ASSESSMENT OF STRUCTURES CONTAINING DEFECTS DUE TO STRESS CORROSION CRACKING CAUSED BY HOT DIP GALVANISING

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ABSTRACT

In the period between 2001 and 2005 severe damages were found within components of hot-dip galvanised steel structures. These damages – cracks due to liquid metal embrittlement (LME) – have been caused by the hot-dip galvanising. The assessment of structural integrity of those structures is not trivial for several reasons. The influence of the formation of LME-cracks on the fracture toughness and on the crack driving force, compared to fatigue cracks, is not well known. Hence, experimental investigations on C(T)-specimens with LME cracks have been carried out. Another point of special interest is the determination of the grade of plastification of the ligament $L_r$. The LME-cracks occur frequently in the web of girders, starting from half plates or from flame cut copes, and the crack tip is exposed to mixed mode loading conditions. For those details, limit load solutions do not exist and the determination of the ligament is nontrivial. The ligament yielding parameter $L_r$ is verified with the reference stress method, to enable later on assessments with a linear-elastic calculation.

KEYWORDS

Fracture tests, liquid metal embrittlement, hot-dip galvanising, reference stress method

INTRODUCTION

Steel structures are often hot-dip galvanised to protect them against corrosion. The hot-dip galvanising process was known as well-engineered, until in 2001 severe damages were found within components of hot-dip galvanised steel structures. In some cases, the cracks were visible without non destructive testing (Fig. 1). In consequence of those damages, more than 120 galvanised steel structures have been inspected with non-destructive testing methods by Feldmann [1]. At about 60 percent of the investigated buildings indications for the existence of damages were found, whereas not all damages are caused by hot dip galvanising.

Fig. 1: Girder with LME-crack in the web, starting from the half plate
In the majority of the cases, the damages were not as severe as shown in figure 1 and the structural integrity of the structures can be sufficient. The assessment of the structural integrity is of course possible with fracture mechanics – for civil engineering problems, normally the Failure-Assessment-Diagram of CEGB-R6 Option 0 [2, 3] is used – but it is uncertain how the special characteristic of the LME-crack has to be considered. On the one hand, there is some evidence that there is a shielding effect due to the branching at the crack tip (Fig. 2). In [4], a reduction ratio of 0.6 is listed for the stress intensity factor of a branched crack in comparison with the value for an unbranched crack, but there is also mentioned, that the reduction factor is not verified by experiments. On the other hand, there is some evidence that alloying elements (Sn, Pb, Bi) diffuse to the region ahead of the crack front and weaken the granular structure at the grain boundaries. It is unknown, if this leads to reduced fracture toughness. Whether an impact of LME-crack characteristic must be considered in the integrity assessment or not, shall be verified by experiments.

Fig. 2: LME-crack with branching [5]

Another point which makes the structural integrity assessment of steel structures with LME-cracks due to galvanising quite difficult is the geometry of the affected components (Fig. 3). In many cases, the cracks occur in the webs of girders, starting from notches. Limit load solutions do not exist for those details and also with a FEM calculation choosing elastic-plastic material behaviour, the determination of the ligament yielding parameter $L_r$ is not easy. The global limit load is reached in many cases before the ligament is totally plastic. It is possible to carry out the assessment with the fracture toughness for $L_r = 1$ of course. However, this approach is unsatisfactory because it underestimates the capability of the component and leads possibly to extensive reinforcement measures where a closer look to this problem would approve the structural integrity.

Fig. 3: Frequently affected details according to [1]

The presented results have been carried out at the TU Darmstadt as part of a German national research project [5] with six partners.
EXPERIMENTS

To determine the influence of the special characteristics of LME-cracks, fracture mechanics tests on C(T) subsize specimens (W35B10) with LME-cracks and on reference specimens with fatigue cracks were carried out. The investigations in [1] have shown that the tendency for the development of LME-cracks in the zinc bath next to the component geometry is strongly influenced by the used alloy and the used steel grade. Therefore, two steel grades (S355J2, P460N) and two different zinc alloys (alloy 1 (A1): 1% Sn and 1% Pb, alloy 2 (A2): 1% Pb) were used for the investigations. In this paper, the results for the steel grade S355J2 will be presented. First the results for the non-galvanised specimens are presented and subsequently the results for the galvanised specimens.

