RELIABILITY BASED FAILURE ANALYSES FOR THE EASTERN SCHELDT BARRIER STEEL DOORS

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A probabilistic model for the determination of failure probabilities of tubular joints due to fatigue and fracture is presented. The model is based on fracture mechanics fatigue crack growth and the PD 6493 fracture model. The deterministic failure assessment diagram was replaced by a failure probability distribution based on fracture tests. The results follow the line of expectation.
The shape of the failure surface is highly non-linear. Therefore approximation methods like FORM have difficulties in finding a solution and the more robust Monte Carlo method was used for the larger failure probabilities.

INTRODUCTION

Reliability based failure analyses have been carried out for the steel doors in the Eastern Scheldt storm surge barrier. This work was initiated by the Dutch Ministry of Transport and Public Works. The work was carried out by TNO (Netherlands organization for applied scientific research).

The barrier consists of a steel plate structure supported by two or three tubular trusses (see figure 1). During the fabrication of the structure it was discovered that relatively coarse grained material was present in the tubular trusses. This was discovered rather late during fabrication and therefore a special investigation was carried out to see whether replacement of the coarse grained material was necessary or not. This investigation showed that a limited amount of coarse grained material had to be replaced by normal fine grained material.

The main concern was brittle fracture at the weld toes in the tubular joints. When the barrier is closed the steel doors are

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loaded by a fluctuating wave load. This can result in fatigue crack growth from small fabrication defects, like undercuts or slag inclusions. After some time an instable (brittle) fracture can be initiated from the small fatigue cracks in the brittle material by an extreme high wave loading.

It was anticipated that reliability based failure analyses could give a better insight in the real failure probability and in the most important parameters. The results of these analyses are used for an inspection and maintenance schedule for the barrier.

The probabilistic failure analysis was based on a fracture mechanics fatigue crack growth model and a fracture mechanics brittle fracture model. These models were incorporated in a general probabilistic framework in which it is possible to carry out different approaches of reliability assessment (PROBAN [1]).

This paper describes the combined failure (fatigue and fracture) model, the input parameters used and the results of the reliability analyses.

FAILURE MODEL

General

A failure model suited to be used in combination with a probabilistic approach was developed at TNO. This model determines a value for the failure parameter g_x. A negative value of g_x corresponds with failure of the joint and a positive value corresponds with a no failure (safe) situation.

This model is called by the PROBAN computer and calls in the subroutines for the fatigue model and the fracture model. It finally passes the value of g_x back to PROBAN.

Fatigue model

The fatigue model is based on a fatigue crack growth fracture mechanics approach. This approach and the way it is used at TNO has extensively been published earlier, therefore the model is described here in a very brief way. More general information is given by Dijkstra et al [2 and 3], while application to welded steel tubular joints is given by Van Straalen and Dijkstra [4].

In the fatigue fracture mechanics model the tubular joint is simplified to a flat plate with a transverse attachment (see figure 2). The flat plate (representing the chord wall) is loaded with the stress field at the hot spot of the tubular joint (including the overall stress concentration factor). The stress intensity factors for the cracked geometry are determined with analytical expressions from literature. The weld toe influence is taken into account by using a stress intensity concentration factor (M_k). Initial defects as undercuts and slag inclusions are assumed to be present at the weld toes. The defects are schematized as semi-elliptical surface defects with depth a and half width c, for initial dimensions (a_i and c_i) see section 'Input parameters'. The Paris relation is used as a crack growth law for crack depth and crack width extension.

The results of the fatigue model are the crack dimensions (depth a and half width c) after a given number of cycles. These results are input parameters for the fracture model.

Fracture model

The fracture model is based on the two parameter approach as is used in the revised PD 6493 [5]. In this model the fracture parameter (Kr) and the plastic collapse parameter (Lr) are determined using the same flat plate model as used for the fatigue model (see fig. 2). For plastic collapse the flat plate model for normal bending restraint as given in PD 6493 is used.

