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Design of the Steel Gates for the Eastern Scheldt Storm Surge Barrier

Dimensionnement des vannes en acier pour le barrage anti-tempête de l'Escaut oriental

Bemessung der stählernen Schützen des Sturmflutwehres an der Ostschelde

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SUMMARY
The steel gates of the barrier have main support structures of tubular steel trusses. Heavy storms will create high stresses in the tubular connections because of stress concentration. As the waves have periods of 6 to 10 seconds, some 15'000 load cycles may be expected in a 24 hour storm. For economic reasons the designers expect and accept fatigue cracks after 30 to 40 years of use and will give special instructions for inspection on that basis.

RESUME
Les vannes en acier du barrage sont constituées d'une structure principale en treillis composé de tubes d'acier. Des contraintes élevées dans les assemblages entre tubes sont dues à des effets de concentration de contraintes, lors de violentes tempêtes. Les vagues ayant une période de 6 à 10 secondes, il peut se produire quelques 15'000 cycles de charge lors d'une tempête de 24 heures. Pour des raisons économiques, les ingénieurs projeteurs prévoient et acceptent l'apparition de fissures de fatigue après une durée d'utilisation de 30 à 40 ans et fournissent des instructions spéciales pour un contrôle des ouvrages.

ZUSAMMENFASSUNG
Die Tragkonstruktion der stählernen Schützen des Sturmflutwehres besteht aus Rohrträgern. Infolge der Spannungskonzentration verursacht ein schwerer Sturm hohe Spannungen in den Verbindungen. Da die Wellen Wiederkehrperioden von 6 bis 10 Sekunden aufweisen, ergeben sich ungefähr 15'000 Belastungszyklen während eines Sturmes von 24 Stunden Dauer. Aus wirtschaftlichen Gründen werden bei einer Nutzungsdauer von 30 bis 40 Jahren Ermüdungsbrüche akzeptiert und spezielle Inspektionsvorschriften erlassen.

