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Autor(en): **Maarschalkerwaart, H.M.C.M. van**

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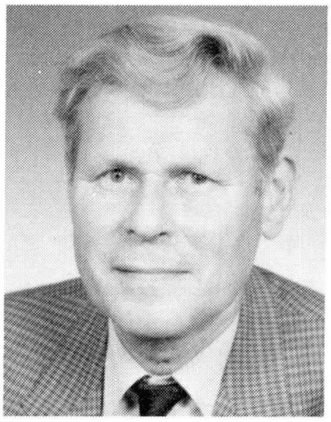
Determination of Inspection Intervals for Riveted Structures

Détermination des intervalles d'inspection pour des constructions rivetées

Bestimmung von Inspektionsintervallen für genietete Konstruktionen

H.M.C.M. van MAARSCHALKERWAART
Eng.
Netherlands Railways
Utrecht, The Netherlands



Mr. van Maarschalkerwaart, born 1927, joined the Netherlands Railways in 1948 and was, until the end of 1989, involved in the design of steel railway bridges. Over the last 10 years, he has been head of the Section for Design and Maintenance of Steel Bridges and a member of the Sub-Committee for Bridges of the UIC.

SUMMARY

Fatigue life calculations of bridges sometimes result in the conclusion that there is no remaining life while in reality, no cracks are observed. Assuming that small cracks emanating from rivet holes are present, an attempt is made to determine the length of inspection intervals in order to detect the assumed cracks before they grow to a critical size. Crack extension has been investigated using fracture mechanics methods and particularly, the severity of edge cracks is pointed out. Results of fatigue crack growth calculations are compared with available test data.

RÉSUMÉ

Les calculs de la durée de vie des ponts aboutissent parfois à la conclusion qu'il n'existe aucune durée de vie restante, alors qu'en réalité aucune fissure n'a pu être détectée. Sous l'hypothèse qu'il existe des petites fissures provenant des trous des rivets, une tentative de détermination de la durée des intervalles d'inspection est faite dans le but de détecter les fissures possibles avant qu'elles n'atteignent une dimension critique. La propagation de la fissure a été analysée à l'aide des méthodes de la mécanique de la rupture, et plus particulièrement en mettant l'accent sur la sévérité des fissures de bord. Les résultats des calculs de la propagation de fissures de fatigue sont comparés avec les résultats d'essai à disposition.

ZUSAMMENFASSUNG

Oft folgt aus der Berechnung der Ermüdungslebensdauer einer Brücke, dass deren Restlebensdauer erschöpft ist, obwohl am Objekt selbst noch keine Risse beobachtet werden können. Vorausgestzt kleine, von Nietlöchern ausgehende Risse vorhanden sind, wird versucht, die Länge der Inspektionsintervalle so zu bestimmen, dass diese Risse entdeckt werden können, bevor sie eine kritische Grösse erreichen. Mit Hilfe bruchmechanischer Berechnungsmethoden wird die Rissausbreitung untersucht. Auf die Gefährlichkeit wird besonders von Kantenrissen hingewiesen. Die Rissausbreitungsberechnungen werden mit Versuchsresultaten verglichen.

1. INTRODUCTION

Judging old bridges it may occur that fatigue life calculations result in the conclusion that a bridge has exceeded its theoretical fatigue life.
Even when conservative assumptions are corrected by results of stress measurements there may be situations of a calculated negative life while in reality in a bridge no cracks are present. This situation especially can occur when little is known about previous loading and safe assumptions have to be made for that. In such cases bridges have to be inspected frequently.
Starting from an actual situation that no cracks have been found, but assuming a certain crack length in the most critical bridge elements, it is tried in this paper to define the length of inspection intervals within which the assumed crack does not grow to a critical size.
For that, fracture mechanics methods may be helpful. While in early times many bridges have been built as riveted structures, fatigue crack propagation behaviour of these structures forms an important aspect judging the reliability.

2. FATIGUE CRACK GROWTH OF WROUGHT IRON AND EARLY MILD STEEL

In order to determine a safe inspection interval one needs information about crack propagation.
The crack growth rate da/dN is described by the Paris power law.

$$\frac{da}{dN} = C.\Delta K^m \qquad (1)$$

where ΔK is the range of the stress intensity factor. C and m are constants.
To define the crack growth rate, fatigue crack growth tests were carried out with center-cracked specimens of early steel.
Figure 1 shows the results presented as a relationship between the crack growth rate, da/dN, and the range of the stress intensity factor ΔK.
Adopting for the constant m the value m = 3, for the constant C was found $C = 4.10^{-13}$ for the upper bound, and $C = 1.10^{-13}$ for the lower bound.

