

Fatigue tests on aluminium bridges

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Traffic bridges are subjected to variable loads and should therefore be checked on fatigue. Especially low weight materials, like aluminium, are sensitive to fatigue, because the variable load is a substantial part of the total load. This paper shows the structural design of an aluminium bridge loaded by heavy traffic. The S-N curves of a welded detail that is often applied in the deck of aluminium bridges were determined by testing and the test results were compared to the standard SN curve prescribed by standard prEN 1999-1-3 (1). Additional tests were carried out in which the passage of vehicles was simulated on a model of the entire bridge, in order to obtain a better approximation of the real fatigue load on the bridge. The fatigue lifetimes resulting from these tests are compared to the arithmetical lifetimes, determined by using the S-N curve and Miner's summation.

The paper shows that aluminium is suitable as structural material for heavily loaded bridges.

Key words: Design, fatigue, tests, aluminium, bridges

1 Introduction

In the last decades, several aluminium bridges for pedestrians and cyclists have been constructed in the Netherlands. Also, industry and government show increasing interest for aluminium bridges in main routes of car traffic. This development asked for fundamental research on the structural behaviour of aluminium bridges. For this reason, a joint industry project has been carried out in which a movable aluminium bridge was designed and evaluated. In the part of the project concerning fatigue of the bridge, two test series were carried out: one series on a bridge deck with constant amplitude loading and one series on a model of the entire bridge with a moving, variable amplitude load. In this paper, the design of the bridge is given and the test results are discussed.

An artist's impression of the bridge is shown in figure 1. The bridge consists of two equal sections, one for each direction, with a span of 18 m. With this design, it is possible to span most of the waterways in Groningen (in the northern part of the Netherlands). The advantage of using aluminium in this case, is that it is possible to lift each section of the bridge with a

single actuator. Because construction of an expensive cellar for counterweights is thus not necessary, the aluminium bridge is an economic alternative for a steel bridge, considering construction costs. Further cost reduction during lifetime is achieved by lower maintenance costs for aluminium, because of the corrosion resistance of aluminium.

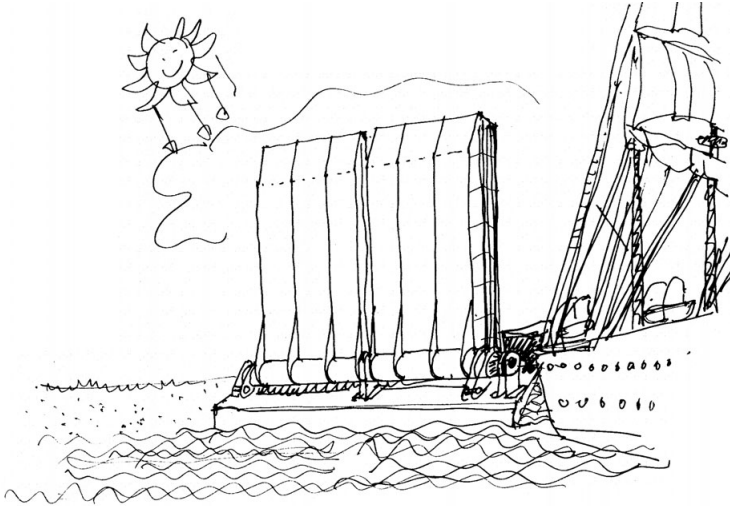


Figure 1: Artist's impression of the design of a movable, aluminium bridge (XX architects)

2 Structural design

The structural design of the bridge consists of a deck that is supported by webs with a distance of 1.5 m in between. The construction is closed on the lower side with a bottom flange. The longitudinal cross-section and the transverse cross-section of the bridge are given in figure 2. Aluminium plates of alloy 5083 H321 with a thickness of 12 mm are applied for the webs and bottom flange. Aluminium extrusions made of alloy 6063 T6 are welded together to form the deck. A more detailed description of the design is given in (4).

