fig. 3 Joint 2A, Lack of penetration of the filler metal and lack of fusion (arrows)

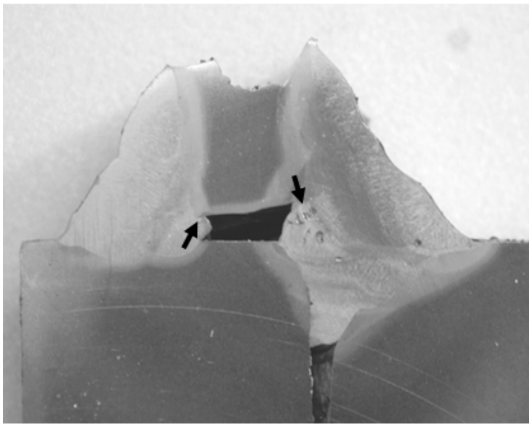

Fig. 4 Joint 3, Lack of penetration of the filler metal and lack of fusion (arrows)

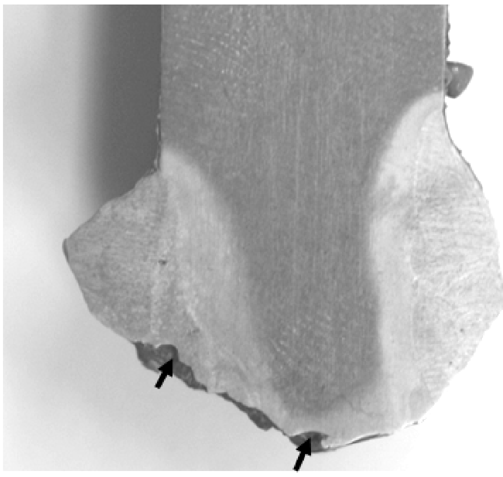

Fig. 5 Joint 2B, Presence of vacuoles along the fracture margin (arrows)

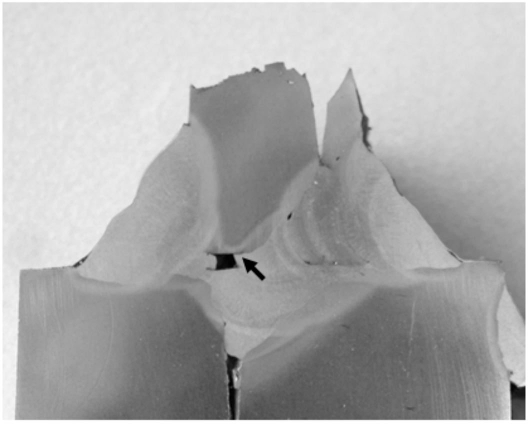

Fig. 6 Joint 4, Welding seam between the corner profile and the plate overlaps to the joint between the two elements making up the plates. Lack of penetration of the filler metal and lack of fusion (arrows)

In joint 2, the fracture occurred partially in the filler material. In the specific case, the breakage surface is rich in pores and slags (Fig. 5).

The examination of the connection plates corresponding to the broken joints revealed that they are not monolithic, but they were obtained by joining two elements by welding. Locally, the welding seam between the corner profile and the plate overlaps the joint between the two elements making up the plates (Fig. 6). Welding on an existing welded joint is not in accordance with practice and is not recommended.

Some imperfections are visible in some joints, as defined in standard EN 6520-1 [5]: lack of penetration of the filler metal and lack of fusion. Both imperfections can be attributable to operational errors, therefore avoidable by applying adequate techniques and precautions during welding (e.g. adequate cleaning and preheating of the edges to be welded).

All four broken joints feature the presence of a millimeter-sized cavity between the corner profile and the plate due to incomplete penetration of the filler material. In the intact joints this characteristic is not found, in fact in these cases the cavities are practically non-existent.

C. Metallographic Analysis

The joints were analyzed by metallographic examination of shiny sections of the samples.