Fatigue crack growth tests were also carried out with specimens made of wrought iron. The results are shown in figure 2.
It can be seen from this figure that there is a great scatter. At lower values of ΔK the crack growth is slower than that of early steel.
At higher values of ΔK the maximum magnitudes of the crack growth rate are close to the upper bound of early steel.

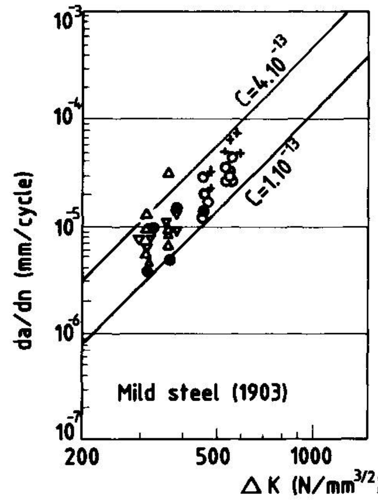


Fig 1 Relationship between crack growth rate da/dN and ΔK of early mild steel.

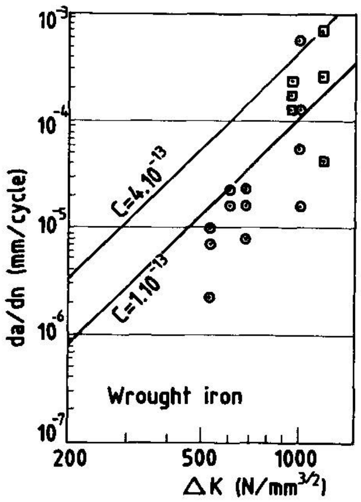


Fig 2 Relationship between crack growth rate da/dN and ΔK of wrought iron.

3. FATIGUE CRACK PROPAGATION ANALYSIS OF RIVETED COMPONENTS USING FRACTURE MECHANICS

3.1 Fatigue crack growth of several configurations

Fatigue cracks in riveted structures generally emanate from rivet holes at stages most subjected to tension.
However in the case of sections deteriorated by corrosion, cracks can develop at edges with reduced area. In particular also components subjected to tension are sensitive for that.
In the present study the effect of force redistribution to other section components during crack extension is neglected.
The conservative assumption is made that, having a built up member, all parts simultaneous start to crack at the same location, at both sides of a hole, and redundancy is not taken in account.

In order to evaluate fatigue-crack growth of several configurations numerical analysis were carried out using equation (1) with values of $C = 4.10^{-13}$ and $m = 3$.
As constant amplitude loading a stress range of $\Delta\sigma = 75$ N/mm² (gross section) was chosen.
For the initial crack at the hole two opposing cracks with a size of a = 16 mm were assumed, being a situation of appear of the crack just beyond the rivet head.
Cracks at rivet holes nearest to the edge of members were assumed to be most severe (excentric crack in a plate).
To determine the influence of the edge distance of the rivets, in one example the edge distance was varied.
To define the values of Δ K the correction factors F (a) for excentric cracks were taken from literature [1].
The results of the calculations are shown in figure 3. The extension of the cracks is plotted against the number of cycles.

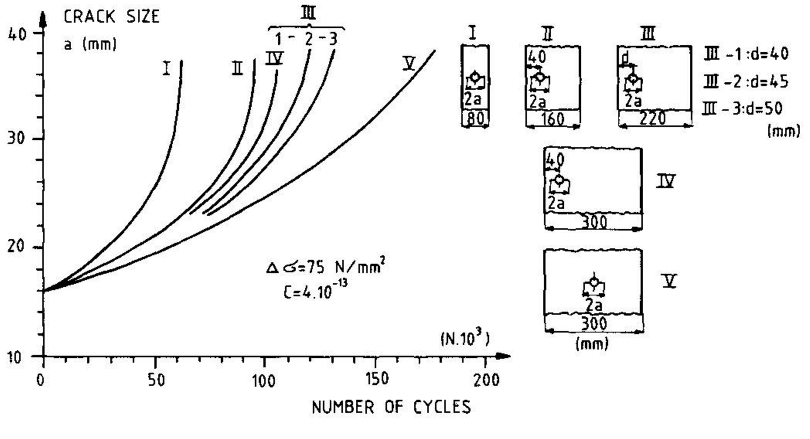


Fig. 3 Crack growth curves of several configurations. Cracks emanating from unloaded rivet holes.