General description of the design of the flood barrier

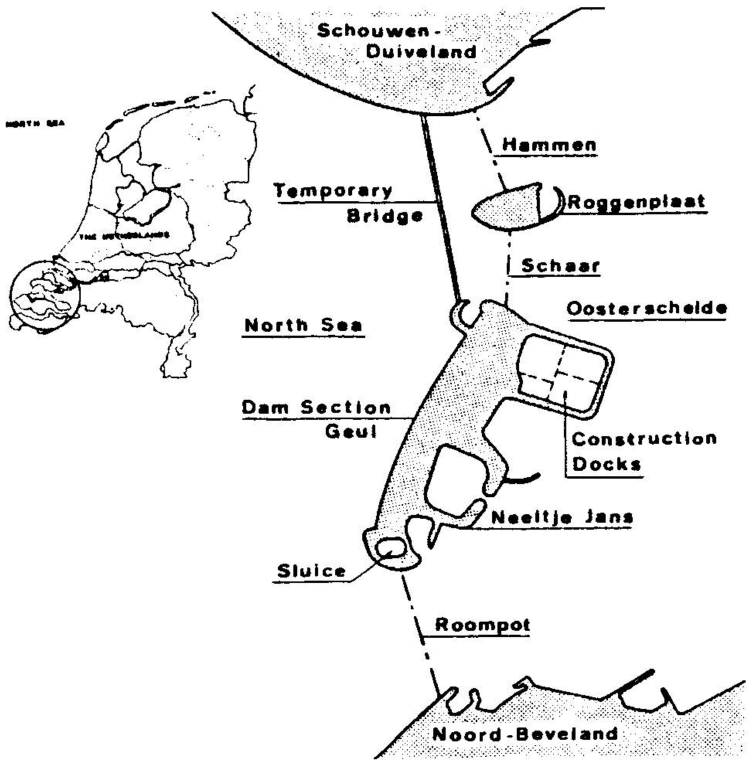


fig. 1 The mouth of the Oosterschelde with trace of stormflood barrier

The mouth of the estuary of the Eastern Scheldt has three channels, named Hammen, Schaar and Roompot. Between the channels, totally 3,5 kilometers wide, is shallow water in which islands constructions are made (fig. 1).
In the three channels 66 piers, forming 63 apertures, will be placed on 45 m centre-to-centre distance. The piers are 45 m high and have base plates measuring 25 x 50 m2. The sills between the piers will be increased in height and box-beams will span the piers, thereby achieving the desired effective flow opening of 14.000 m2 between sills and box-beams. The tidal range will still be 77% of what it is today and as a result of that, the salt water tidal environment in the Eastern Scheldt will be kept intact. This will conserve the mussel and oyster cultures and other specific flora and fauna.
A steel gate will be installed between each pair of piers. Under normal conditions the gates are open, allowing seawater to flow in and out the Eastern Scheldt. The existing environment will thus be kept intact. Under storm condtions the gates will be closed. The hydraulic electro-mechanical devices which operate the gates, will be housed in the prestressed concrete bridge elements spanning the piers.

Steel gates

The closure system of the flood barrier consists of a static part, the sill and box-beam and a mobile part, the steel gates. There are 63 steel gates with a gross flow profile of 18.000 m2. The gross flow profile of 18.000 m2 has an effective profile of 14.000 m2 taking flow contraction and blocking of two gates for maintenance into account. With the effective flow profile of 14.000 m2 a tidal range of 2.70 metres is achieved.

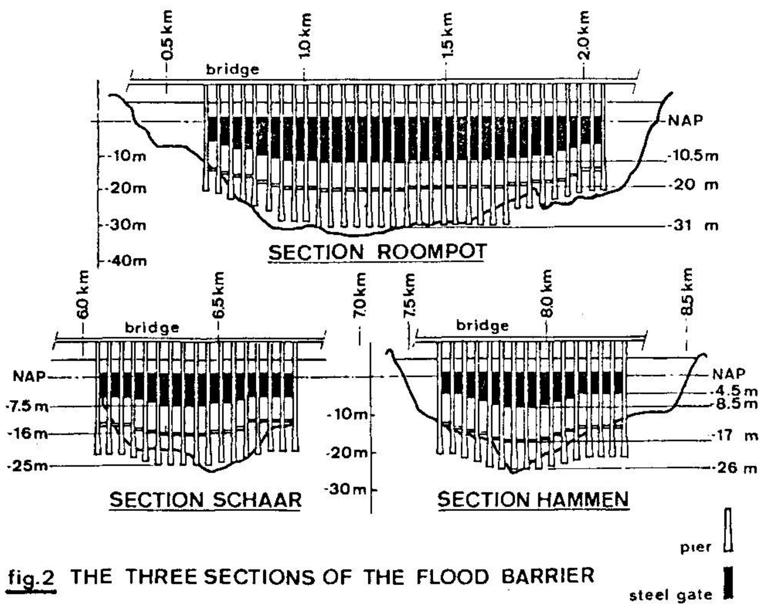


fig.2 THE THREE SECTIONS OF THE FLOOD BARRIER

The 63 steel gates are divided over the three channels as follows:
15 in the Hammen;
16 in the Schaar van Roggenplaat;
32 in the Roompot.

These numbers are determined by the flow volumes in the channels. The height dimension of the steel gates will be determined by the cross-sectional profile of the channel (see also fig. 2) and varies in steps of one metre from 5.90 metres to 11.90 metres; weights vary between 300 and 520 tons. In their closed position the steel gates extend from the concrete sills upwards to Amsterdam Zero + 1.20 metres (the under side of the box-beams). From Amsterdam Zero + 1.20 metres to Amsterdam Zero + 5.80 metres the concrete box-beam acts as a barrier. The thickness of the gates is 5.40 metres. There will be 7 different types of gates, due to the difference in height. Because the piers, between which the steel gates are sliding up and down, are founded independent of each other, positioning tolerances (with respect to centre-to-centre distances and nonparallelity) will have to be