In the fusion welded joint there are three different areas: the fusion zone (FZ), the HAZ and the base material. The three areas have different microstructure. The conditions of the material can be clarified specifically, the implementation of surface treatments, any thermal treatments and therefore ascertaining the existence of probable deterioration phenomena (fatigue breakages, wear phenomena, surface corrosion, etc.) [6]. To highlight the microstructure of the samples, the glossy sections are subjected to an acid etching process (Nital 2%). The images are obtained with an optical microscope with reflected light in bright field mode. The microstructure of the corner profiles in the unaltered areas is characterized by the alternation of bands of ferrite and perlite oriented parallel to the axis of the profiles (Fig. 7). This is a typical structure of hot rolled products. The HAZ of the corner profiles has an approximate width of 2-3 mm and is characterized by the gradual dissolution of the perlite bands and by the formation of a globular ferritic-pearlitic structure with refined grain, similar to that obtainable by normalization treatment (Fig. 8). The structure of the corner profile in the area adjacent to the FZ is bainitic with enlarged grains (Fig. 9). The filler metal is characterized by a ferritic-bainitic structure.

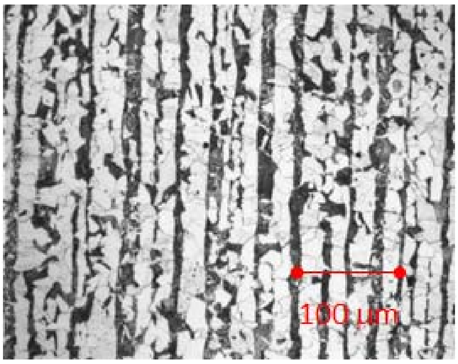

Fig. 7 Joint 1, Corner profile, base metal: micrograph #.1

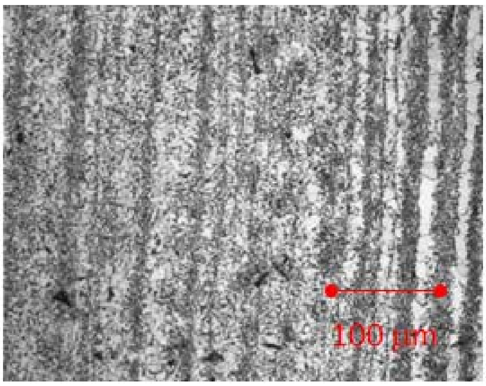

Fig. 8 Joint 1, corner profile, HAZ: micrograph #.2

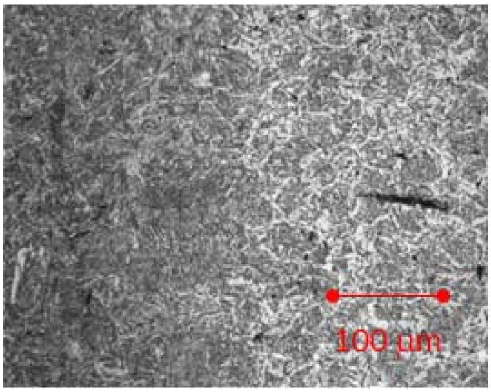

Fig. 9 Joint 1, corner profile, FZ: micrograph #.4

At joint no. 2, in particular on specimen 2B, the presence of a marginal crack inside the HAZ of the corner profile is observed (Figs. 10, 11). It propagates from the upper edge of the weld seam and initially runs along the border line with the FZ, and then continues towards the core of the profile. It is a cold crack. This two-dimensional defect is unacceptable as it represents a discontinuity which, over time can lead to the failure of the joint, depending on the operating stress.

