

Probabilistic maintenance planning for the tubular joints in the steel gates in the Eastern Scheldt storm surge barrier

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Abstract

This article is a summary of a study on the tubular joints in the steel gates of the Eastern Scheldt storm surge barrier in the Netherlands. This study was commissioned by the Directorate-General for Public Works and Water Management (Rijkswaterstaat) and carried out in the period 1985–1992 [1].

At a late stage during the fabrication of the Eastern Scheldt storm surge barrier it was found that, due to improper control during rolling, many tubes were made of steel with a relatively coarse grain. It was therefore decided to use probabilistic methods to determine the failure probability and optimum inspection strategy. The optimum strategy was determined on economic grounds, based on a consideration of the investments, costs of inspection, costs of repair and failure costs. Safety was included as a boundary condition. The study indicated that it was necessary for financial reasons to differentiate inspection schedules, depending on the load and type of material.

Keywords: management, maintenance, inspection, steel, brittle fracture, fatigue, repairs, probabilistics.

1 Introduction

When fabricating the steel gates for the Eastern Scheldt storm surge barrier in the Netherlands it was discovered that the tubes of the main structure contained coarse-grained steel. This was due to insufficient control during hot rolling of the plates to produce these tubes. Coarse-grain material may lead to brittleness. This was confirmed by further tests (Charpy V and CTOD).

When the barrier is closed and exposed to a large difference in water levels and high wave loads, unstable cracks may grow from weld defects (undercuts or slag inclusion) or fatigue cracks in the tubular joints.

Experiments on coarse-grain Y-joints removed from the structure showed that a chord could fail completely due to such cracks [2].

At the time the presence of coarse-grain structures was discovered a number of gates had already been installed, while others were ready for installation. Given the progress of the project, it would have been unattractive simply to replace all coarse-grained tubes.

Instead, a comprehensive study into the seriousness and scope of the problem (i.e. fatigue crack growth followed by brittle fracture) was started. Initially, safety was the sole criterion. As a result tubes (tubular joints) were replaced at some locations [3]. After completion of the gates the study was continued and then focused on the most appropriate maintenance planning.

The objective of the latter part of the study was:

Determining inspection periods leading to the lowest expected costs subject to the constraint that the protection of Zeeland against flooding would be guaranteed for the lifetime of the structure.

The study concerned the tubular joints in the truss girders.

The following techniques were used:

- a. Statistical methods to determine the distribution of the values of relevant stochastic parameters;
- b. Fracture mechanics and crack growth models to describe the behaviour of the steel tubular joints under fatigue and extreme loads;
- c. Probabilistic methods to determine failure probabilities and crack detection probabilities.

These techniques were used to develop decision models based on the expected costs and level of safety.

The barrier consists of three sections (Schaar, Hammen and Roompot) with a total of 62 gates. The steel gates are supported on both sides by concrete piers. Depending on the height of a gate, its loadbearing structure consists of two or three tubular truss girders (see Figure 1). The dimensions of the tubes in these girders depend on the loads the girders are

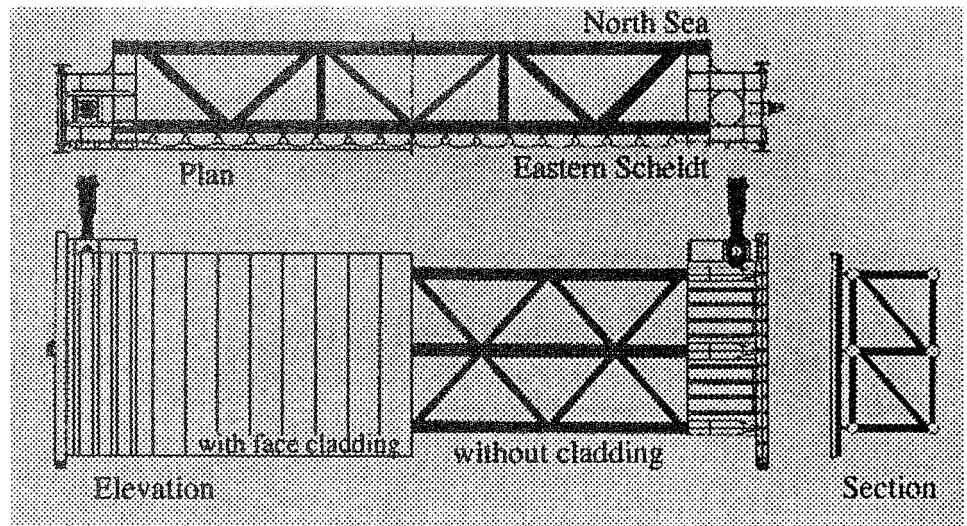


Fig. 1. Design of a three girder gate.

exposed to. There are eight girder types: A to H. A is the lightest type of girder with a chord diameter of 508 mm, H is the heaviest, with a chord diameter of 812.8 mm (see Figure 2). The system dimensions, i.e. the location of the centre lines of the tubes, are the same in all girders. There is a total of 157 girders. Each girder contains 16 tubular joints. Thus, there is a total of $157 \times 16 = 2512$ joints.

Hence, this study covers these 2512 tubular joints in the primary lattice structure.

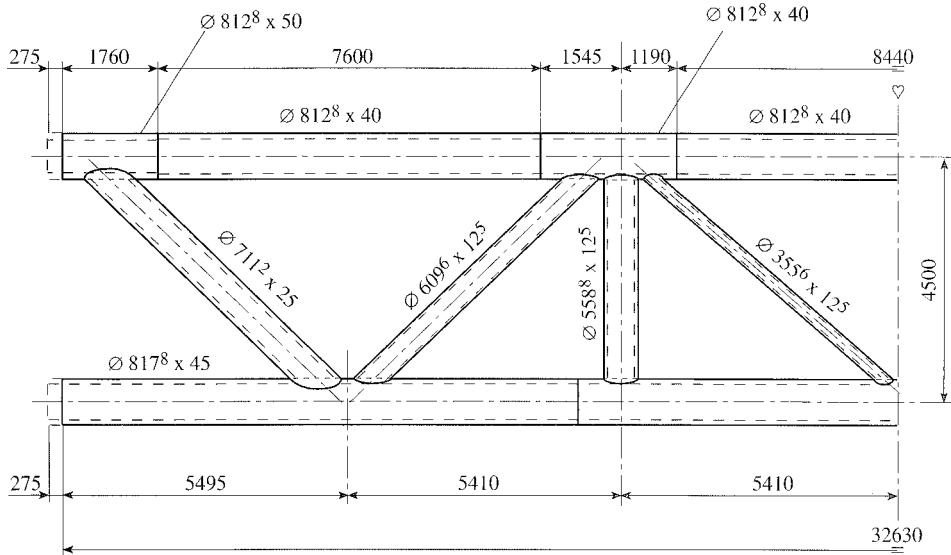


Fig. 2. Dimensions of girder type H.

2 Models

2.1 General

Two types of models are used to determine the management strategy: condition models and maintenance models.

The *condition models* are mathematical models to describe events occurring in the structure. In the condition (mathematical) model the geometry of the welded tube joint is simplified to a flat plate with a transverse attachment, see Figure 3. Where possible the properties of the tube joint are transferred to the simplified model.

The mathematical model contains the following components: the *fatigue crack growth model*, the *unstable failure model*, the *failure model* and the *detection model*. This models are incorporated in the PROBAN computer program [4] which was used to calculate the probability of certain events (like failure, crack detection, etc.). The condition models will be discussed in greater detail in section 2.2.