To represent situations of cracks developing at edges affected by corrosion, or to evaluate cases when cracks emanating from rivet holes have reached edges, numerical analyses were also carried out for the chosen configurations assuming edge cracks.
The results are shown in figure 4.

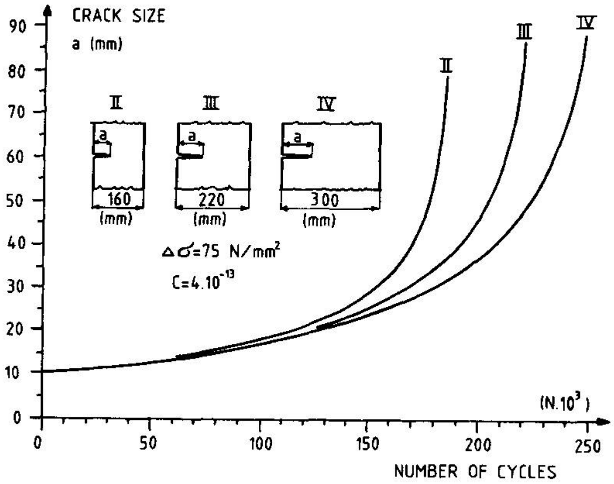
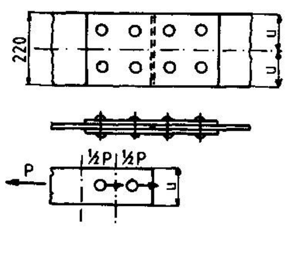


Fig. 4 Crack growth curves of several configurations. Edge cracks.

3.2 Influence of loaded rivets on crack growth

In the preceding part crack growth has been evaluated in riveted components having rivets with a function of only clamping.
In cases of shear forces or connections, rivets transmit load, and pressure on the holes is involved.
The case of a crack with internal pressure is described in literature [1].
The stress intensity factor for a finite plate with a loaded rivet hole can be obtained by superposition of the stress intensity factor of a plate with a crack and the stress intensity factor of a plate with a hole with internal pressure and two cracks [2].



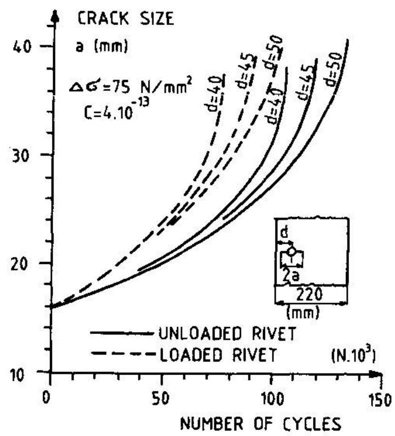


Fig. 5 Configuration of the investigated example with loaded rivets.

Fig. 6 Crack growth curves. Comparison between loaded and unloaded rivets. Influence of different edge distances.

To show the influence of the pressure on a rivet hole an example of a fracture mechanics calculation is given for a configuration with a width of 220 mm (fig. 5).
The conservative assumption is made that, dividing the component in gage strips, there are two rivets in a line, and one rivet transmits half the load, while in the strip itself half the load is present already.
The results of this calculation are shown in fig. 6.

3.3 Examination of fracture mechanics analysis

As can be seen in the figures 3, 4 and 6 the computed crack propagating life, starting from the initial crack size a_i = 16 mm, is relatively short.
Reaching the edge the crack size becomes critical. Increase of edge distance shows an increase of the number of cycles previous to reach the critical crack size.
When the crack has grown to the edge, there is a transition of the crack geometry into an edge crack.
Considering an edge crack with a size of about 80 mm, it can be seen from figure 4 that in this stage the remaining life is very short.
For lower or higher stress ranges the critical crack size has the same value, only the number of cycles to reach the critical crack size differs.