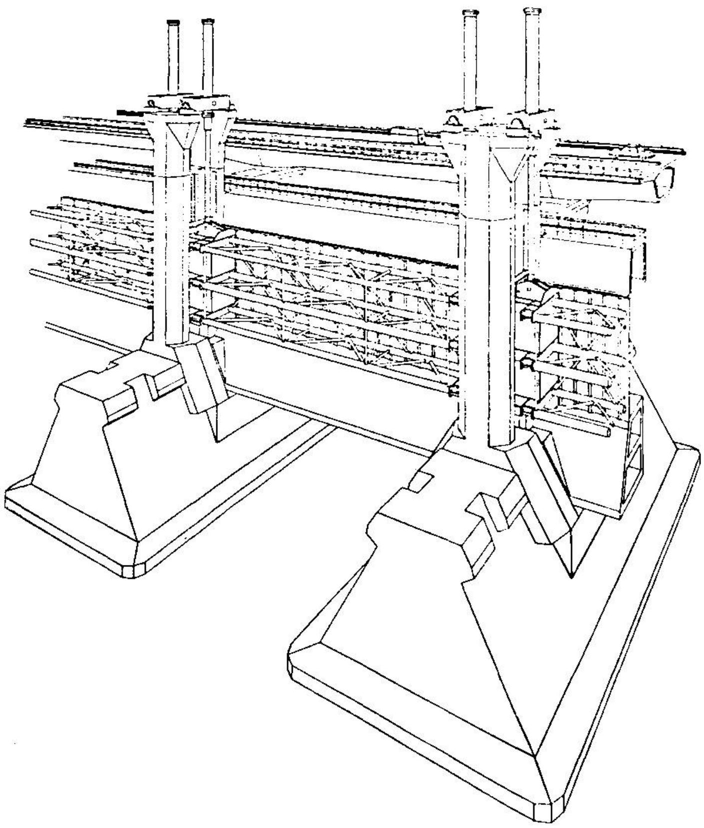
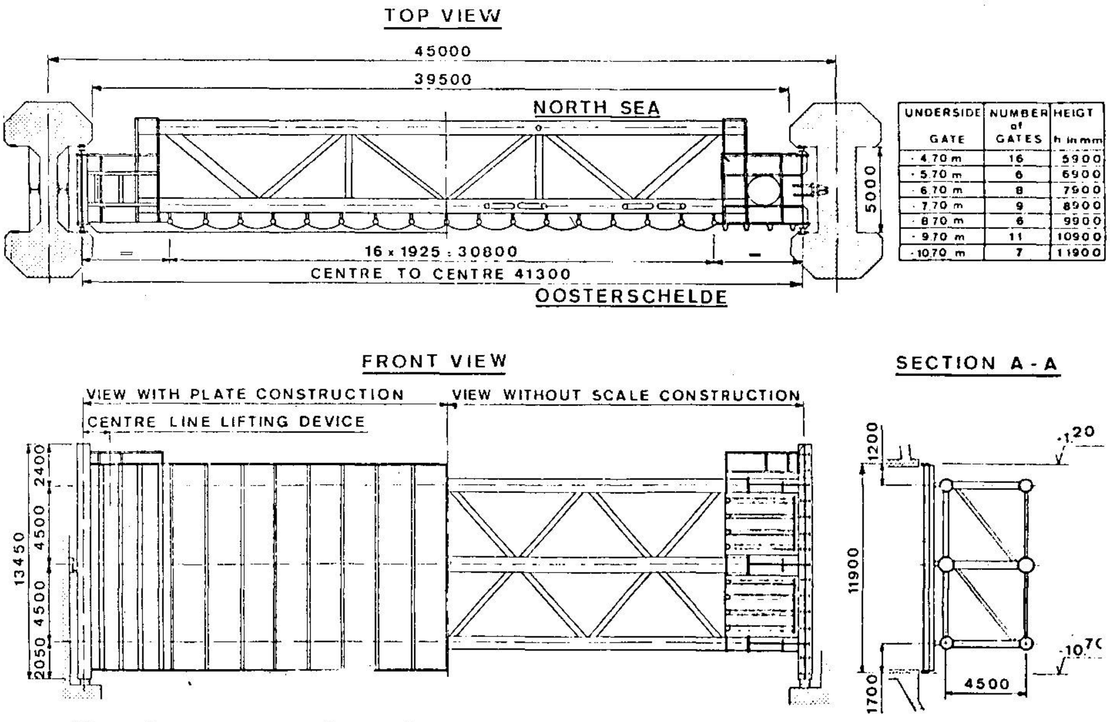