Instead of the deterministic assessment line used at level 3 of PD 6493 a failure probability distribution could be derived on the basis of 38 fracture tests. The Kr and Lr values of the tests were determined at the actual failure load using the CTOD as the fracture toughness parameter. The experiments were selected from a larger database using the condition that the fracture process of the CTOD test and the fracture test were both brittle. The 38 tests consisted of:6 wide plates with a through thickness crack,8 wide plates with a surface crack, 4 wide plates with a crack emanating from a central hole, 4 plate specimens with a cruciform attachment, with a crack at the toe of the weld, 3 curved wide plates of tubular joint chord material with a surface defect, 8 wide plates with a surface crack located at a weld toe and 5 tubular joints with a surface crack located at a weld toe (2 T-joints and 3 Y-joints).

The failure points can be represented by the polar coordinates R_{fail} and Φ as indicated in figure 3. These points were determined with the average values of the measured CTOD. As the distribution of the failure points turned out to be independent of Φ the distribution obtained depends on R_{fail} only. The distribution of R_{fail} appeared to be lognormal with a mean of 1.682 and a standard deviation of 0.424 (see figure 3).

ANALYSES

Input parameters

The input parameters are given in table 1. For the material only two classes (M-I being coarse grained material and M-V being fine grained material) are considered here. In the complete study five classes were investigated. For the loading also two classes (the highest two classes, S-I and S-II) are considered instead of four in the entire investigation.

Results

The results of the analyses are given in table 2 and figure 4. The failure probabilities at 0 cycles were determined with FORM (First Order Reliability Method) while the results at higher number of cycles were determined by the Monte Carlo approach.

TABLE 1 -INPUT PARAMETERS (Dimensions in N and mm).

Parameter		Distri-bution	Mean	Standard deviation	Remark
<u>Geometry</u>					
.wall thickness	T	normal	35	0.75	
.weld toe angle	θ	normal	60°	10°	
<u>Defect</u>					
-undercut (uc)					
.depth	a_i	uniform	0.125	0.07216	
.width factor	Fc	normal	70	17.5	c_i = Fc * a_i
-slag inclusion(si)					
.depth	a_i	normal	2.5	0.25	
.width factor	Fc	lognormal	16	13	c_i = Fc * a_i lower bound 0
<u>Material properties</u>					
-fatigue					
.constant C					
with	C_{gem}	determin.	8.833E-13	-	$C = C_{gem} * 10^{fc2}$
and	fc2	normal	0	0.1021	
.exponent	m	determin.	2.8	-	
-fracture					
.σ_y for M-I		normal	297.7	13.5	
for M-V		normal	398.3	13.7	
.CTOD for M-I		lognormal	0.144	0.071	lower bound 0
for M-V		lognormal	2.206	0.704	lower bound 0
<u>Loading</u>					
-fatigue					
$\Delta\sigma_e$ for S-I		determin.	117.5	-	
for S-II		determin.	100.0	-	
-fracture					
σ_{max} for S-I		gumbel	83.73	63.74	nominal 470
for S-II		gumbel	71.26	54.25	nominal 400
-residual stress factor	frac	normal	0.75	0.125	σ_{res}=frac * σ_y
<u>Failure</u>	R_{fail}	lognormal	1.682	0.424	lower bound 0

Discussion of the results

The initial defect size (a_i) plays, as expected, an important role. The probabilities of failure due to slag inclusions are markedly higher than those due to undercuts. At zero load cycles the probability of failure is not affected by the crack growth rate. At higher number of load cycles where cracking becomes dominant all probabilities of failure tend to one.

The extreme load (σ_{max}) has, as expected, a significant influence on the failure probability along the whole range of cycles.