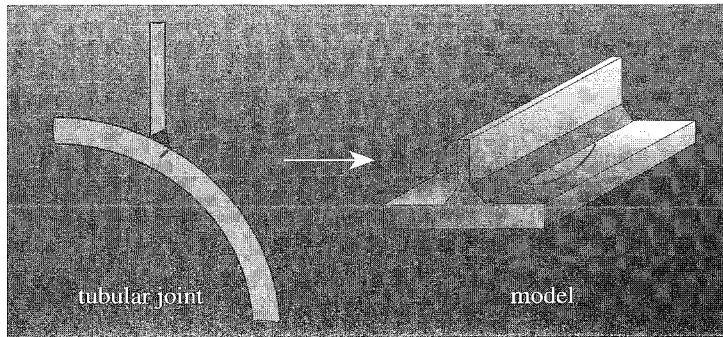


Fig. 3. Simplified geometry.

The *maintenance models* depend on the selected management and maintenance strategy. In the maintenance or cost models the probability of certain events calculated with the condition models and the associated costs are combined to provide the overall costs of the different strategies.

There are three, fundamentally different, maintenance and management strategies: *corrective maintenance*, *use-based maintenance* and *condition-based maintenance*.

The costs for each alternative are calculated. Many of these costs are incurred immediately (investment) and in most cases uncertain future costs, e.g. those associated with failure, are also relevant. These costs are incorporated by multiplying them by the probability that they will occur, i.e. as *expected costs*. This is also referred to as *risk*.

To compare the expected costs, all costs are converted to a cost at $t = 0$ (using the effective interest rate) and added up. The amount arrived at is known as the net present value (NPV). The maintenance models will be discussed in greater detail in section 2.3.

2.2 Condition models

2.2.1 Fatigue crack growth model

The fatigue crack growth model is based on fracture mechanics [5]. The crack growth is determined using a crack growth law defining the correlation between the stress intensity factor range (ΔK) and the crack growth per load cycle. K is a measure of the stress in the vicinity of the crack tip.

$$\Delta K = Y \Delta \sigma \sqrt{\pi a} \quad (1)$$

Where:

Y = factor depending on the geometry and crack size

$\Delta \sigma$ = fatigue stress range

a = crack depth

The crack growth law used here is the Paris-Erdogan (see part II of Figure 4):

$$\frac{da}{dN} = C (\Delta K)^m \quad (2)$$

Where:

da/dN = crack growth rate

C = constant in the Paris-Erdogan law

m = exponent in the Paris-Erdogan law

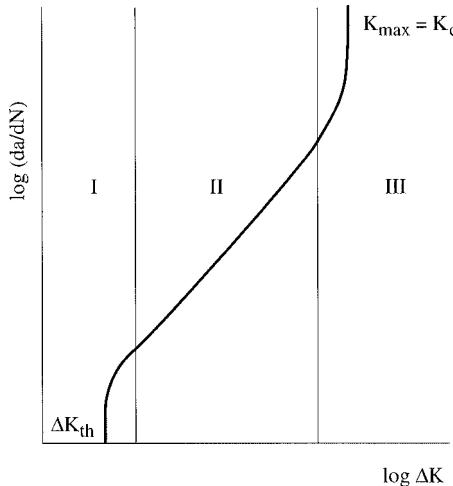


Fig. 4. Crack growth curve.

Integration of (2) for an initial defect a_i to a final defect a_N results in:

$$N = \int_{a_i}^{a_N} \frac{da}{C (\Delta K)^m} \quad (3)$$

As ΔK is generally a fairly complex term, numerical integration was applied to (2). A component of the FAFRAM (FAtigue FRActure Mechanics) program developed by TNO Building and Construction Research was used, which contains a suitable numerical integration procedure. In this way the correlation between crack growth and number of cycles can be determined (see Figure 5).

Eventually, the fatigue growth model indicates the crack size after the specified number of cycles (N):

a_N = crack depth after N cycles

c_N = half crack width after N cycles

These results can then be used in the unstable failure model or the detection model.

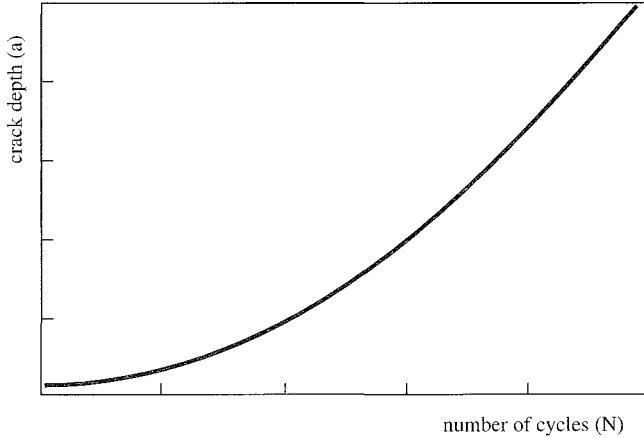


Fig. 5. Correlation between the crack depth and the number of load cycles.

2.2.2 Unstable failure model

The unstable failure model is based on the method described in PD 6493 [6], using the level 3 Failure Assessment Diagram (FAD).

In the FAD the brittle failure parameter Kr is plotted vertically against the ductile failure parameter Lr on the horizontal axis. This defines a point on the graph. In the deterministic approach the situation is safe if the point is located within the curve and unsafe if the point lies beyond the curve. The modification of this diagram for the probabilistic method is described in section 2.2.3.

The ductile failure parameter Lr may be interpreted as the ratio between the acting stress in the net cross-section and the yield stress. Lr is therefore dependent on the geometry, particularly the net cross-section, the yield stress and the peak load (extreme load).

The brittle failure parameter Kr may be interpreted as the ratio between the stress intensity factor due to the load and the stress intensity factor at which brittle failure would occur. Kr is therefore dependent on the geometry, particularly the crack geometry, the fracture toughness (CTOD), yield stress and peak load.

The unstable failure model produces values for Lr and Kr , based on the crack dimensions after N cycles. These results are then used in the failure model.

2.2.3 Failure model

The failure model is derived from the deterministic FAD. Its modification was based on the results of 38 experiments. For each sample, the position in the FAD, expressed by the polar coordinates Φ and R , at the time of failure was determined (see Figure 6). It was found that the location of the set of points was independent of the value of Φ , thus only the value of R was relevant. It was found that $R(\text{fracture})$ could be approximated by a log-normal distribution with a mean of 1.7 and a standard deviation of 0.4.

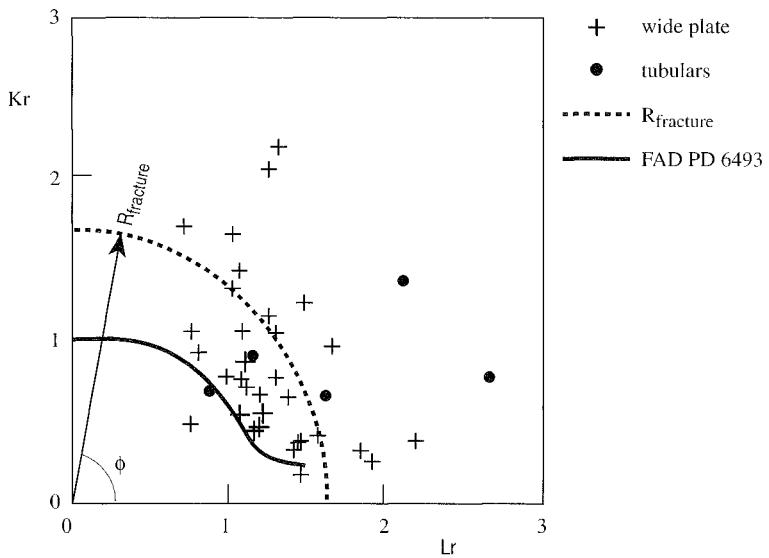


Fig. 6. Failure Assessment Diagram with the results of the experiments.