<table>
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<th></th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Al</th>
<th>B</th>
<th>Cr</th>
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<td>0.211</td>
<td>1.45</td>
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<td>0.02</td>
<td>0.026</td>
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<td>0.586</td>
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<tr>
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<td>0.002</td>
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<tr>
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<td>0.002</td>
<td>0.009</td>
<td>0.001</td>
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<td>0.001</td>
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Table 1: Chemical composition (in weight %)

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<tr>
<th></th>
<th>Rp0.2 [MPa]</th>
<th>Rm [MPa]</th>
<th>E [MPa]</th>
<th>T27J [°C]</th>
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<tr>
<td>S355J2</td>
<td>420</td>
<td>570</td>
<td>208.239</td>
<td>-102 °C</td>
</tr>
<tr>
<td>P460N</td>
<td>531</td>
<td>655</td>
<td>208.500</td>
<td>-99 °C</td>
</tr>
</tbody>
</table>

Table 2: Conventional mechanical properties

The specimens with LME-cracks were cut up from so called LN(T) specimens (Long Notched), which were used from Institut für Eisenhüttenkunde of RWTH Aachen – one of the partners in the national research project [5] – to investigate the exposure for LME-crack development of different combinations of steel grades and alloys (Fig. 4). For the preparation of the specimens of the reference series the same material as for the test series of the galvanised specimens was used.

![LN(T) specimen with LME-crack](image1)

![Cut-out position of C(T) specimen](image2)

Fig. 4: LN(T) specimen and cut-out position of C(T) specimen

At the design of experiments was considered that the fracture toughness of ferritic steels – used for structural steelwork – depends on the temperature of the material. Due to the fact that the toughness of the delivered material exceeds the standardised toughness considerably, it was tested in preliminary experiments, at which temperatures brittle failure
can be expected. Based on the results of preliminary investigations, the temperature for conducting the experiments was determined to $T = -140^\circ C$. It should be noted, that the precracking was carried out in accordance with [6] but the loading procedure did not follow the specifications in [6]. To obtain additional information on the influence of the special characteristic of LME-crack on the fracture behaviour, the loading procedure contained intermediate unloadings in accordance with the procedure in [7]. The results of the non-galvanised reference experiments are presented first and consecutively the results of the experiments of the galvanised specimens with LME-cracks.

The most important results of the experimental series “S355J2, non-galvanised” are shown in figure 5. All measured load-displacement-curves start with a nearly constant slope and decreasing of the slope appears only just before fracture. This may be the result of plastic deformation or an indication for ductile crack elongation. Also on the fracture surfaces, no macroscopic evidence for stable crack growth could be found in all experiments, the failure mechanism brittle failure was clearly identified. The mean value (6 tests, $T = -140^\circ C$) of the fracture toughness was determined to $K_{IC} = 110 \text{ MPa}\sqrt{\text{m}}$.

![Load – Displacement – Curves](image1)

![Fracture surface V042](image2)

**Fig. 5:** Test series “S355J2, non-galvanised”

The results of the test series “S355 J2, A1” (Fig. 6) are quite different from the results of the reference test series (Fig. 5). Besides the differences in the loads at rupture and the related displacements, which are mainly caused by the different crack lengths, the load-displacement-curves of the selected representative tests exhibit significantly different developments. By some of the conducted tests pop-ins were observed whereas the load drops were more or less pronounced. The curves give some indications for ductile crack elongation but with increasing load, the extension of the unloading branch points to the starting point of the test, which is an indication for elastic behaviour without stable crack growth. As observed in the tests of the reference test series the fracture surfaces give no macroscopic evidence for stable crack growth. It is obvious that the LME-crack face runs in contrast to the fatigue crack in different planes and the LME-crack front is not straight. The straightening of the crack front at fracture could be a possible explanation for the apparently stable crack growth at the beginning. A more precise and concluding explanation is probably possible after the micro analytic investigations of the fracture surface are carried out. The mean value (8 tests, $T = -140^\circ C$) of the fracture toughness was determined to $K_{IC} = 105 \text{ MPa}\sqrt{\text{m}}$, whereas the pop-ins were neglected firstly.
The results of the test series “S355J2, A2” (Fig. 7) are more uniformly in comparison with the results of the test series “S355 J2, A1” (Fig. 6). The load-displacement-curves are mainly linear and show the typical shape for brittle failure. A comparison of page views and the plan views of the fracture surfaces shows that the characteristics of the LME-cracks of the two test series “S355J2, A2” and “S355J2, A1” are very different. The LME-crack initiation of the series “S355J2, A2” occurs later than observed at the series “S355J2, A1” and the crack length of the LN(T) specimens of this series is significantly smaller. The crack faces are as well not plain and the crack fronts are not straight, but the appearance is not fissured as that of test series “S355J2, A1”. Another characteristic of the test series “S355J2, A2” is the development of several cracks along the notch root, while in series “S355J2, A1” a single crack was initiated. The mean value (4 tests, T = -140°C) of the fracture toughness was determined to $K_{IC} = 79 \text{ MPa} \sqrt{\text{m}}$, whereas the shape of the crack was up to now not taken into account.