TABLE 2 -Failure probability per class

number of cycles N *1000	defect **	FORM (F) and Monte Carlo (M) results			
		Load class S-I		Load class S-II	
		Material I	Material V	Material I	Material V
0 0	uc si	0.202E-03 F 0.128E-02 F	0.973E-05 F 0.174E-04 F	0.591E-04 F 0.508E-03 F	0.200E-05 F 0.394E-05 F
300 300	uc si	0.175E+00 M 0.625E+00 M	0.174E+00 M 0.616E+00 M	0.177E-01 M 0.220E+00 M	0.159E-01 M 0.208E+00 M
550 * 550	uc si	0.670E+00 M 0.967E+00 M	0.657E+00 M 0.939E+00 M	0.289E+00 M 0.763E+00 M	0.267E+00 M 0.760E+00 M
700 * 700	uc si	0.837E+00 M 0.990E+00 M	0.819E+00 M 0.989E+00 M	0.491E+00 M 0.902E+00 M	0.486E+00 M 0.902E+00 M

* Depending on the gate 550.000 or 700.000 cycles are equivalent to 200 years

** Defect types : uc = undercut ; si = slag inclusion

Material properties are important in the early stage, where the crack depth is still small to moderate. As the crack propagation properties are taken equal for both materials and failure due to through crack occurrence becomes dominant, the influence of material properties fades.

Summarizing it can be stated that the results follow the line of expectation and give no reasons for additional remarks.

The small failure probabilities at zero load cycles were calculated using the FORM approximation. It turned out that it took a lot of tuning to get results and there is still some doubt how accurate these results actually are. The failure surface is far from linear and the failure boundary is not smooth (differentiable). A SORM approximation did not improve results very much.

This was explicitly tested by comparing the Monte Carlo result of Material I, load class S-II, undercut defect at 300,000 load cycles with the FORM result. The Monte Carlo results in Pr(failure) = 0.0177 (as given in table 2), while FORM gives 0.000858 as the failure probability. The SORM procedure gives even a smaller value of 0,000709. Also other approaches, all based on the existence of a single failure boundary, like directional simulation or axis-orthogonal simulation did not improve the procedure, nor the results. It seems that the actual failure surface might consist of different distinct parts and this will require further investigations in the future.

As the larger probabilities could be calculated by means of the Monte Carlo method, this method is used in all cases with 300,000 cycles and more. The coefficient of variation of the resulting failure probabilities was kept smaller than 10%, by increasing the number of samples.

During the Monte Carlo runs, it was discovered that some small regions of possible input were not properly defined, giving rise to unexpected errors and results. It turned out that these regions were formed by unrealistic combinations of input parameters.

CONCLUSIONS

The presented probabilistic model to predict the failure probabilities of a tubular joint with a growing semi-elliptical crack at a weld toe gives satisfactory results.

The deterministic line of the PD 6493 fracture model could be replaced by a failure probability distribution based on experiments.

Because the shape of the failure surface is highly non-linear, all approximation methods based on a single boundary have difficulties in finding a solution and the results found might not be accurate. The Monte-Carlo procedure is very well suited for the larger failure probabilities, because it is robust and easy to use.

In all cases, the failure function should be well determined for all possible combinations of input parameters. Care should be taken at the choice of distributions of these parameters and the code must be fitted with checks whether input parameters are realistic.

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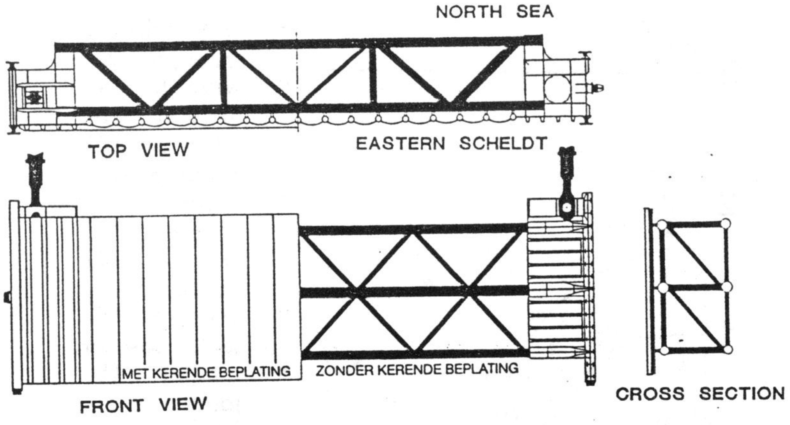