The values for K_r and L_r determined with the unstable failure model were converted to a value for R (acting).

$$R(\text{acting}) = \sqrt{K_r^2 + L_r^2} \quad (4)$$

The actual failure model is then defined as:

$$Z(\text{failure}) = R(\text{fracture}) - R(\text{acting}) \quad (5)$$

If $Z(\text{failure})$ is negative failure will occur.

If $Z(\text{failure})$ is positive failure will not occur.

2.2.4 Detection model

The detection model is used to determine the probability of detecting a fatigue crack during inspection. The detection model contains the size distribution of a growing fatigue crack (a_g) as determined with the fatigue crack growth model and the size distribution of a detectable crack (a_d), which depends on the inspection method. The distribution of a_d is described by the POD (Probability Of Detection) curve (see Figure 7):

$$POD = 1 - e^{-\frac{(a - \alpha)}{\beta}} \quad (6)$$

Where:

POD = probability of detection for a crack of depth a

α = crack depth below which no crack will be found

β = crack parameter determining the shape of the POD curve

The detection model can now be defined as:

$$Z(\text{detection}) = a_n - a_d \quad (7)$$

If $Z(\text{detection})$ is negative, no crack will be detected.

If $Z(\text{detection})$ is positive, a crack will be detected.

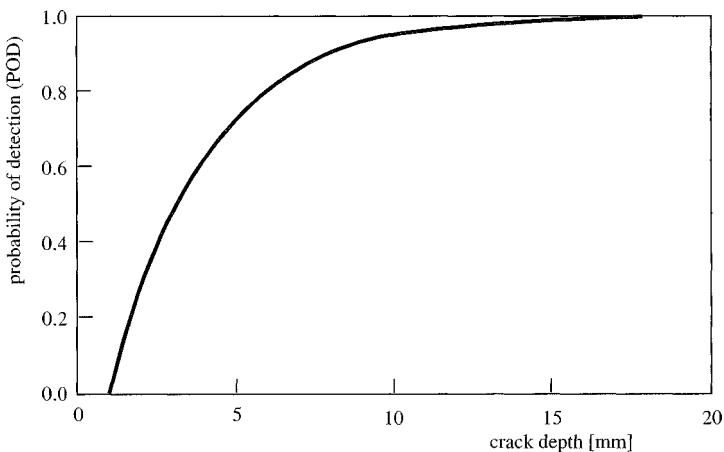


Fig. 7. POD curve.

2.3 Maintenance models

2.3.1 Corrective maintenance (CM)

Corrective maintenance means that no action is undertaken until actual damage occurs. In the Eastern Scheldt storm surge barrier this would mean waiting until a gate fails. This would only be acceptable if the level of safety specified in the Delta Act was not affected. In practice this type of maintenance is attractive if the consequences of failure are not serious and if avoiding failure is expensive.

If the gate fails in the reference period, damage will occur and the complete gate will be replaced. It is assumed that the gate will not fail again during the remaining reference period, i.e. during this time the probability of failure will be zero.

Figure 8 illustrates the event tree for this situation. The gate may fail at time $t = t_f$. No costs are incurred if the gate does not fail. If the gate fails, there are immediate costs of failure and replacement, which decrease in time due to the effective interest.

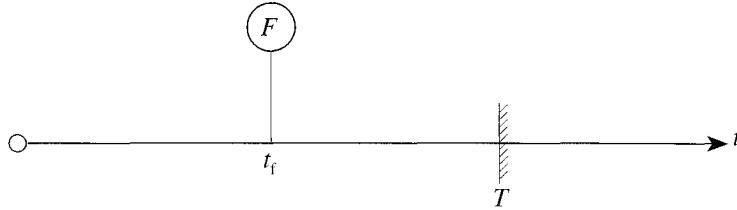


Fig. 8. Event tree for corrective maintenance.

The reference period T is divided into N intervals, say N years. If failure occurs in year n it is assumed that the costs of failure (C_f) are included in the accounts by the end of year n . The NPV for failure in year n (C_n) can be expressed as:
(r = effective interest rate)

$$C_n = \frac{C_f}{(1+r)^n} \quad (8)$$

These costs can also be interpreted as follows: if at time $t = 0$ a capital sum C_n is reserved, capital C_f will be available at time $t = t_f$ (i.e. after n years).

If the probability of failure in year n is referred to as Pf_n the expected costs in year n can be defined:

$$E_n = C_n \cdot Pf_n = \frac{C_f}{(1+r)^n} \cdot Pf_n \quad (9)$$

The costs of corrective maintenance during the full reference period T (N years) amount to the sum of the expected costs in each year:

$$E_{CM} = \sum_{n=1}^N E_n = C_f \sum_{n=1}^N \frac{Pf_n}{(1+r)^n} \quad (10)$$

If the toes of the welds are ground (grinding costs C_g) at the start of the reference period, i.e. at $t = 0$, the total expected costs, per gate, over the period T , are:

$$E_{CM} = C_g + C_f \sum_{n=1}^N \frac{Pf_n}{(1+r)^n} \quad (11)$$

In (11) Pf_n refers to the failure probability of the ground weld toes, in (10) Pf_n refers to the failure probability of the unground welds, both in year n .

2.3.2 Use-based maintenance (UBM)

Use-base maintenance means that components are replaced by new components according to a fixed schedule. For the barrier this would mean that at a given time (t_v) the gates made of brittle material would be replaced by gates of ductile material, irrespective of their condition. This is a form of preventive maintenance. The parameter t_v can be optimised.

However, a gate might fail before replacement. Failure will result in damage and the gate would have to be replaced completely. If a gate is replaced at $t = t_v$, only the costs of replacement are incurred (C_v). It is assumed that the gate will not fail after replacement: i.e. the failure probability will remain zero.

Again the investments and costs are determined at $t = 0$. In this approach the best, i.e. cheapest, replacement period t_v also has to be determined. In a variation to this approach the condition is imposed that the failure probability of any gate should not exceed 10^{-3} . At that time the gate would always be replaced. Again it is assumed that the failure probability after replacement would remain zero.

It is also assumed that there will be no costs if the gate does not fail throughout the reference period T , other than any initial costs of grinding.

The event tree for this maintenance approach is illustrated in Figure 9.

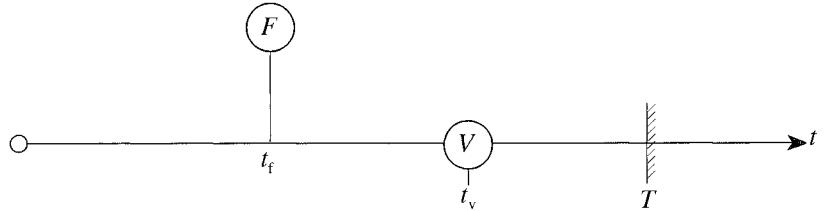


Fig. 9. Event tree for use-based maintenance.