Several alternatives were developed for the geometry of this deck, see figure 3. The selection between the alternatives is based on criteria extrudability, strength, stiffness, dimensions, weight and fatigue sensitivity. In order to determine the sensitivity to fatigue, the stress situation near the welds was determined with finite element models for each deck. A detailed description of alternatives considered is given in (5).

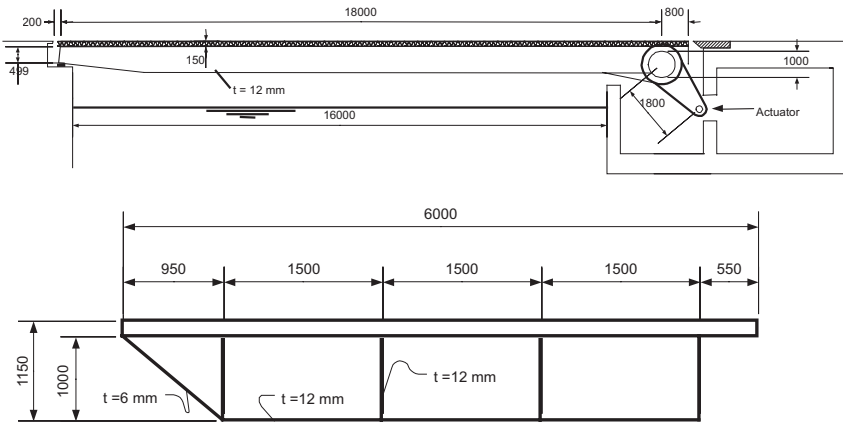


Figure 2: Longitudinal (top) and transverse (bottom) cross-section of the bridge

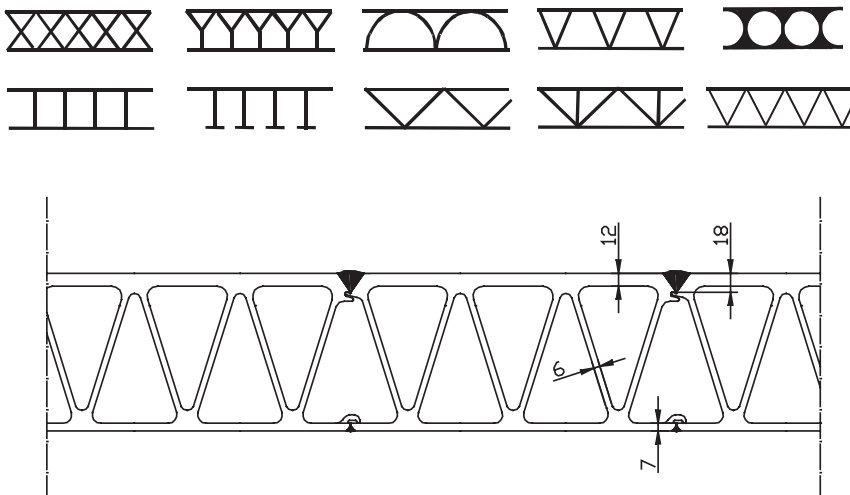


Figure 3: Alternatives considered for the deck (top) and dimensions of the chosen deck (bottom)

The following structural aspects of the design are evaluated, using Eurocode 9:

- Static design, according to prEN 1999-1-1 (2);
- Dynamic aspects of the bridge;
- Fatigue design, according to prEN 1999-1-3 (1).

The fatigue design of the bridge turned out to be decisive for most parts and details of the bridge. For more information, it is referred to (6).

3 Fatigue design

The European standard EN 1991-1-3 (3) provides the fatigue load on the bridge. Five heavy vehicles are being defined, with different axle loads, wheel prints and distances between the axles. Five tracks in transverse direction in which the vehicles drive are defined. Also, the distribution of the vehicles and tracks is prescribed, depending on the type of road. The design lifetime of the bridge was chosen to be 100 years. The average amount of heavy vehicles was assumed to be 350000 per year.

With finite element models, the stress intervals caused by the passage of the different vehicles are determined for all critical details.

In the procedure prescribed, it is implicitly assumed that load cycles caused by small vehicles do not contribute to the fatigue damage.