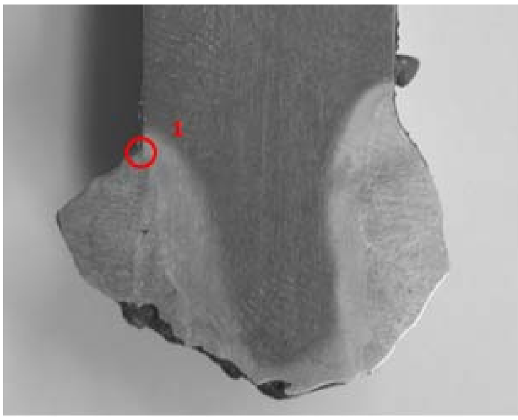

Fig. 10 Joint 2B, Corner profile, location micrograph #.1

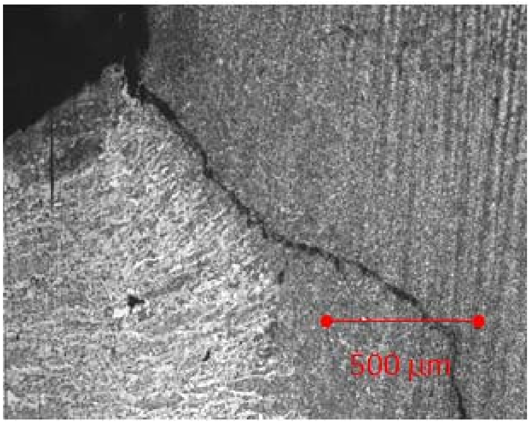

Fig. 11 Joint 2B, corner profile, HAZ: micrograph #.1. Cold cracking

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IV. Discussion

The breakage of the tower element occurred in the corner profiles near the welded joints. Therefore the analyses focused on this area with the aim of assessing the weldability of the steel used for the profiles and the plates.

The weldability of steel, i.e. its aptitude to assume a hardening or transition structure to cooling after welding, can be assessed in terms of C_{ev}. According to the data available in technical literature [7], [8], good weldability of steel is not guaranteed with C_{ev} values higher than 0,45%. For higher values, the alloy is characterized by a moderate trend to change of the microstructure as a secondary effect of the welding process. Therefore the latter can be carried out following the adoption of special precautionary procedures such as preheating of the joint.

The results of the chemical analyses carried out on the corner profiles and the upper plates show that the steel used for their realization has a composition for which weldability can be complicated. Problems include the presence of fragile and hard phases in the HAZ, which can increase the susceptibility of the material to the formation of cold cracks.

The metallographic examination in the HAZs of the profiles allowed ascertaining the presence of phases with a bainitic structure, sometimes with enlarged grains. This confirms the tendency of the material to change into hardening structures, under the influence of thermal welding cycles. This trend is also confirmed by hardness measurements, which show a significant increase in the HAZ. The crack observed in the HAZ of joint n. 2 illustrates the initial stage of the mechanism that led to the collapse (Fig. 11). The shrinkage generated was probably due to too rapid cooling. The hardened base metal did not adapt to the dimensional change, thus causing cracks in the HAZ.

During the subsequent operating life of the element and under the influence of the connected service tensions, they gradually developed, bringing the structure to collapse. These findings are compatible with the presence of corrosion products on the broken surface of the joints observed on the samples immediately after the collapse, which support the hypothesis of the presence of pre-existing cracks.

Based on the results obtained from the analyses carried out, the hypothesis can also be made that the susceptibility of the steel of the corner profiles to the formation of cold cracks could have been increased by hydrogen embrittlement of the material, due to insufficient preparation of the edges to be welded (e.g. moisture in the coating of the electrodes or damp edges; insufficient cleaning of rust and other residues) [9]. In support of this hypothesis, in several joints (especially in joint n. 2), an abundant presence of vacuoles and pores in the filler material was found.

V. Conclusions

A real case investigation to establish the failure mechanism of a tower crane was carried out. The chemical analyzes indicated that the steel used for the corner profiles had a critical weldability.

Defects, such as: lack of penetration, lack of fusion, incomplete penetration, porosity, in the upper welding joints due to operational errors (adequate cleaning and preheating) demonstrate a lack of care in the execution compared to that of the lower joints.

Microstructural conditions (such as: bainitic structure with enlarged grains; hardening structures) that promoted the formation of cold cracks developed in correspondence with the HAZ of the welded joints which, during the service life of the element, propagated causing their corrosion and structural failure.

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