Again, the reference period T is divided into N intervals, e.g. N years. If failure occurs in year n (which is before the year of replacement: $t_f < t_v$), the following costs will be incurred:

$$C_n = \frac{C_f}{(1+r)^n} \quad (12)$$

Again, the failure probability in year n is Pf_n ; thus, the expected costs in year n are:

$$E_n = C_n \cdot Pf_n = \frac{C_f}{(1+r)^n} \cdot Pf_n \quad (13)$$

The total expected costs of failure up to time $t = t_v$, where $n = n_v$, are:

$$E_f = \sum_{n=1}^{n_v} E_n = C_f \sum_{n=1}^{n_v} \frac{Pf_n}{(1+r)^n} \quad (14)$$

In the event of replacement, the fixed costs, including interest and inflation, will be incurred:

$$E_v = \frac{C_v}{(1+r)^{n_v}} \quad (15)$$

after which the failure probability will be zero. The total expected costs of use-dependent maintenance during the reference period T are

$$E_{UBM} = E_v + E_f = \frac{C_v}{(1+r)^{n_v}} + C_f \sum_{n=1}^{n_v} \frac{Pf_n}{(1+r)^n} \quad (16)$$

If the weld toes are ground (grinding costs C_g) at the beginning of the reference period, at $t = 0$, the total expected costs, per gate, over the period T , are::

$$E_{UBM} = C_g + \frac{C_v}{(1+r)^{n_v}} + C_f \sum_{n=1}^{n_v} \frac{Pf_n}{(1+r)^n} \quad (17)$$

2.3.3 Condition-based maintenance (CBM)

When *condition-based maintenance* is used the condition of the component concerned is inspected at specified times. Repairs may or may not be carried out, depending on the outcome of the inspection. The inspection times may be predetermined, the intervals may be the same or different. Similarly, only the next inspection time might be determined, i.e. it is determined after each inspection. Condition-based maintenance is attractive if the costs of failure are high, if the costs of repairs and inspection are relatively low and, most importantly, if the condition of the component concerned can be determined with sufficient accuracy. For the Eastern Scheldt storm surge barrier this means that the inspections will be concerned with the expected crack growth. In theory, repairs need not be carried out as soon as a crack is found. However, given the ratio between the costs of repair and costs of inspection, it was decided that any repairs would be carried out immediately.

The strategy is selected on financial grounds using a defined minimum safety level as a constraint (boundary condition). The maximum acceptable failure probability of a single gate is 10^{-3} . This is linked to the probability of flooding large parts of Zeeland, which is 10^{-7} .

The expected costs associated with condition-based maintenance of the gates in the barrier have only been determined for condition-based maintenance using constant inspection intervals. The optimum inspection interval was determined by finding the cost minimum in a range of inspection intervals.

In this event an inspection means that the presence of any cracks is determined. Repairs will be carried out immediately if cracks are found. The condition model (failure probability calculation) is restarted at that point in time: the input parameters at the original $t = 0$ can then be used again.

Again, the investment and cost calculations are based on time $t = 0$. There are two further costs: the inspection costs (C_i) and the repair costs (C_r).

The reference period T (N years) is divided into K inspection intervals. An inspection is made at the end of each interval. Hence, each inspection interval amounts to $j = N/K$ years. If it is assumed that no inspections are carried out at the start and end of the reference period, K inspection intervals will be associated with $(K-1)$ inspection events and as many – possible – repair events.

In this case the expected costs cannot be derived from the expected annual costs but have to be determined on the basis of a complex event tree.

Figure 10 shows a complete tree with three inspection intervals. Please note that this event tree covers only one welded joint!

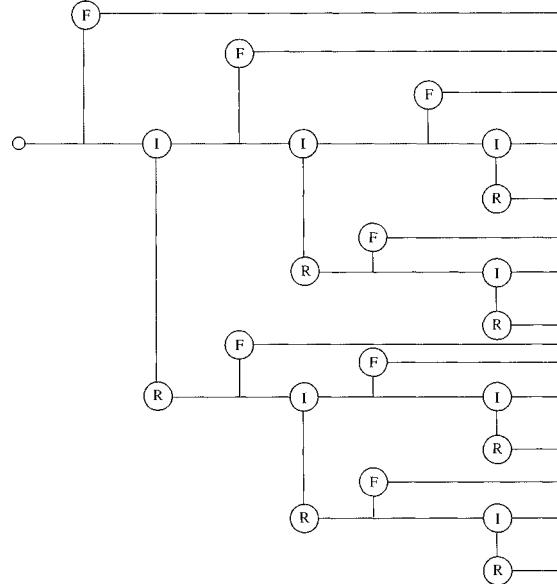


Fig. 10. Event tree for condition-based maintenance.

After a repair a lower level tree is followed; qualitatively speaking it is identical with the high level tree. Multiplying the probabilities of the branches of the tree and the costs of the associated events results in the following contributions:

1. The failure events. If it is assumed that no further expected costs will be incurred after failure and replacement (this assumption was also used in earlier chapters), the probabilities multiplied by the costs are:

$$E(f) = \sum_{k=1}^K \sum_{j=1}^J \frac{C_f}{(1+r)^{J(k-1)+j}} + Pf_{kj} + \sum_{k=2}^K \sum_{j=1}^J \sum_{m=1}^{k-1} \frac{C_i}{(1+r)^{mj}} Pf_{kj} \quad (18)$$

Pf_{kj} is the probability of failure in the j -e subinterval before inspection k . The first term of the equation contains all expected costs of the failure events. The second term contains all expected costs of the inspections preceding failure.

2. The branch of the tree without failure or repairs. In this event only the inspection costs will be incurred. The probability of this is the complement of all preceding failure and repair probabilities.

$$E(nf/nr) = \left(1 - \sum_{k=1}^{K-1} Pr_k - \sum_{k=1}^K \sum_{j=1}^J Pf_{kj} \right) \sum_{k=1}^{K-1} \frac{C_i}{(1+r)^{kj}} \quad (19)$$

3. The repair events. After repair a new lower level tree is followed, which is similar to the higher level tree. Costs multiplied by probabilities:

$$E(r) = \sum_{k=1}^{K-1} \left(\frac{C_r}{(1+r)^{kj}} + \frac{E_{CBM}(K-k)}{(1+r)^{kj}} + \sum_{m=1}^k \frac{C_i}{(1+r)^{mj}} \right) Pr_k \quad (20)$$

The first term refers to all expected costs of the repair events. The second term refers to all expected costs in the lower level tree following repair, the factor $E_{CBM}(K-k)$ refers to the expected costs of lower level tree $(K-k)$. This tree is also a function of K as K determines the probabilities in the lower level tree. This relationship may be expressed in recursive form if it is assumed that the probabilities of failure and repair (discovery of a defect by inspection) after repair will be the same as in the original situation. The third term refers to all expected costs of the inspections preceding repairs.

Thus, the total expected costs of condition-based maintenance are:

$$E_{CBM} = E(f) + E(nf/nr) + E(r) \quad (21)$$

When grinding is included the costs are:

$$E_{\text{CBM}} = C_g + E(f) + E(nf/nr) + E(r) \quad (22)$$

The practical problem associated with these formulas concerns the calculation of the probabilities. These are highly dependent on preceding events, particularly any repairs to the welds.