fig. 3 Artist impression of flood barrier



UNDERSIDE GATE	NUMBER of GATES	HEIGT h in mm
- 4.70 m	16	5900
- 5.70 m	6	6900
- 6.70 m	8	7900
- 7.70 m	9	8900
- 8.70 m	6	9900
- 9.70 m	11	10900
- 10.70 m	7	11900

fig. 4 Construction of steel gate

taken into account during the designing phase of the gates.
Furthermore, differences in subsidence between the piers occur as a result of the loads on the barrier, which could cause the gates to become jammed. To compensate for these influences, the gates have a variable length and a torsionally weak construction is required.
The correct length of each gate can be determined only after the corresponding piers have been positioned and the sill is constructed between the piers at the location of the gate. Therefore the gate will be assembled in three parts of which one is overlong. The three parts are the two "box type" end constructions and the tube truss constructions, the latter being overlong.
After the correct span length has been measured, this part is adjusted to the desired length. The three parts are then attached to each other with welded connections.
Since great horizontal loads must be absorbed during closing and opening, a lever gate with slide supports was chosen, whereby loads are transfered throughout the entire height of the gate to the pier.
Worst-case conditions for the strength calculation for the steel gate in closed position are:
a water level on the North Sea side of Amsterdam Zero + 5.5 m and on the Eastern Scheldt side of Amsterdam Zero - 0.7 m. The "significant" wave height then is 3.8 metres (by "significant" wave height is meant the average height of the highest one-third of the waves occurring in a storm).
Consideration must be given to the slamming effects of waves against members of the gate construction.

Wave - loading KN/lin.metre gate \ Fall loading KN/lin. metre gate	<100	100–150	150–200	200–250	250–300	300–350	350–400	400–450	450–500	500–550	550–600	600–650	650–700	700–750	750–800	800–850
380–400																
360–380										1						
340–360									1	1						
320–340							1	1	1	1	1					
300–320					1	2	2	4	2	3	2					
280–300				1	2	6	7	11	5	7	3	1	1			
260–280			1	6	8	20	21	30	13	15	7	2	1			
240–260		1	4	22	28	60	66	78	29	35	14	3	2	1		
220–240	1	4	14	79	90	175	197	192	64	68	25	6	4	1		
200–220	4	12	43	251	271	473	556	448	132	151	43	9	7	2		
180–200	11	34	118	715	741	1137	1454	909	257	239	74	14	10	3		
160–180	23	37	291	1306	1824	2726	3463	2059	472	407	114	21	14	4	1	
140–160	63	195	639	4025	3991	5659	7409	3830	808	647	165	29	19	5	1	
120–140	123	382	1233	7361	7701	10497	14069	6722	1230	954	221	36	24	6	1	1
100–120	210	651	2030	13366	12985	17189	23457	10450	1847	1290	273	43	28	6	1	1
80–100	309	955	3023	[illegible]	[illegible]	24504	33891	14330	2387	1576	307	46	29	6	1	1
60–80	334	1186	3740	24269	23351	29803	41625	15947	2698	1701	309	45	28	6	1	1
40–60	390	1203	3780	24598	23604	29816	41924	16629	2364	1561	267	38	24	5	1	0
20–40	295	912	2859	13638	17857	22410	31645	12348	1865	1109	185	26	16	3	1	0
0–20	111	342	1070	6982	6684	8362	11832	4531	685	403	65	9	6	1	0	0