To determine the fatigue damage during lifetime, the European standard prEN 1999-1-3 (1) provides design S-N curves for standard (welded) details. The relative damage caused by each stress interval (i) is determined by dividing the number of cycles with the specific stress interval occurring during lifetime (n) by the maximum admissible number of cycles for the stress interval according to the S-N curve (N). The total arithmetical damage is defined by the sum of the relative damages for each stress interval (i), which is called Miner's summation. This Miner's summation should be equal to or smaller than 1, see equation (1).

$$\sum_i \frac{n_i}{N_i} \leq 1 \tag{1}$$

Miner's summation was larger than 1 for some details in the initial design. The design was adjusted in order to obtain the required lifetime. For example, transverse plates that were initially present between the webs of the bridge for assembly reasons were omitted in the final design.

The butt weld in the upper flange of the deck section was decisive in the final design. prEN 1999-1-3 (1) does not give an S-N curve for the specific geometry of the butt weld in the upper flange of the deck. Therefore, the S-N curve of a butt weld in a flat plate was used for evaluation of the weld in the deck of the bridge. The S-N curve is then corresponding to weld 4 in figure 4. The prescribed S-N curve for this detail is EC9 25-3.2 (parameters $m=3.2$ and $\sigma_{(N=10^6)} = 25 \text{ N/mm}^2$). Based on a fracture mechanics calculation described in (7), this S-N curve is expected to give conservative results for the deck.

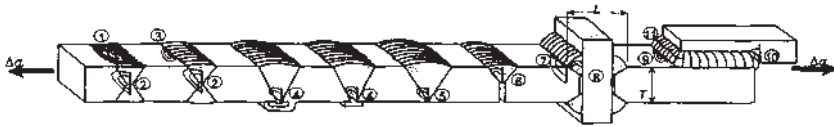


Figure 4: Butt weld in a flat plat, for which the SN curve is given in prEN 1999-1-3 (1)

In order to reduce the stress intervals to such a level, that fatigue failure does not occur during the design lifetime, the dimensions of the deck extrusions needed to be relatively large. For example, the thickness of the upper flange of the deck needed to be 12 mm and the weld thickness was consequently 18 mm, see figure 3. These large dimensions result from the conservative S-N curve that was used. It was expected, that the dimensions could be reduced when an S-N curve for the specific geometry had been available. A test series was therefore carried out, to determine this S-N curve.

Some remarks can be made about the standardised procedure to determine the arithmetical damage during lifetime:

- The arithmetical lifetime using Miner's summation is a simplification of the real fatigue behaviour. For instance, sequence effects of the load cycles, that may have influence on the lifetime, are not taken into consideration in Miner's summation;
- S-N curves are determined with simple tests with a fixed position of load application, while in reality the position of the load moves across the bridge and causes more complicated stress situations;
- S-N curves are based on a limited number of test results with relatively high stress intervals, so that the duration of the test period is acceptable. The path of the S-N curves for smaller stress intervals is determined with a general approach prescribed by prEN 1999-1-3 (1), which is not checked for the specific detail considered. Because the number of cycles with smaller stress intervals is normally large in real structures, the path of the SN-curve for smaller stresses may be important in calculating the design lifetime.

Because of these remarks it is not clear whether the real fatigue lifetime of the bridge corresponds with the arithmetical lifetime. In order to check the design procedure, additional tests were carried out on a model of the entire bridge with such loading conditions, that the stresses in the decisive detail of the real bridge are approximated as good as possible. The resulting fatigue lifetime is compared with the arithmetical lifetime.

4 Constant amplitude tests on fully supported bridge deck specimens

To determine the S-N curve of the butt weld in the deck, tests with constant amplitude loads were carried out on the welded deck extrusions. The bottom flange of the specimens was

completely supported, as indicated in figure 5. Rubber blocks between the actuator and the specimen are applied to simulate the wheel prints. The test-set up is shown in figure 6.