Alternatively, the expected costs can be calculated by traversing the event tree (Figure 10) and calculating the total probability for each branch. It is assumed that the events in any branch are independent of the events in the preceding branch. In that case, the absolute probability associated with any branch is easily calculated by multiplying the probability of the preceding branch by the conditional probability of that branch. This is expressed in the formula below:

$$P\{A\} = P\{B\} \cdot P\{A|B\} \quad (23)$$

It is also assumed that failure in any year is independent of any failure in preceding years. This procedure was implemented as a computer program. The results presented here were calculated with this program.

3 Input parameters for failure probability calculations

A large number of input parameters is used. When using probabilistic methods the distribution of each parameter has to be specified, rather than a single value. Many of the parameters used here have a normal distribution. However, other distributions, such as log-normal, uniform and Gumbel, were used for some parameters. A general discussion follows and Table 1 provides comprehensive information about the distributions of the input parameters.

The geometry of the tubular joints is simplified to a flat plate (nominal thickness = 35 mm) with stiffener (transverse attachment). The weld geometry can be included in the calculations using the weld angle.

Two initial defect types are considered: undercuts at the toe of the weld and slag inclusions.

On the basis of the requirements and further inspections of y-nodes it was assumed that the initial crack depth due to undercuts would be uniformly distributed between 0 to 0.25 mm.

The assumed slag inclusions were based on a review of some of the fabrication inspection reports and a further evaluation. The probability that a slag inclusion occurs in the hot spot region of a connection is 5.10^{-3} .

The average crack growth parameters in Paris' law are based on measurements on material taken from the barrier; their scatter was based on the literature [7].

The materials were divided into five classes, with different mechanical properties:

Class	Abbreviation	Description
M-I	HRCGNC	Hot-rolled, coarse-grained, niobium-containing
M-II	HRMS	Hot-rolled, mixed structure
M-III	HRCGNF	Hot-rolled, coarse-grained, niobium free
M-IV	CR	Cold-rolled
M-V	HRFG	Hot-rolled, fine-grained

The loads on the girders and the maximum stress in the nodes were based on calculations carried out by the Directorate-General for Public Works and Water Management.

The maximum static load due to fall and wave loads to be used in the deterministic calculations was selected such that the probability of it being exceeded is $4 \cdot 10^{-4}$. Using Miner's rule the load spectrum was converted to an equivalent stress range when considering fatigue. Five stress classes were distinguished.

The residual stress due to the welding operations was assumed to be linearly dependent on the yield stress.

It is expected that the barrier will be subjected to eddy current inspection. Thus, there is no need to remove the paint coating for inspections. The shape of the POD is determined by parameters α and β (see also section 2.2.4).

The Failure Assessment Diagram (FAD) is determined by parameter R(fracture). On the basis of experiments a log-normal distribution was selected, with a mean of 1.682 and a standard deviation of 0.424 (see also section 2.2.3).

Table 1. Input parameters for the failure probability calculation.

Parameter	Distribution	Mean	St. dev.	Notes
<i>Geometry</i>				
wall thickness t [mm]	normal	35	0.75	
weld angle θ [$^{\circ}$]	normal	60	10	
<i>Initial defect</i>				
a) undercut				
– depth a_i [mm]	uniform			min. = 0 max. = 0.25
– factor F_c [-]	normal	70	17.5	$c_i = F_c \cdot a_i$
b) slag inclusion				probability of occurrence 0.005
– depth a_i [mm]	normal	2.5	0.25	
– factor F_c [-]	normal	16	13	$c_i = F_c \cdot a_i$
<i>Crack growth parameter</i>				
– constant C_{ave}	constant	8.833E-12	–	
– exponent f_{c2} [-]	normal	0	0.1021	$C = C_{ave} \cdot 10^{f_{c2}}$
– exponent m [-]	constant	2.8	–	

Table 1. Input parameters for the failure probability calculation (continued).

Parameter	Distribution	Mean	St. dev.	Notes
<i>Material properties</i>				
M-I HRCGNC				
– yield stress R_e [N/mm ²]	normal	297.7	13.5	
– CTOD [mm]	lognormal	0.144	0.071	lower limit 0
<i>M-II HRMS</i>				
– yield stress R_e [N/mm ²]	normal	320.1	35.6	
– CTOD [mm]	lognormal	0.203	0.092	lower limit 0
<i>M-III HRCGNF</i>				
– yield stress R_e [N/mm ²]	normal	307.7	12.0	
– CTOC [mm]	lognormal	0.245	0.142	lower limit 0
<i>M-IV CR</i>				
– yield stress R_e [N/mm ²]	normal	425.7	19.3	
– CTOD [mm]	lognormal	0.409	0.274	lower limit 0
<i>M-V HRFG</i>				
– yield stress R_e [N/mm ²]	normal	398.3	13.7	
– CTOD [mm]	lognormal	2.206	0.704	lower limit 0
<i>Load categories</i>				
<i>S-I</i> $\sigma_{\text{nom}} = 470$				
– fatigue $\Delta\sigma$	constant	117.5	–	
– peak stress	Gumbel	83.73	63.74	membrane stress proportion 0.5306
<i>S-I</i> $\sigma_{\text{nom}} = 400$				
– fatigue $\Delta\sigma$	constant	100	–	bending stress proportion 0.4694
– peak stress	Gumbel	71.26	54.25	and
<i>S-I</i> $\sigma_{\text{nom}} = 330$				
– fatigue $\Delta\sigma$	constant	82.5	–	
– peak stress	Gumbel	58.79	44.76	correlationfactor for wall thickness
<i>S-I</i> $\sigma_{\text{nom}} = 150$				
– fatigue $\Delta\sigma$	constant	50	–	
– peak stress	Gumbel	26.72	20.34	[2 - $t_{\text{actual}}/t_{\text{mean}}$]
general				
– factor $F\sigma 2$ [-]	normal	1	0.09766	distribution factor $\sigma_{\text{cor}} = \sigma_{\text{nom}} \cdot F\sigma 2$
<i>Residual stresses</i>				
– factor frac [-]	normal	0.75	0.125	$\sigma_{\text{res}} = \text{frac} \cdot R_e$
<i>Inspections</i>				
– α [mm]	constant	1	–	lower limit
– β [mm]	constant	3	–	shape factor
<i>Failure diagram</i>				
– $R(\text{frac})$ [-]	lognormal	1.682	0.424	lower limit = 0

4 Classification by category and failure probabilities

4.1 General

A database containing the most important information was created to obtain an overview of the most relevant parameters of the 2512 nodes. This database can be queried using selection criteria.

4.2 Classification by category

The database was used to classify the nodes by category. The material grade and maximum stress level were used as the classification criteria.

The number of categories used was limited to 20 by using 5 material classes (M-I to M-V) and 4 stress classes (S-I to S-IV).

This produced the classification used in Table 2, which lists the number of welded joints in each category.

Table 2. Number of joints, by stress class and material.

Stress class σ_{\max} [N/mm ²]	Weld condition ²	Material grade					Total per stress class
		M-I HRCGNC	M-II HRMS	M-III HRCGNF	M-IV CR	M-V HRFG	
S-I 400–470	AW		1		168	15	186
	G		2	2			4
S-II 330–400	AW	1	18	5	170	163	361
	G			3		2	5
S-III 260–330	AW	3	44	28	346	268	5
	G		1	5			6
150–260	no joints in this stress class						
S-IV 0–150	AW		32	10	925	276	12
	G			1			1
total per material	AW	4	95	43	1609	722	23
	G		3	11		2	<u>2512</u>

¹ The material grade of 23 joints could not be determined with certainty.