Figure 1 The structure of the Eastern Scheldt barrier

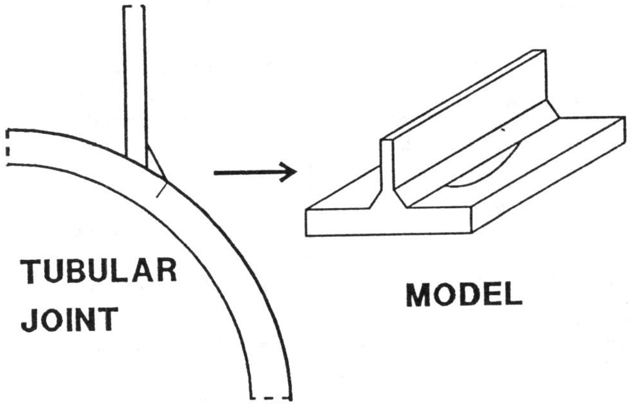

Figure 2 Simplified fracture mechanics model of tubular joint.

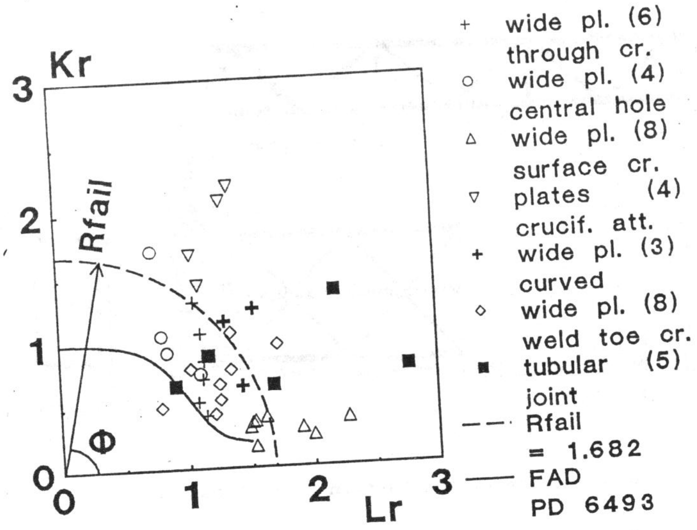

Figure 3 Probabilistic failure assessment diagram based on fracture tests.

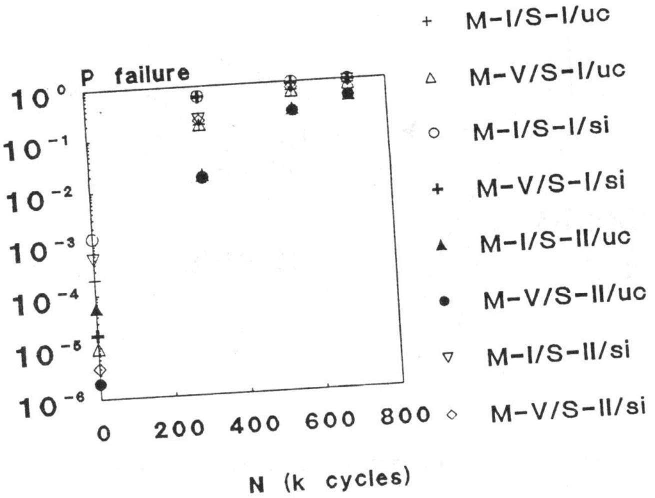

Figure 4 Relation failure probabilities, material, stress level, defect type and number of cycles.