The load in these tests is a simplification of reality: the load on the specimen is a constant amplitude load applied on one position, while on the real bridge, the axle load varies per vehicle and the load moves from one side of the bridge to the other side. Also, the support conditions do not correspond to the real bridge: the bottom flange of the bridge deck specimen was fully supported, while in reality, the deck spans the distance between the webs of the bridge. The influence of these simplifications is discussed in chapter 5 of this paper.

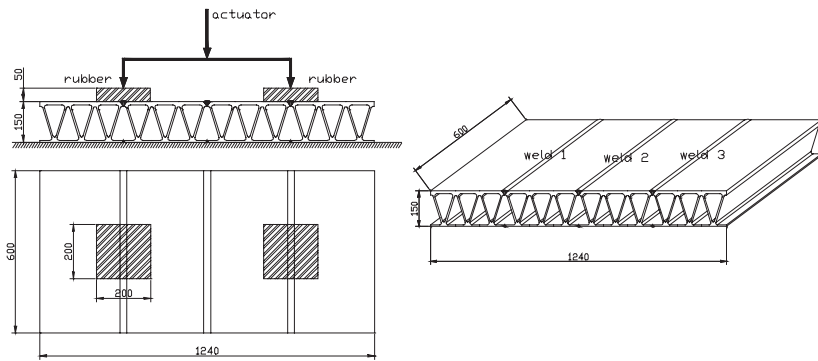


Figure 5: Support and loading in the bridge deck tests (left) and specimen (right)

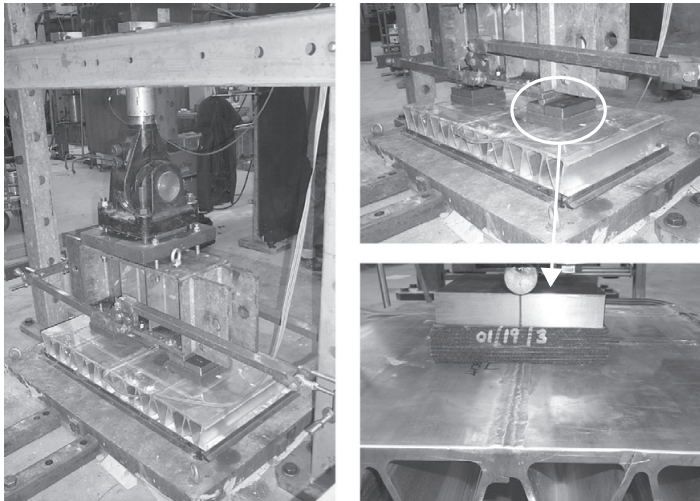


Figure 6: Set-up for the bridge deck tests

Three specimens were tested with a geometry according to figure 3. The weld throat thickness for these specimens was 18 mm. Three specimens with a thinner upper flange were also tested. The thickness of the upper flange of these specimens was 9 mm and the weld thickness was 15 mm. For each specimen, two welds were loaded. The load applied was different for each specimen. Consequently, six test results were obtained with three different stress levels for each of the two geometries.

The stress levels in the specimens were determined with finite element models. Strain gauges could not be used for this purpose, as the rubber blocks influence the measurements. Strain gauges were only used to indicate a crack initiation. The specimens were regularly examined visually, using penetrating liquid to follow the crack growth.

Figure 7 shows the resulting lifetime of the tests as a function of the load on the wheel print. Compared to other fatigue test series on aluminium specimens, e.g. described in (8), the scatter in test results is small.

It is shown that the lifetime of the specimens after crack initiation was large. This large lifetime after initiation is due to the entire support of the bottom flange, resulting in a relatively small increase in nominal stresses after crack initiation, and resulting in mainly bending stresses in the detail considered. In the following, the lifetime of the detail is taken as the amount of cycles to crack initiation.