TABLE 1 Number of loading combinations wave loading — fall loading gate 16 Roompot

wave loading KN/lin.m	total number of loadings in 200 years	number of reduced loadings in 200 years
20.	41132.	36.
40.	110165.	1991.
60.	146403.	15627.
80.	146093.	54975.
100.	119856.	119856.
120.	83877.	186405.
140.	51113.	223138.
160.	27534.	215732.
180.	13296.	174508.
200.	5846.	121723.
220.	2383.	75325.
240.	919.	42525.
260.	343.	22536.
280.	126.	11453.
300.	46.	5657.
320.	16.	2610.
340.	6.	1277.
360.	2.	547.
380.	1.	347.
	749157.	1276259.

TABLE 2 Number of wave loadings in 200 years, number of reduced loadings gate # 16 Roompot

Dynamic loading of the gates

For the consideration of the effects of the dynamic loading, a long term distribution of the loading intervals has been made considering a life time of the construction of 200 years. The stress level and stress distribution depends of:

a. the location of the gate in the barrier;
b. the relation of tide and wave height;
c. the "opened periods and the "closed" periods of the gate;
d. the shape of the construction having effect on the transfer;
   wave → wave loading → stress in construction.

Extensive calculations have been made to determine the probability of the dynamic loading on each gate. An illustration of the distribution of the dynamic loading of gate number 16 in the Roompot is given in table 1. Since the periods of the loadings due to water level difference are long, their loading effect can be neglected in the calculations of the effects of the dynamic loadings. Resulting, consideration is only given to the wave loading, the total number of loadings in 200 years is given in table 2.

In order to receive a more or less identical safety guarantee for all the gates, the load-spectra of the various main members of the gates have been reduced to a standard load-spectrum. This method is acceptable since the main members are of an identical construction type and therefore the same S-N curve is applicable. For the tube truss constructions this is the X-X line of the Americal Welding Society (fig. 5).

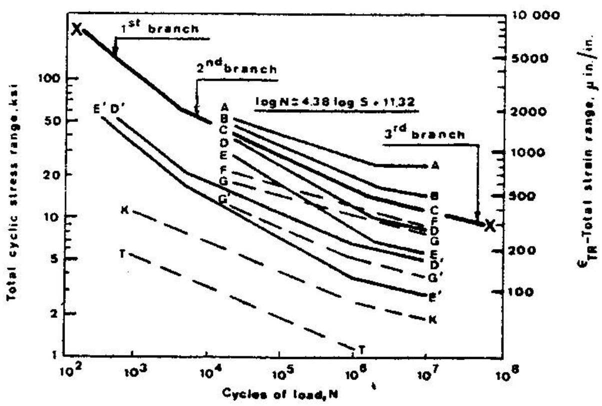


fig. 5 Allowable fatigue stress and strain ranges for stress categories (American Welding Society)

For the reduction it is acceptable to use the second branch of the S-N curve. The equation of this branch is approximately:

$\log N = 4.38 \log S + 11.32$ (S in ksi)

$N = C_1 \times S^{4.38}$ $(C_1 = \text{constant})$

Since the stress S is linear dependent on the loading L, it can also be written:

$N = C_2 \times L^{4.38}$

Taking:

