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Non-intuitive fracture pattern of a failed crane-hanger: A fracture mechanics-based explanation

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ABSTRACT

A crane hanger in a paper factory failed during service, causing the crash of the transported paper spool weighing 10 tons. Fatigue cracking over 1/3 of the cross section was visible, surprisingly starting at the contact point with the crane hook, where the lifted load produces compressive stresses. This counter-intuitive crack origin could be explained by the manufacturing residual stresses, but still not the final fracture of the hanger.

The fractography by SEM revealed a multi-modal fracture pattern, including a cleavage fast crack region, surprisingly sandwiched between two sections of fatigue cracking. For explanation of this non-intuitive pattern, a residual strength approach has been chosen.

For this, the bending moment “M” due to the manufacturing constraints and the corresponding bending resistance “M_c” of the hanger’s critical cross section were determined as a function of the crack length “a”. The function $M(a)$ was computed with a finite element model of the cracked hanger. The function $M_c(a)$ was defined by means of fracture mechanics methodology. The stress intensity model is based upon the existing solution of a shaft in bending, adapted for the curved shape of the hanger’s arch and extended for deep cracks using the compounding technique. In order to find the conditions for on-set and arrest of the crack, the stress intensity was replaced by the fracture toughness of the steel. This material property was estimated using a semi empirical theory, which uses classical mechanical steel properties and accounts for the effect of the thickness and dynamic loading on fracture toughness.

The cross points of the obtained $M(a)$ and the $M_c(a)$ curves in the residual strength diagram correlate well with the observed crack lengths both at on-set and at arrest of brittle fast cracking between phases of fatigue cracking. This consistency indicates the general suitability of the proposed fracture mechanics model.

1. Introduction

In a paper factory heavy paper spools weighing up to 10 tons were transported with a crane equipped with a load spreader. The two steel hangers of the load spreader were attached to the double hook of the crane (Fig. 1a).

After 20 years in service, one hanger of the pair failed at the contact point with the crane hook, causing the crash of the paper spool hanging on it (Fig. 1b). In the paper, the main stages of the interdisciplinary failure analysis are presented and discussed, with the focus on the fracture mechanics approach explaining the brittle fast crack region sandwiched between two fatigue cracks.

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2. Preliminary investigations

2.1. Material characterization

The microstructure showed the typical picture of normalized carbon steel, see Fig. 2. In a standard tensile test [1] and in a Charpy test [2] yield strength, ultimate strength as well as the fracture energy at 0 °C and 23 °C were determined, see Table 1. While the tensile properties were in the expected range for this type of steel, the fracture energies at 0 °C were unsufficient. These material properties were used both in the later described finite element stress analyses and for the estimation of the fracture toughness.

2.2. Macroscopic appearance of the fracture surface

The fracture surfaces of the broken hanger were almost free of secondary damage, with the exception of a small region at the inner side of the arch (Fig. 3). From the first view with naked eye a plastic collapse due to an overload event could be excluded. Only a very small part of the fracture surface showed signs of plastic deformation. Distinct beach marks over 1/3 of the fracture surface indicated fatigue cracking, being apparently the main failure mechanism. A fatigue failure might not be surprising after the service life of 20 years, being equivalent to approximately 200,000 lifting cycles. However, the crack origin is clearly located on the *inner side* of the arch, where *compressive* stresses are induced by the lifting force (Fig. 1b). In fact, a mirror image of this pattern, with a fatigue crack origin at the *outer* side of the arch, would be the intuitive one. Though, no straight forward explanation was found up to this point in the investigation.

2.3. Analysis of the manufacturing constraints

As the only reasonable explanation for the fatigue crack growing from the arch's inside seemed that the stiffener (Fig. 1b) forced the arms of the hanger apart, i.e. expanding the arch, inducing residual stress type III [3].

This hypothesis could only be tested on the intact hanger of the pair, because in the failed hanger the fracture already released any potential constraints by opening the structure. First, a piece of the stiffener was cut out and removed (Fig. 4). By doing this, the arms sprang inward by 8.2 mm (measured at the stiffener), supporting the hypothesis. In order to determine the corresponding residual bending moment in the arch, the force required to spread the arms apart by the same amount was measured. The obtained force of $F = 1.4$ kN, multiplied by the length of the lever arm of $L = 0.46$ m in respect to the critical cross section, results in a significant bending moment of $M = 650$ N m. An estimation of the corresponding maximum tensile stress at the arch's inner side, based on classical beam theory for a straight shaft, amounts to $\sigma = 150$ MPa.

It turned out that the constraint was generated during the manufacturing process of the hanger, which consisted of the following steps:

- The bulk material was a rod of construction steel, with a diameter of 35 mm.
- The rod was hot bent over a roller slightly beyond the 180°, as exaggerated in the sketch (Fig. 5).
- The arms were pulled apart temporarily in order to allow for inserting the stiffener, which was tailored to the exact length for parallel arms.
- Finally, the stiffener was welded to the arms. (No stress realising heat treatment was performed on the finished hanger.)

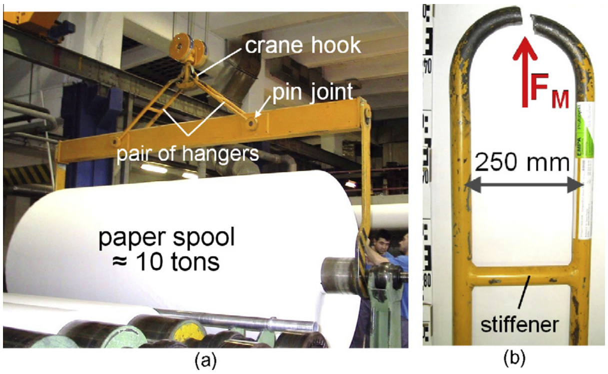

Fig. 1. (a) Overview prior to failure. A paper spool attached to the load spreader, before lifting it up from the support. (b) Failed hanger. F_M: operational load of the hanger at the contact point with the crane hook.