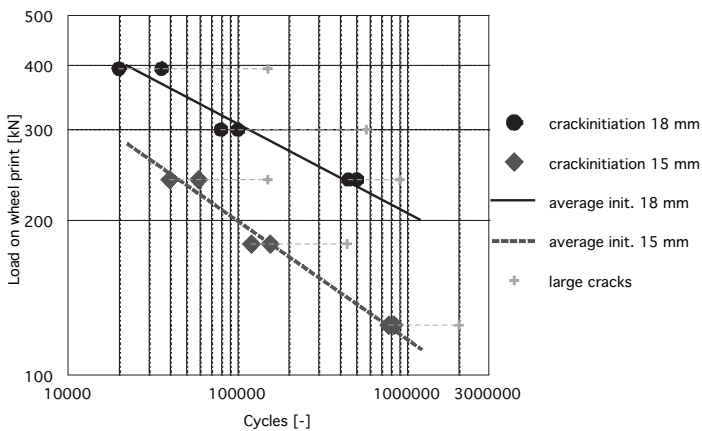


Figure 7: Wheel print load and number of cycles for bridge deck tests

Figure 8 shows the crack initiation for both geometries, using the calculated nominal stress range at the weld toe, instead of the applied load on the wheel print. By using the results from the tests on both geometries, the resulting S-N curve is, between certain limits, independent of the flange thickness.

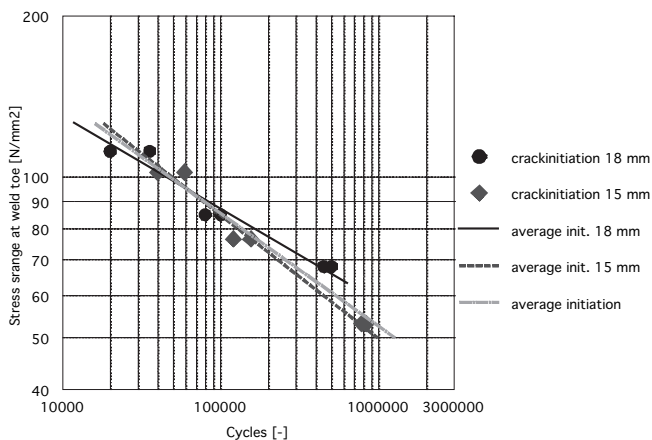


Figure 8: Crack initiation for both geometries tested and average S-N curve.

prEN 1999-1-3 (1) prescribes a method with which the design S-N curve can be determined, based on the average S-N curve. The design S-N curve is the lowest curve of the following transformations of the average curve:

- 80% of the stress of the average S-N curve;
- Shifting the average S-N curve with two times the standard deviation.

This procedure is necessary because the specimens are usually constructed by one manufacturer. By applying this procedure, it is expected that the S-N curve can be used independent of the manufacturer.

The path of the S-N curve outside the tested area is prescribed in prEN 1999-1-3 (1). Figure 9 shows the average S-N curve resulting from the test and the design S-N curve by applying the method in prEN 1999-1-3 (1). In the same figure, also the standard S-N curve for a butt weld in a flat plate is given (EC9 3.2-25).

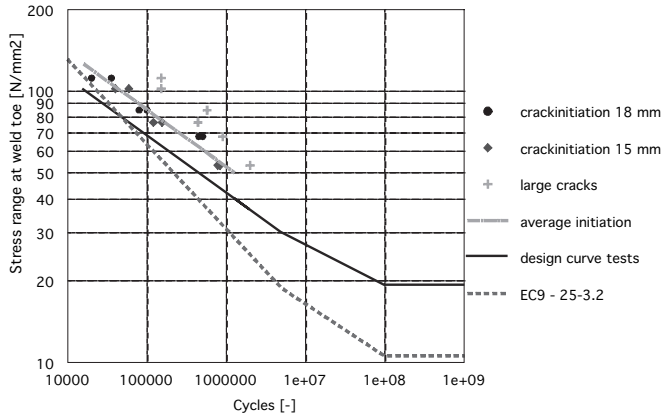


Figure 9: Average S-N curve of tests and design S-N curve of prEN 1999-1-3 (1)

It is shown that the design S-N curve for the butt weld in the deck, determined with the above described tests is less conservative than the standard S-N curve for a butt weld in a flat plate, especially for small stress intervals. Besides, a large lifetime after crack initiation was found.