A final review of the influence of the special characteristics of the LME-cracks due to hot-dip galvanising on the fracture toughness is not possible, since not all tests were performed. From the presents results it is expected that the fracture toughness is affected not that much by the characteristics of the LME-cracks and a shielding effect at the crack tip due to
branching as mentioned in [4] could not be observed. How to deal with the pop-ins has to be investigated by micro analytics, due to the fact that the experiments were conducted in deformation control.

**LIGAMENT YIELDING PARAMETER** $L_r$

For some of the details, which are frequently affected by the LME-cracking problem (Fig. 3), it is difficult to get the limit load solution for the failure assessment. Analytical approaches as listed in handbooks [8] are not available. In those cases, a FEM analysis for elastic-plastic material behaviour can be helpful, but in some cases the global collapse load is reached much earlier than the local limit load. For those cases it is possible to calculate the ligament yielding parameter $L_r$ with the global collapse load – but this can be a very conservative assumption – or to do a J-Integral analysis for elastic-plastic material behaviour. Another possibility is, if the use of the global collapse load is known as to conservative and the amount of affected components is too big for doing J-Integral analysis for elastic-plastic material behaviour in all cases, to make some efforts to get the local limit load solution. This can be done by a sub model analysis with the cutting boundaries far away from the crack tip or by changing the stiffness of the area with the plastic hinge if it does not falsify the stress strain field near the crack tip.

This latter approach was chosen for the investigation of a simply supported girder with uniformly distributed load and a LME-crack at the bearing, starting at a half plate (Fig. 8). Due to the fact, that this design of the bearing is frequently affected by LME-cracking, limit load solutions are needed to enable failure assessments based on calculations for elastic material behaviour. Two different material types were chosen to enable an increase of the applied load until the ligament is totally plastic. For the region of the bearing, where the crack is included, the material was assumed as elastic perfectly plastic (material 1) and in the midspan, where previously the plastic hinge appeared, the material behaviour was assumed as linear elastic (material 2).

![Fig. 8: Girder with LME-crack starting at the half plate, steel grade S355J2](image)

Despite this approach, the limit load solution for ligament yielding can not be determined easily by the evaluation of the load deflection behaviour. The crack is close to the bearing and the ligament is supported by the half plate and the flange. These supporting effects possibly cause stress rearrangements and there is no clear separation between elastic and plastic deformation behaviour. The use of the load which refers to the plastic hinge at the bearing is possibly not conservative and should not be used. To find the loading, at that the ligament is locally completely plastic, some more detailed investigations are necessary. Therefore, the development of the J-Integral with the increase of the load was analysed and the local limit load was determined by the reference stress method [9]. By the combination of the definition of the failure assessment line $f(L_r)$ for Option 0 [2] Eq. (1) with the correlation of the J-Integral of a nonlinear analysis with the J-Integral for linear material behaviour by Eq. (2), the load which refers to ligament yielding can be determined as shown in Eq. (3).
With this method, the local limit load $F(\sigma_{gy})$ can be determined as $F(\sigma_{gy}) = 475 \text{ kN}$ (Fig. 9).

To demonstrate the benefit, achieved by the closer examination of the local limit load with the reference stress method, a failure assessment for the cracked component is done (Fig 10). The ligament yielding parameter $L_r$ is calculated using the reaction force referring to the plastic hinge in the midspan – as a conservative assumption of the local limit load – respectively the reaction force referring to the local limit load of the ligament. The mixed mode loading is considered by the evaluation of a mixed mode stress intensity factor $K_V$ according to [4] as shown in Eq. (4). It is assumed that the component is loaded up to the design load, with the reaction force $F = 180 \text{ kN}$, and the fracture toughness is $K_{mat} = 100 \text{ MPa}\sqrt{\text{m}}$ at the operating conditions ($T_{Ed} = -30^\circ \text{C}$).

$$K_V = \frac{K_L}{2} + 0.5 \cdot \sqrt{K_L^2 + 4 \cdot (1.155 \cdot K_H)^2}$$

(4)

The locations of the assessment points in the FAD (Fig 10) are quite different and the example demonstrates the relevance of an accurate local limit load solution for the failure assessment.
SUMMARY AND CONCLUSIONS

The appearance of LME-cracks is quite different from the appearance of fatigue cracks. It is not well known to what extent the fracture toughness and the crack driving force are influenced by the characteristic of LME-cracks. By comparison of the results of fracture tests on C(T)-specimens with fatigue cracks respectively LME-cracks could be shown that the shape of the crack face and of the crack front of LME-cracks is strongly influenced by the used steel grade and zinc alloy. The load displacement behaviour of fracture specimens with LME-cracks is heterogeneous and strongly influenced by the characteristic of the LME-cracks. A significant influence on the fracture toughness can not be identified from the experiments conducted up to now.

Further an approach was shown that allows the determination of the local limit load solution by the reference stress method for those components where the global limit load is reached before the local limit load.

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