L_r = loading to which actual loading is reduced

L_a = actual loading

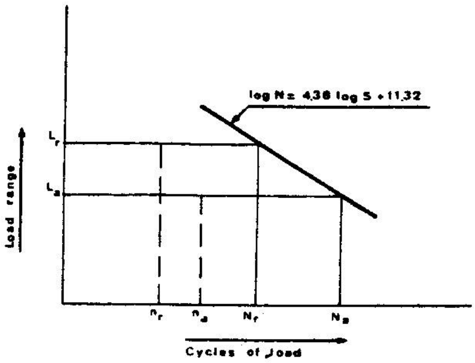


fig. 6 S-N curve

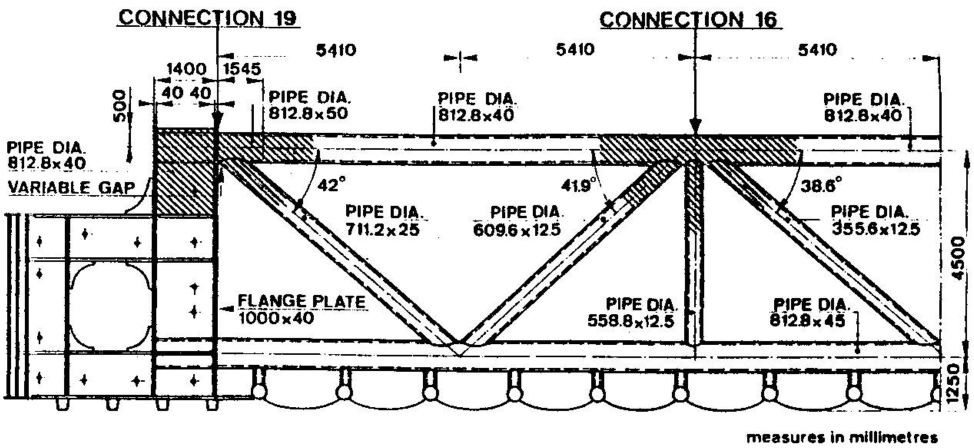


fig. 7 LOCATION OF CONNECTIONS VERIFIED IN LABORATORY

n_r = reduced number of cycles
n_a = actual number of cycles

then

$$n_r = n_a \times \left(\frac{L_a}{L_r}\right)^{4.38}$$

This means that n_r cycles of loading L_r give the same result towards fatigue as n_a cycles of loading L_a.
For the gate number 16 in the Roompot this method of reduction results in the number of reduced loadings as given in table 2.
For the reduced loading is taken

L = 100 KN/lin. metre

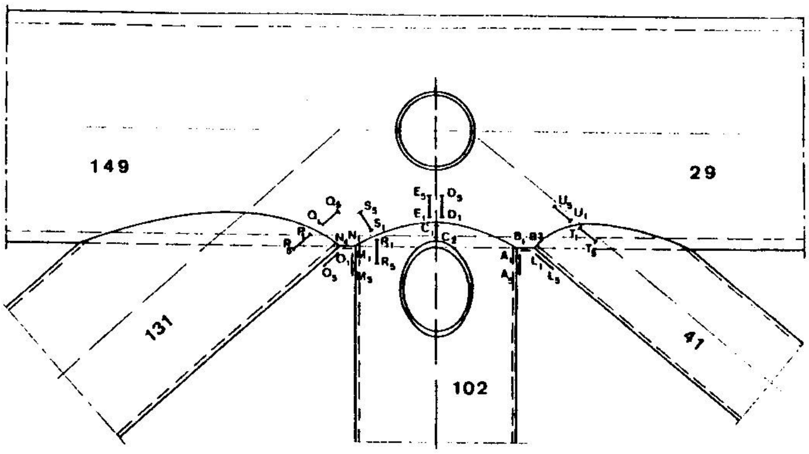


fig.8 LOCATION OF STRAIN GAUGES IN CONNECTION No.16

Stress concentrations, strain concentrations (S.C.F. - S.N.C.F.)

For the less complicated mutual connections of the tubes the calculation method of Kuang, Potvin and Leick [1] for the determination of the stress concentration factor has been applied in the preliminary design phase.
For the more complicated connections the three dimensional effects were too large. For these connections perspex models were tested to verify the S.N.C.F. (see fig. 7). The strain ganges were placed in such positions that the required informations regarding the hot spot stresses would be received (see fig. 8).
In fig. 9 the forces and bending moments acting in the members in the neighbourhood of the connection are illustrated. The forces and moments in the members I and II were small as compared to the other forces and are neglected in the model tests.
The results of the model tests are given in figure 10.
For an easy comparison the results are made dimensionless by dividing the measured strain by the strain due to the axial force in member 41. From fig. 8 and 10 it can be seen that the highest strain appears at the crown position of the connection of member 102 to the chord.