5 Variable amplitude tests with moving loads on a model of the entire bridge

The above described tests are not fully representative for the real bridge. Both the support conditions and the load conditions are not equal to the real situation. This causes a difference in stress situation in the weld. Besides, the arithmetical lifetime calculated by Miner's summation is a simplification of the real lifetime of the bridge with a variable amplitude load. In order to evaluate the simplified method, two tests were carried out with geometry, support conditions and load conditions that are a closer approximation of the real bridge.

Figure 10 shows the geometry and supports of the specimens, together with the idealistic load situation. The deck applied has the dimensions indicated in figure 3, with a weld thickness of 18 mm. Because of the reduced span of the specimen in comparison with the real bridge, two actuators, spaced 1,79 m, are necessary to introduce the global bending moment in the specimen that is present during the passage of a heavy vehicle in the real bridge. The driving wheel should simulate the local load introduced by the axle and wheel print of the heavy vehicle.

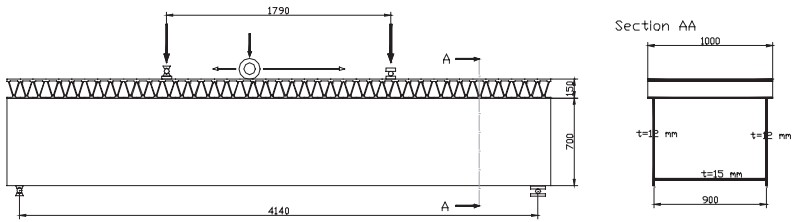


Figure 10: Geometry, supports and ideal load of the variable amplitude bridge tests

In order to generate acceptable test times, it was necessary to increase the load. The loads on the actuators and on the wheel had to be multiplied with at least a factor four. However, tires that are capable of carrying such extreme loads do not exist. For this reason, the wheel was replaced by six actuators that were loaded in sequence, see figure 11. With finite element calculations, the positions of load applications that resulted in maximum and minimum stress levels in the weld were determined. The decisive positions turned out to be exactly centred on the weld (maximum stress in the weld toe, minimum stress in the root) and 200 mm next to the weld (minimum stress in the weld toe, maximum stress in the root). The stress intervals in both the toe and the root of welds two and four in figure 11 are thus corresponding to the stress intervals caused by a gliding wheel, because for these welds, the stress intervals are the largest when the actuators are loaded in sequence, see figure 12. The stress intervals in the toe of weld three are slightly lower, because the distance between the weld and the load is 100 mm instead of 200 mm for this weld. Figure 13 shows the test set-up.