² AW = as welded, G = ground

The correlation between maximum stress and equivalent fatigue stress range was determined by database queries. Conservative values for the ratio $\Delta\sigma/\sigma_{\max}$ are 1/4 for stress classes I, II and III, and 1/3 for stress class IV.

4.3 Failure probabilities by category

The failure probabilities for each category were calculated after 0, 300,000, 550,000 and 700,000 cycles. Depending on the location of the gates, a 200-year period amounts to 550,000 or 700,000 cycles.

The values discussed in Chapter 3 were used as input parameters. The combined failure probabilities due to undercuts and slag inclusion (probability 0.005) are listed in Table 3. The low failure probabilities were calculated by the FORM method, while the high failure probabilities were determined using the Monte Carlo method.

Table 3. Combined failure probability, by category (FORM (F) and Monte Carlo (M)).

		Material grade				
Number of cycles N*1000	Stress class σ_{\max}	M-I HRCGNC	M-II HRMS	M-III HRCGNF	M-IV CR	M-V HRFG
0	S-I 470	0.209E-03 F	0.135E-03 F	0.128E-03 F	0.801E-05 F	0.982E-05 F
	S-II 400	0.617E-04 F	–	–	0.172E-05 F	0.202E-05 F
	S-III330	0.125E-04 F	0.751E-05 F	0.644E-05 F	0.230E-06 F	0.251E-06 F
	S-IV150	0.740E-08 F	0.166E-08 F	0.164E-08 F	0.502E-09 F	0.377E-11 F
300	S-I 470	0.178E+00 M	0.163E+00 M	0.172E+00 M	0.191E+00 M	0.177E+00 M
	S-II 400	0.188E-01 M	0.198E-01 M	0.194E-01 M	0.174E-01 M	0.169E-01 M
	S-III330	–	–	–	–	–
	S-IV150	0.300E-07 F	0.476E-08 F	0.579E-08 F	–	0.487E-11 F
550	S-I 470	0.675E+00 M	0.659E+00 M	0.679E+00 M	0.690E+00 M	0.662E+00 M
	S-II 400	0.293E+00 M	0.285E+00 M	0.263E+00 M	0.274E+00 M	0.271E+00 M
	S-III330	0.289E-01 M	0.264E-01 M	0.272E-01 M	0.269E-01 M	0.294E-01 M
	S-IV150	0.860E-07 F	0.107E-07 F	0.161E-07 F	0.408E-08 F	0.603E-11 F
700	S-I 470	0.842E+00 M	0.854E+00 M	0.844E+00 M	0.840E+00 M	0.824E+00 M
	S-II 400	0.495E+00 M	0.506E+00 M	0.500E+00 M	0.488E+00 M	0.491E+00 M
	S-III330	0.983E-01 M	0.974E-01 M	0.102E+00 M	0.795E-01 M	0.943E-01 M
	S-IV150	0.143E-07 F	0.161E-07 F	0.269E-07 F	0.814E-08 F	0.682E-11 F

The provisional conclusions based on these calculations are:

- The failure probability at the lowest stress level is so low, in relative terms, that inspection of these joints (i.e. half the total number of joints), does not appear to be productive.
- For lower cycle numbers a distinction can be made between HRCGNC, HRMS and HRCGNF on the one hand, and CR and HRFG on the other. At 0 cycles the first group has a failure probability one order of magnitude higher than the second group.
- At higher cycle numbers the differences in failure probabilities between the various materials are vanishing.

5 Maintenance costs

5.1 General

The maintenance costs were determined for three maintenance and management models (see also section 2.3):

- corrective maintenance;
- use-based maintenance;
- condition-based maintenance.

All calculations were based on an effective interest rate of 5%. The effective interest rate is the nominal interest rate minus inflation.

These calculations cover a 200-year period. This period was selected as the design life was 200 years. It was also assumed that there will be about 3500 load cycles per year. The design calculations specify about 550,000 cycles in 200 years for the gates in the Schaar and Hammen, and about 700,000 cycles for the Roompot.

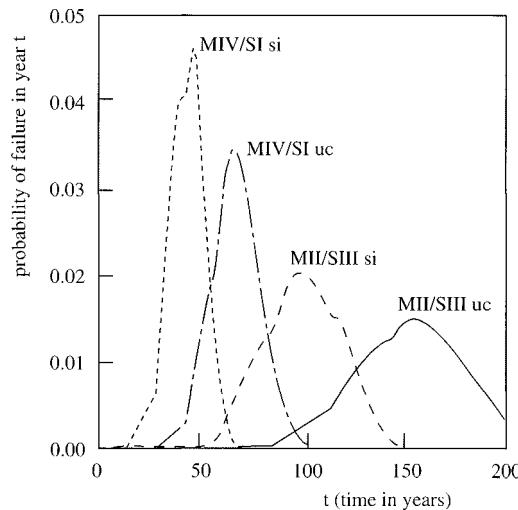


Fig. 11. Failure probability in year t , including the probability of weld failure in the preceding period.

Figure 11 illustrates the calculated failure probabilities for a T-node in the most heavily loaded B girder for two different combinations of material grade and stress level, i.e. M-II, S-III and M-IV, S-I. The probability of failure, as function of time, is given under the condition that either one of the two initial defects is present: an undercut (uc) or slag inclusion (si). The probability that a gate has failed, before the time considered, is included in this calculation. The actual values of the input data are discussed in Chapter 3.

Unground weld toes always contain undercuts. It was also assumed that slag inclusions occurred during welding in 0.5% of the joints. It was assumed that undercuts would be eliminated completely by grinding the weld toes.

To calculate the failure probability of any gate, the correlation between the failure probability of a welded joint and the failure probability of the gate has to be known. It was assumed that the failure probability of a gate would be a factor 10 higher than the failure probability of a welded joint. A further study indicated that this factor is actually 5. This will reduce the costs; however, it hardly affects the optimum inspection period.

The calculations include a number of costs:

1. The *replacement costs* $C_v = MG$ (million guilders) 15, i.e. the costs associated with a new gate.
2. The *damage costs* $C_d = MG$ 15, i.e. the costs due to damage incurred when a gate fails.
3. The *failure costs* C_f , i.e. the costs associated with failure. Failure leads to damage costs and replacement; thus: $C_f = C_d + C_v = MG$ 30.
4. The *grinding costs* per gate $C_g = kG$ (thousand guilders) 480. The cost of grinding a single joint were estimated at kG 10. It was assumed that each gate contains 48 joints.
5. The *inspection costs* per gate $C_i = kG$ 10.
6. The *repair costs* per gate $C_r = kG$ 160. This concerns the costs of repairing cracks. The costs per welded joint were estimated at kG 16. The repair costs per gate are based on the assumption that each gate has 10 critical joints.

5.2 Corrective maintenance

When corrective maintenance is applied, actions are only undertaken after failure of the structure. Thus, the safety constraint ($P_f < 10^{-3}$) is ignored in this approach. There are no parameters to be optimised.

If a gate fails during the reference period, damage will occur. The complete gate will then be replaced, using material of the required quality. It is then assumed that the gate will not fail again during the remaining part of the reference period. During this remaining time the failure probability will be zero.

Table 4 lists the resulting values, based on 5% interest, in kiloguilders, net present value.

When this approach to maintenance is adopted, it should therefore be concluded that the joints of M-II/S-III combinations should not be ground, while the joints in M-IV/SI combinations should be ground.

Table 4. Corrective maintenance, effective interest rate 5%.