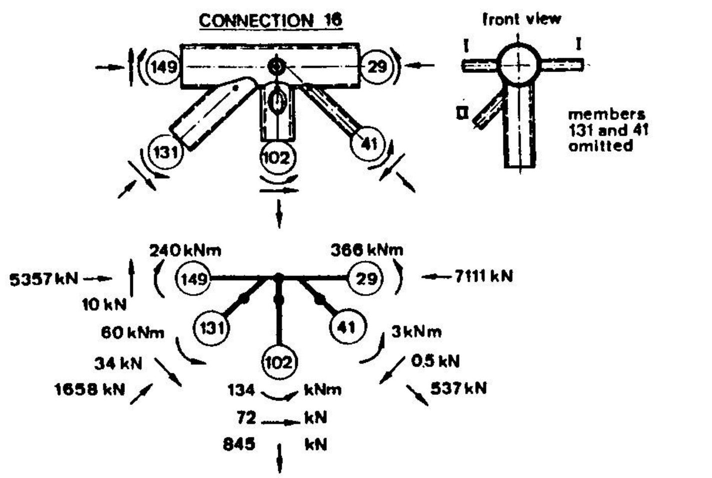


fig. 9 FORCES AND MOMENTS ACTING IN THE MEMBERS OF CONNECTION 16

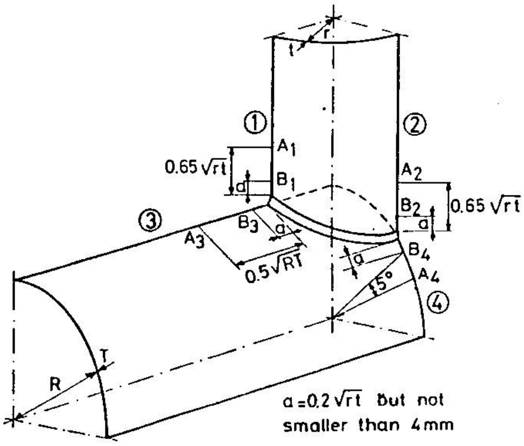


Fig.11 Locations of straingages for linear extrapolation to weldtoe to determine strain concentration factor.

The extrapolation of the measured strains to the weld toe has been carried out according to the procedure outlined by the European Working Group III "Tubular joints", see also fig. 11. This linear extrapolation includes the influence of the geometry of the joint and the geometry of the weld, but not the influence of the condition of the weld toe such as notches, the angle between weld and parent metal etc. These influences must be taken into account by considering the applicable S-N curve.

Due to the difference in height there are 7 different types of gates, which are composed of 2 or 3 trussed girders. As a result of the difference in loading the total number of different types of trussed girders is 13. In order to apply the results of the investigated connection for other geometries the results have been converted in stresses and compared with the calculated stress concentration factors (S.C.F.).