4. DETERMINATION OF INSPECTION INTERVALS

Determining inspection intervals it is important to know how long it will take the crack to grow from the minimum detectable size to the critical size.
Experience [3] has indicated that performing a visual inspection with the aid of a magnifying glass and good illumination, cracks can be detected when they appear about 10 mm beyond the rivet head.
Such a crack means a size of about a = 26 mm.
To evaluate an inspection interval a crack propagation of a_i = 28 mm to a_j = 33 mm is assumed. That includes a possible crack extension during the inspection interval of 5 mm.
Fracture mechanics calculations have shown that dependent on the width of the components and the edge distance of the rivets, crack sizes of a = 35 mm to a = 40 mm become critical.
It has to be pointed out that when cracks of such sizes in reality are found in primary members, repair or replacement of a bridge has to be considered.
Numerical integration of the crack growth rate description between the two crack sizes results into a SN-curve for a crack, propagating from a_i = 28 mm to a_j = 33 mm. For the constant C the value $C = 4.10^{-13}$ is used.

$$N = \int_{a_i}^{a_j} \frac{da}{C \cdot \Delta K^3} \qquad (2)$$

where $\Delta K = F(a) . \Delta\sigma . \sqrt{\pi a}$

F(a) is a geometric correction factor.

For several configurations SN-curves are presented in figure 7, indicated by the value $\Delta\sigma$ (gross section) at $N = 2.10^6$ cycles and a slope m = 3.
A fatigue limit is disregarded.

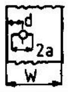
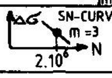
		UNLOADED RIVETS						LOADED RIVETS					
	W mm	80	160	220	220	220	300	80	160	220	220	220	300
	d mm	40	40	40	45	50	40	40	40	40	45	50	40
 SN-CURVE m = 3		$\Delta\sigma_{2.10^6}$ (N/mm²) a_i=28-a_f=33mm						$\Delta\sigma_{2.10^6}$ (N/mm²) a_i=28-a_f=33mm					
		11	13	14	15	15	14	11	13	13	14	15	13

Fig. 7 SN-curves crack growth a_i = 28 to a_j = 33 mm for several configurations of riveted structures (mild steel).

To determine the fatigue crack propagating life, growing the crack between the two crack sizes, a representative stress spectrum with variable amplitude and a number of cycles n_s, is transformed into a spectrum with an equivalent stress range $\Delta\sigma_e$ of constant amplitude and the same number of cycles n_s, causing the same damage.

$$\Delta\sigma_e = \left[\frac{\Sigma n_i \cdot \Delta\sigma_i^3}{n_s}\right]^{1/3} \tag{3}$$

Using the SN-curve for the crack extension of 5 mm and the equivalent stress range $\Delta\sigma_e$ (gross section), the propagating life N can be computed.

Now the inspection interval ΔT_i has to be estimated as:

$$\Delta T_i = \frac{N}{n_s} \tag{4}$$

Only cracks visible from outside can be detected by a visual inspection.
At splices internal cracks cannot be detected visually before reaching the edge and then they are unstable.
In such cases it is necessary to apply radiographic inspection methods.

5. NUMERICAL EXAMPLE

Suppose a riveted railway bridge with a span of 10 m has been in service for about 85 years.
Recalculation with the UIC-loading included dynamic increment results in a stress range $\Delta\sigma_{UIC}$ = 125 N/mm² (net section).
The measured stress range spectrum yields to an equivalent stress range $\Delta\sigma_e$ = 25 N/mm² (gross section) and a number of cycles n_s = 8,9.10⁵ per year.

Using the evaluated SN-curve with $\Delta\sigma$ = 15 N/mm² at N = 2.10^6 cycles and m = 3, the propagating life N for $\Delta\sigma_e$ = 25 N/mm² is computed at N = $4{,}33.10^5$ cycles.
The inspection interval is estimated at:

$$\Delta T_i = \frac{N}{n_s} = \frac{4{,}33.10^5}{8{,}9.10^5} = 0{,}5 \text{ year}$$

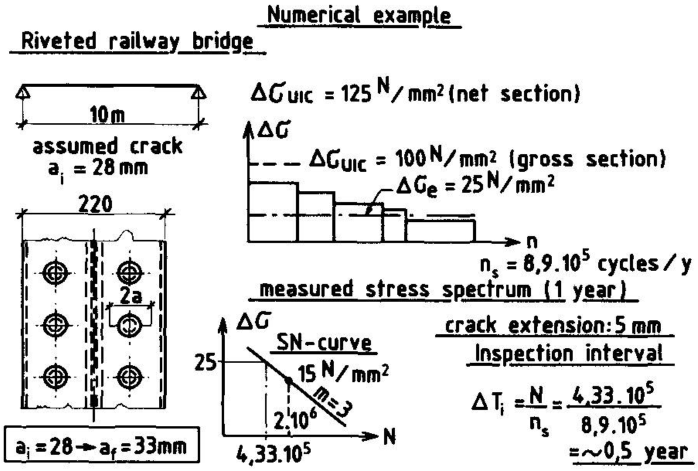


Fig. 8 Example determination inspection interval of a riveted railway bridge.