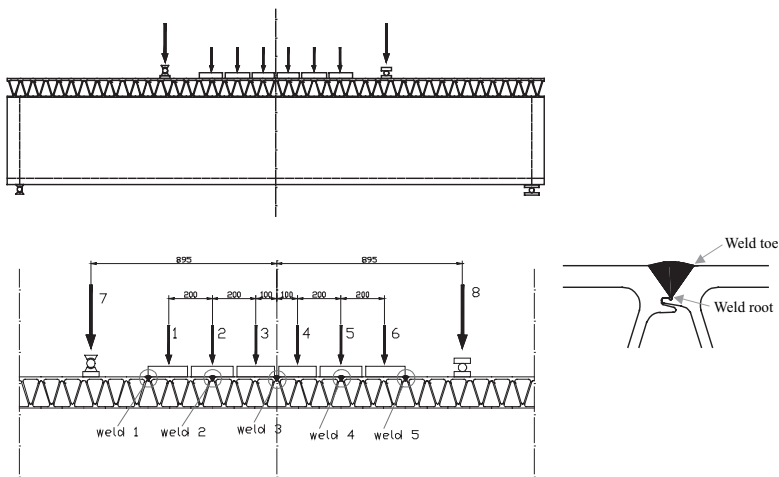


Figure 11: Loads and tested welds in the variable amplitude tests

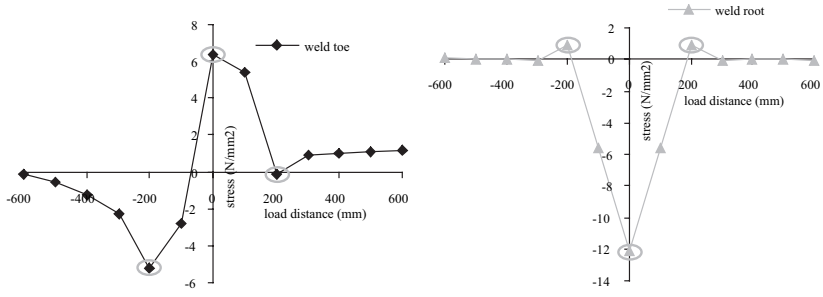


Figure 12: Stresses determined in the weld toe and root for various positions of the wheel

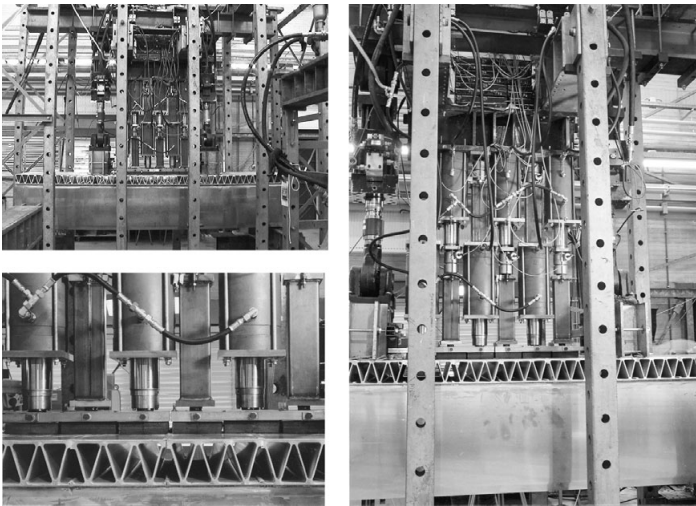


Figure 13: Set-up for the variable amplitude bridge tests

The stresses in welds two and four (figure 11) are determined for loading by each individual actuator with a finite element model of the tests. This finite element model consists of shell elements in combination with solid elements for the part of the deck near the decisive welds, see figure 14.

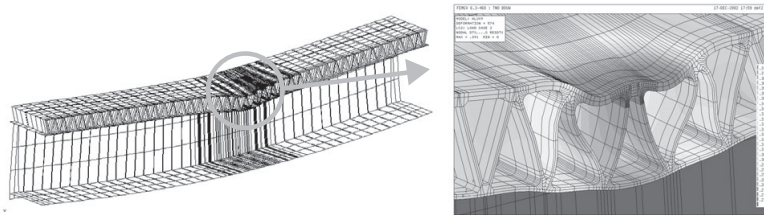


Figure 14: Finite element model of the variable amplitude tests

In the real bridge, with a design according to figure two, the middle weld is the heaviest loaded, as the global moment caused by the weight of a vehicle is maximal in the middle of the bridge. For the passage of each of the five heavy vehicles and the five tracks defined in EN1991-1-3 (3), the stress intervals in the root and the toe of the decisive middle weld are determined with a finite element model of the entire bridge.

For the passage of each of the defined vehicles, the loads on the actuators are determined in order to generate the same stress situations and stress intervals as present in the real bridge. The thus simulated passages of the different vehicles and different tracks are placed in random sequence with the distribution of vehicles and tracks according to EN1991-1-3 (3).

For the first specimen tested, the load on the bridge was multiplied by a factor four. Crack initiation in welds two and four was determined with strain gauges. The specimen was regularly visually examined.

Using the average S-N curve of the bridge deck tests, the lifetime (amount of cycles to crack initiation) could be determined with Miner's summation. The stress interval level corresponding to this amount of cycles according to the S-N line is called the equivalent stress range.

The equivalent stress range applied in the test is compared with the average S-N curve resulting from the tests with constant amplitude load on the totally supported deck in figure 15. In this figure, the average S-N curve of the bridge deck tests is shown, together with the upper and lower limit of these tests, which are defined by shifting the average curve by two times the standard deviation of the bridge deck test results.