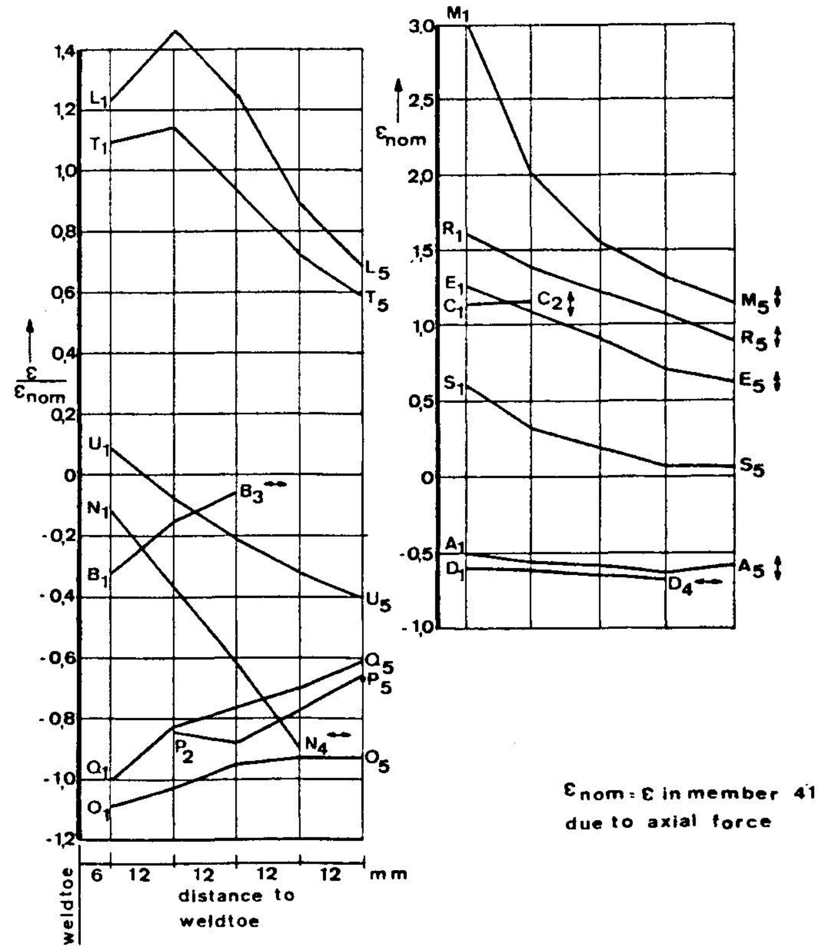


fig 10 $\frac{\varepsilon}{\varepsilon_{norm}}$ in connection 16

For calculating the S.C.F. of a K-T joint with branches of which the diameters and loads are not equal, formulas are not available in the literature, even if the members I and II (see fig. 9) are omitted. Considering the joint as a K-joint, consisting of the branches 131 and 102 (see fig. 9) and all branches having the diameter of member 102, the best agreement is obtained by using the formulas of Wordsworth [2].

The strain in joints with different parameters is calculated by

$$\varepsilon_i = \sigma_{hs} \times \left(\frac{\varepsilon_{measured}}{\sigma_{hs_{calculated}}} \right)_{joint\ 16}$$

From fatigue tests it has appeared that the first visible crack occurs at appr. 25% of the lifetime of the specimen [3].

Since the design lifetime of a gate structure must be 120 years and the adopted AWS X-X curve is based on complete failure of the connection, it means that it is accepted that the first visible crack will occur after approximately 30 years. After every storm-closure the most critical joints of the gates will be inspected. If a crack is not perceived immediately, it would not mean that a gate will fail during the next storm.

The ratio between the number of cycles after which the crack is completely through the wall and the number of cycles required for the first visible crack is greater than 1,5 [3], e.g. for gate number 16 appr. 225.000 load cycles may occur after the first visible crack is in existence, before that crack is completely through and through. The total number of load cycles during a 24-hours storm is approx. 15.000, this means that approx. 15 heavy storms are required after occurrence of the first crack before complete failure of the connections has been reached.
After a crack has been perceived, the crack will be repaired. From fatigue tests on repaired tubular joints it has appeared that the fatigue strength is equal or even greater than the fatigue strenght of the original specimen [3].
All joints are designed as non-overlapped joints to ensure inspection and possibility of reparation of all welds.
In order to carry out a reliable and quick inspection of the critical joints an investigation is started to the application of acoustic or magnetic methods, capable of detecting cracks in uncleaned surfaces.

[1] Kuang, J.G.; Potvin, A.B.; and Leick, R.D.:
"Stress Concentrations in Tubular Joints", paper OTC 2205 presented at the 7th Annual Offshore Technology Conference, Houston, Texas, May 1975

[2] Wordsworth, A.C. "Stress concentration factors at K and KT tubular joints"

[3] Dijkstra, O.D.; De Back, J.:
"Fatigue strength of welded tubular T-and X-joints", paper OTC 3696, presented at 12th Annual OTC in Houston, Texas, May 1980

[4] De Back, J. and Vaessen, G.H.G.:
"Fatigue and corrosion fatigue behaviour of offshore steel structures", ECSC Convention 7210-KB/6/602 (J.7.1 f/76), April 1981