6. EVALUATION METHOD OF PREDICTION

6.1 Influence way of the crack growth

The presented method of determination inspection intervals for riveted structures is based on the assumption that cracks grow at the same time from both sides of a hole, and increase at each side with 5 mm.
Observing crack growth in practice [3], it can be seen that cracks many times emanate at first from one side of a hole, extend to the edge, and then start to grow, or increase in growing, at the other side of the hole.
The question can be posed whether the presented method is too conservative or not.
Therefore the results of the fracture mechanics analysis of one of the examples, shown in figure 3, are compared with the results of an analysis like that for the situation of an asymmetrical crack growth.

The example has been chosen of the plate with a width of W = 220 mm and a hole of 20 mm diameter, center 45 mm from the edge.
It is assumed that cracks with a size of 13 mm beyond the rivet head are present, being the intial crack size used for the presented method of determination inspection intervals.
Again the constant amplitude loading with a stress range $\Delta\sigma$ = 75 N/mm² is chosen.
Three cases of crack growth are compared:

- symmetrical crack growth.
- asymmetrical crack growth, with cracks on both sides of the hole, but one of which hidden by the rivet head.
- asymmetrical crack growth, starting from one side of the hole, growing up to the edge, and then arrested in the hole.

The results of the fracture mechanics calculations are shown in figure 10.

To have an idea of the number of cycles to start the arrested crack, the data concerning the relationship between $\Delta K/\sqrt{\rho}$ and the number of cycles to reinitiation, known from literature [4], [5] and [6], have been used. (ρ is the radius of the hole).

This relationship is transformed into an SN-curve for the considered configuration.
The relationship $\Delta K/\sqrt{\rho}$ versus fatigue life and the SN-curve derived from that are plotted in figure 9.

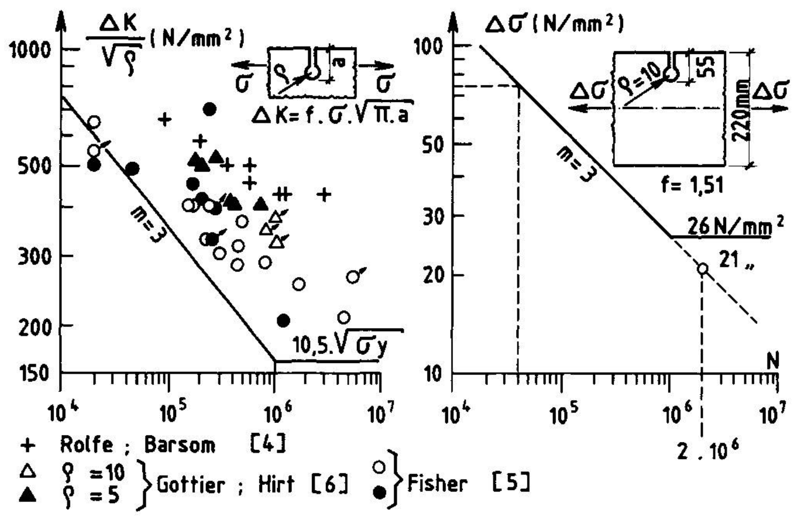


Fig. 9 Relationship $\Delta K/\sqrt{\rho}$ versus fatigue life, and SN-curve of crack initiation.

It can be seen from figure 10 that asymmetrical crack growth is more favourable concerning fatigue life than the assumed pattern of crack growth adopted for the determination of inspection intervals.

However small fatigue cracks easily can be overlooked, and then cracks may emanate up to the edge before detecting.
In that situation also the asymmetrical cracks are close to the critical size.