Combination	M-II/S-III		M-IV/S-I	
Material	Hot-rolled mixed structure (HRMS)		Cold-rolled (CR)	
Stress	$\sigma_{\text{nom}} = 330 \quad \Delta\sigma = 82.5$		$\sigma_{\text{nom}} = 470 \quad \Delta\sigma = 117.5$	
	Unground	Ground	Unground	Ground
Net present value [kG]	303	547	3,457	864

5.3 Use-based maintenance

When use-based maintenance is adopted the gates are replaced after a given period, t_v , irrespective of their condition. However, a gate may fail before replacement. Failure will lead to damage and the complete gate has to be replaced. If replacement is carried out at $t = t_v$, only the replacement costs will be incurred. Again, it is assumed that gates will not fail after replacement, i.e. the failure probability will remain zero. The optimum, i.e. cheapest, replacement period, t_v , can be determined for this approach to maintenance.

The expected costs for the combination M-IV/S-I are plotted as a function of the time of replacement in Figure 12. The welded joints are not ground. As the figure shows, the economic optimum (3,306 kG after 42 years) is very close to the expected costs at 200 years (3,457), i.e. not replacing the gate at all.

This is due to the fact that failure costs are small compared to the replacement costs. In all other cases, the failure costs are even smaller. In all these cases use-based maintenance degenerates to corrective maintenance: use-based maintenance is too expensive.

In a variation to this approach the constraint is introduced that the failure probability of the gates should not exceed 10^{-3} . Gates are replaced when this failure probability is reached.

The failure probability of gates with combination M-II/S-III, with ground or unground weld toes, exceeds 10^{-3} after about 60 years. However, for gates with the combination M-IV/S-I the failure probability will exceed 10^{-3} after only about 18 years (see Table 5).

The conclusion drawn for corrective maintenance also applies to use-based maintenance. Grinding the weld toes of M-IV/S-I combinations would only be a sound investment if the replacement is based on minimum expected costs.

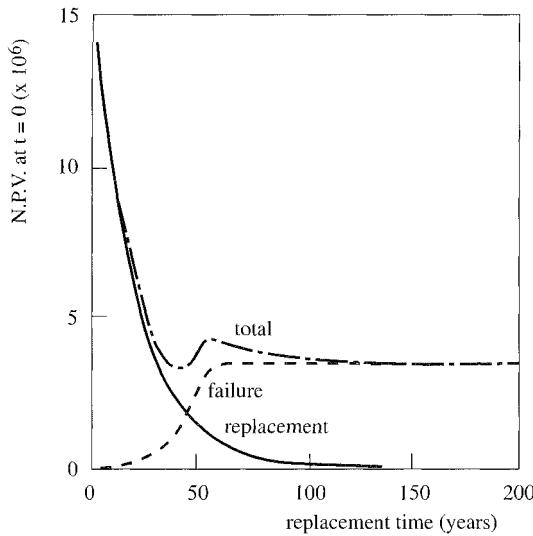


Fig. 12. Expected costs as a function of the time of replacement.

Table 5. Use-based maintenance, effective interest rate 5%.

Combination	M-II/S-III		M-IV/S-I	
Material	Hot-rolled mixed structure (HRMS)		Cold-rolled (CR)	
Stress	$\sigma_{\text{nom}} = 330$	$\Delta\sigma = 82.5$	$\sigma_{\text{nom}} = 470$	$\Delta\sigma = 117.5$
	Unground	Ground	Unground	Ground
Based on * costs	303	547	3,306 $t_v = 42$ years	864
Based on * $P_f < 10^{-3}$	934 $t_v = 59$ years	1271 $t_v = 61$ years	6,306 $t_v = 18$ years	6,454 $t_v = 19$ years

* NPV in kG

5.4 Condition-based maintenance

5.4.1 General

When condition-based maintenance is adopted, inspections are carried out during the planned life of the structure to measure its condition. The time of inspection is determined on the basis of a fixed interval or on the basis of the results of the previous inspection and a model to predict the condition (the condition model). The first option is known as time-dependent inspection, the second as condition-dependent inspection.

There are two forms of time-dependent inspection, inspections at constant intervals, and inspections where a variable interval is determined on the basis of a predefined function.

For the gates inspection means crack inspection. Repairs will be carried out immediately if a crack is detected.

The calculations are based on time-dependent inspection at constant intervals. The optimum inspection interval on financial grounds was determined. Safety was included as a boundary condition.

5.4.2 Crack detection probability

It is likely that an eddy current detection system will be used to inspect the welded joints in the barrier. The POD of eddy current detection is discussed in 2.2.4. All results presented in this chapter were calculated on the basis of $\alpha = 1$ mm and $\beta = 3$ mm.

The probability of detecting a crack in a welded joint in the Eastern Scheldt storm surge barrier can be calculated with the crack growth model discussed in section 2.2.1. The results of these calculations, for the combination M-IV/S-I and both defect types (undercuts and extended slag inclusions) are illustrated in Figure 13.

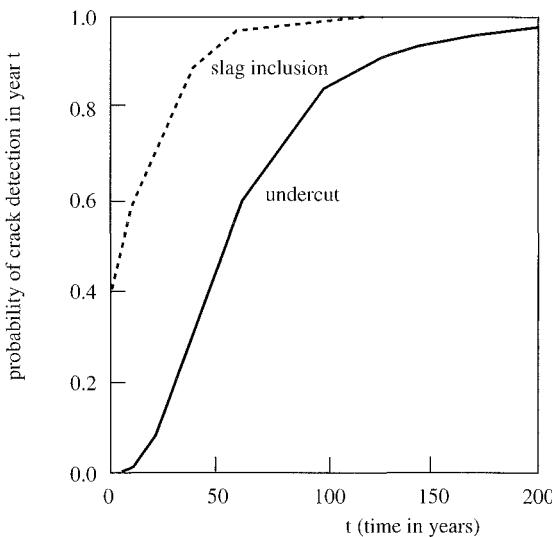


Fig. 13. Crack detection probability for the combination M-IV/S-I, without previous inspections.

As an extended slag inclusion is a relatively large initial defect, there is a relatively high probability of detecting the crack from the start. However, undercuts are initially fairly small and have a low probability of detection.

5.4.3 Results

The results are based on a method which systematically covers all events which may occur over time. The start is at $t = 0$. On the basis of the probabilities of all future events the expected costs can be determined, in principle for all scenarios.

However, in practice it is unfeasible to undertake all calculations as there are too many scenarios; furthermore, this would be unnecessary. If the probability that an event occurs is so small that its associated costs are negligible, the calculation of the expected costs of all possible events following this event becomes unnecessary.

The major assumption in this method is that each event is independent of other events. This does not correspond to reality, but it is expected that the resulting error is not large.

The results, for combination M-IV/S-I and an interest rate of 5%, with unground weld toes, are illustrated in Figure 14.

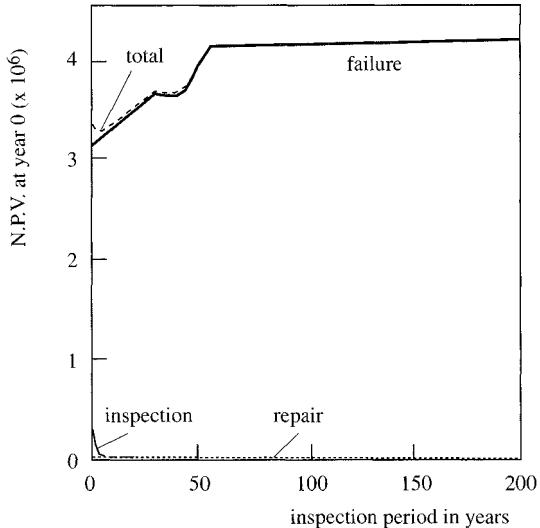


Fig. 14. Expected costs as a function of the inspection interval. Combination M-IV/S-I, unground and interest rate 5%.