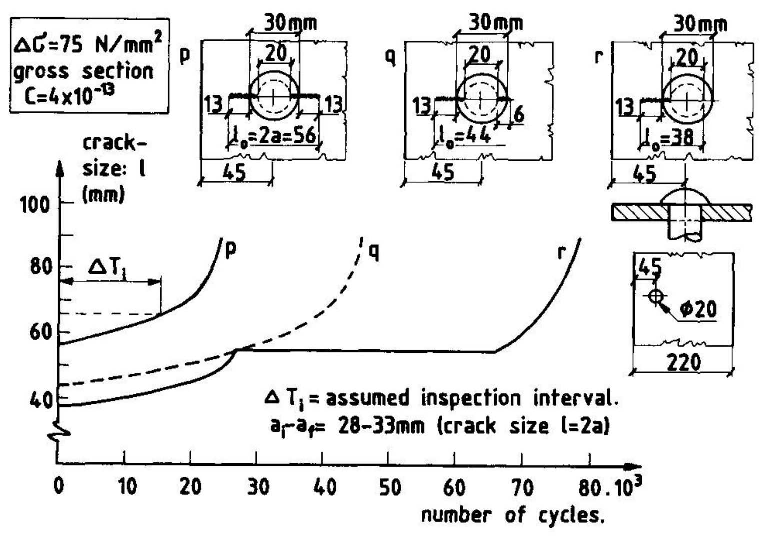


Fig. 10 Comparison influence of different ways of crack growth behaviour on fatigue life.

Even the arrested asymmetrical cracks may be close to that, while no body can see how far the initiation has proceed; unless it is sure that during the former inspection such a crack was not present.
It can be seen from figure 10 that, in cases of crack growth up to the edge, the presented method of determination inspection intervals may provide a certain period in which measures can be taken just after the moment that the crack has reached the edge.

6.2 Influence value of the constant C

Variation of the crack growth constant C in the Paris equation (1) has a linear effect on the results of the calculation of the number of cycles in an inspection interval.
In this paper for the upper bound a value $C = 4.10^{-13}$ was adopted, using units of mm for the crack size, and $N/mm^3/_2$ for ΔK.
Figure 11 shows the influence of ranging the constants from $C = 4.10^{-13}$ to $C = 2.10^{-13}$, and gives a comparison with the results of a crack growth investigation during a fatigue test [3], carried out by ICOM, after growing the crack up to the edge.
The result of the calculation of the inspection interval is also given in this figure.

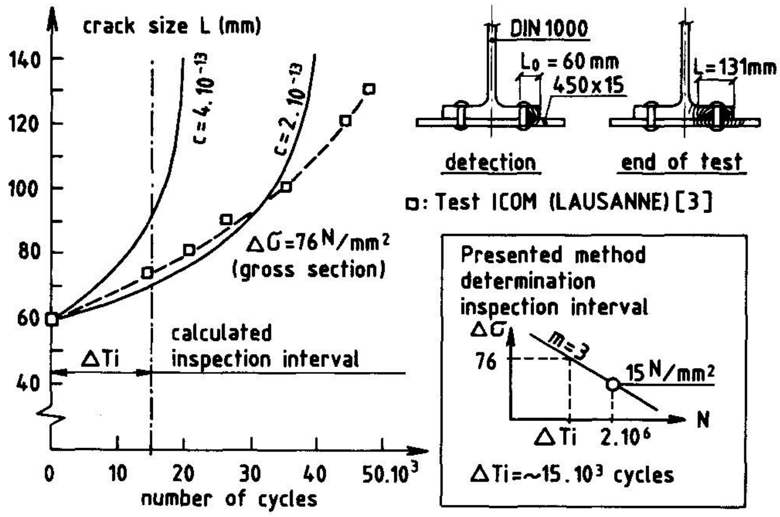


Fig. 11 Influence change of the constant C. Comparison theoretical crack growth with test results.

7. CONCLUDING REMARKS

Only cracks visible from outside can be detected by a visual inspection.
In cases of splices radiographic inspection methods are necessary.

It has to be pointed out that when cracks become visible from outside, in general, the remaining life is very short.

Keeping in mind that in practice symmetric crack growth seems to be improbable, the conclusion could be that the presented method, based on the assumption of a crack extension of 5 mm at both sides of a rivet, may be conservative.

On the other hand small cracks easily can be overlooked and have grown already up to the edge before detecting.
Fracture mechanics calculations show that for the situation of asymmetric crack growth up to the edge the presented method may provide an inspection interval of sufficient length.

It has to be mentioned that a possible redundancy of a structure may be a very important factor in judging.

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