The optimum occurs at an inspection interval of 3 years. The expected costs are listed in Table 6. Note that the minimum is found in a fairly flat region. The expected costs are almost constant for any inspection interval between 2 and 5 years.

Table 6. Condition-dependent maintenance, effective interest rate 5%.

Combination	M-II/S-III		M-IV/S-I	
Material	Hot-rolled mixed structure (HRMS)		Cold-rolled (CR)	
Stress	$\sigma_{\text{nom}} = 330$	$\Delta\sigma = 82.5$	$\sigma_{\text{nom}} = 470$	$\Delta\sigma = 117.5$
	Unground	Ground	Unground	Ground
Costs [kG]	238	488	3,253	527
Insp. period	20 years	55 years	3 years	10 years

5.5 Comparison of the three maintenance strategies

The overall expected costs of three approaches to maintenance were presented above. These were all based on identical data. Table 7 provides a summary of the most significant results.

Table 7. Overall expected costs as NPV in kG, based on an interest rate of 5%.

Combination	M-II/S-III		M-IV/S-I	
Material	Hot-rolled mixed structure (HRMS)		Cold-rolled (CR)	
Stress	$\sigma_{\text{nom}} = 330$	$\Delta\sigma = 82.5$	$\sigma_{\text{nom}} = 470$	$\Delta\sigma = 117.5$
	Unground	Ground	Unground	Ground
Corrective maintenance	303	547	3,457	864
Use-based maintenance				
– based on costs	303	547	3,306 42 years	864
– based on $P_f < 10^{-3}$	934 59 years	1271 61 years	6,306 18 years	6,454 19 years
Condition-based maintenance	238 20 years	488 55 years	3,253 3 years	527 10 years

The years indicate when the gate has to be replaced (use-based maintenance) or the inspection interval (condition-based maintenance).

The table shows that for the M-II/S-III combination:

- a. it is not advisable to grind the welds for any type of maintenance as this would increase the costs;
- b. condition-based maintenance results in the lowest expected costs, i.e. it is worthwhile to inspect the welds.

For the combination M-IV/S-I:

- a. grinding the welds is advisable in any maintenance strategy;
- b. again condition-based maintenance results in the lowest expected overall costs, i.e. again it is worth to inspect the welds.

5.6 Further development of condition-based maintenance

As condition-based maintenance is cheapest, it was decided to calculate the optimum inspection interval for two other weld categories.

These were:

M-IV/S-II cold-rolled material (CR), $\sigma_{\max} = 400 \text{ N/mm}^2$

and

M-IV/S-III cold-rolled material (CR), $\sigma_{\max} = 330 \text{ N/mm}^2$ (S-III)

You are referred to Chapter 3 for further details and the input parameters.

Table 8 is a summary of the results of these calculations. The numbers in brackets refer to the optimum inspection intervals.

Table 8. Total expected costs and maintenance intervals in NPV in [kG] based on interest rate of 5%.

Category	Cat. 1	Cat. 2	Cat. 3	Cat. 4
Material	CR/M-IV	CR/M-IV	CR/M-IV	HRMS/M-II
Stress class	S-I	S-II	S-III	S-III
σ_{\max} (N/mm ²)	470	400	330	330
$\Delta\sigma$ (N/mm ²)	117.5	100	82.5	82.5
Ground	527 (10 years)	513 (20 years)	485 (55 years)	488 (55 years)
Not ground	3.253 (3 years)	622 (10 years)	172 (20 years)	238 (20 years)

These results clearly indicate when grinding is attractive.

One has to be aware that, if it is decided to carry out grinding, a large part of the total costs is due to the grinding costs of kG 480. These costs are based on the assumption that all welded joints have to be ground. However, normally only a small proportion of the joints will need grinding; thus, this item may be considerably lower. If the grinding costs exceed approx. kG 250, it is not attractive to grind welded joints in stress category S-III. However, for the more brittle steel grades in stress category S-I ($\sigma_{\max} = 470 \text{ N/mm}^2$) and S-II ($\sigma_{\max} = 400 \text{ N/mm}^2$) grinding is recommended, even when it is assumed that the costs will be kG 480.

5.7 Recommendations

As steel grades M-I (HRCGNC) and M-III (HRCGNF) are no better than M-IV (CR) and not much worse than M-II (HRMS), the following recommendations can be made:

For all steel grades, with the exception of the hot-rolled, fine-grained steel (HRFG/M-V):

In category S-I ($\sigma_{\max} = 470 \text{ N/mm}^2$):

- grind the welds;
- inspection every 5 to 15 years.

In category S-II ($\sigma_{\max} = 400 \text{ N/mm}^2$):

- grind the welds;
- inspection every 15 to 25 years.

In category S-III ($\sigma_{\max} = 330 \text{ N/mm}^2$):

- do not grind the welds (actually depends on grinding costs);
- inspection every 15 to 25 years.

In category S-IV ($\sigma_{\max} = 150 \text{ N/mm}^2$):

- no special action, rough visual inspection after a storm surge situation (corrective maintenance).

For the hot-rolled, fine-grained steel (HRFG/M-V), for all load categories:

- rough visual inspection after a storm surge situation (large cracks are acceptable, given the toughness of the material).

6 Conclusions

The study was concluded by making the following recommendations about maintenance and management. Please note that these recommendations only refer to the crack growth and brittle fracture failures due to material problems, as covered by this study.

1. The hot-rolled, fine-grained steel (HRFG/M-V) requires neither inspection nor maintenance.

The following strategies are recommended for the other materials:

2. Joints in stress category S-I ($\sigma_{\max} = 470 \text{ N/mm}^2$):
 - welds to be ground immediately;
 - inspection every 5 to 15 years.
3. Joints in stress category S-II ($\sigma_{\max} = 400 \text{ N/mm}^2$):
 - welds to be ground immediately;
 - inspection every 15 to 25 years.
4. Joints in stress category S-III ($\sigma_{\max} = 330 \text{ N/mm}^2$):
 - do not grind the welds if the costs of grinding of this category of joints exceeds approx. kG 250 per gate;
 - inspection every 20 years if the joints are not ground;
 - no further maintenance (i.e. inspection) will be required if the joints are ground.
5. Joints in stress category S-IV ($\sigma_{\max} = 150 \text{ N/mm}^2$):
 - no grinding, no further inspections.

If it is preferred not to grind the weld toes immediately, recommendations 2 and 3 for the other grades should be changed to:

- 2a. Joints in stress category S-I ($\sigma_{\max} = 470 \text{ N/mm}^2$):
 - inspection every 2 to 4 years.
- 3a. Joints in stress category S-II ($\sigma_{\max} = 400 \text{ N/mm}^2$):
 - inspection every 5 to 15 years.

These conclusions are based on the assumption that the ratio between the failure probability of the gate and the failure probability of a joint is 10. Further investigation of one of the gates indicated that the ratio for that particular gate was 5. Further studies suggested that this ratio has a minor effect on the inspection interval; however, the overall costs are affected.

A study with an improved POD curve showed that the proposed inspection intervals need not be changed if better inspection methods become available in the future.

7 References

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