The dots in this figure represent the results of the variable amplitude bridge tests. The round dots represent crack initiation of welds 2 and 4. The resulting fatigue lifetime corresponds very well with the arithmetical lifetime based on the average S-N curve.

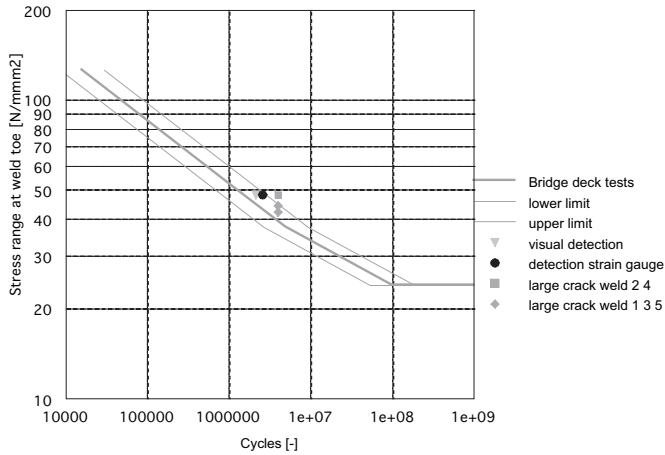


Figure 15: Equivalent stress and lifetime of the first variable amplitude load test in the average S-N curve resulting from the bridge deck test series

In this first specimen, cracks were also found at welds one, three and five, which have a lower equivalent stress range than welds 2 and 4 (see figure 15). Therefore, all five welds were checked with strain gauges in the second specimen. The load on the bridge was multiplied by a factor 4.5 for this second specimen. The equivalent stress range was determined and the amount of cycles at crack initiation for all welds are compared with the average S-N curve determined with the bridge deck tests in figure 15.

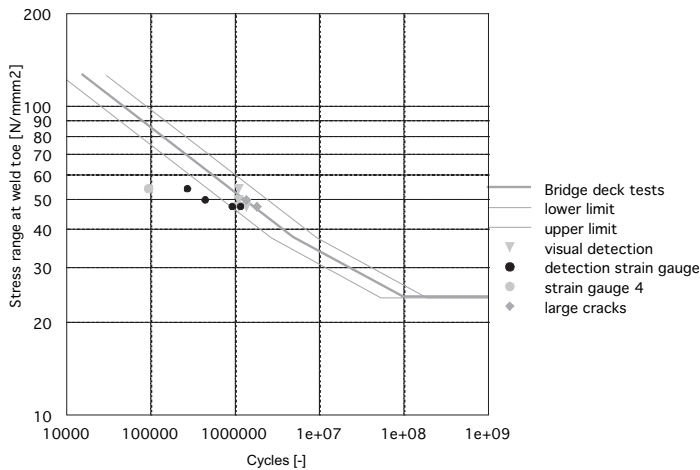


Figure 16: Equivalent stress and lifetime of the second variable amplitude bridge test in the average S-N curve resulting from the bridge deck test series

Strain gauge four measured the strains at the second weld. The strain intervals measured with this strain gauge changed after 94000 cycles, indicating that a crack was initiated. This amount of cycles deviates dramatically from the average S-N curve.

The crack detection by this strain gauge also deviates from the other strain gauges. Moreover, the first very light crack detection with penetrating liquid occurred only after 1350000 cycles. It was therefore assumed that the change in stress intervals observed for strain gauge four does not indicate a crack, but is due to the fact that the strain gauge is malfunctioning. This malfunctioning was also detected for strain gauges in other, comparable tests and was caused by movement of the rubber blocks.

Apart from strain gauge four, the amount of cycles at crack initiation is slightly lower than the average S-N curve. The correspondence is reasonable.

In both tests, the lifetime after crack initiation was limited. This does not correspond to the observations made for the bridge deck tests.

A reasonable explanation for this difference in lifetime after crack initiation is the difference in stress situation in the weld for the test series. The welds in the bridge deck tests were mainly loaded in bending, while the welds in the last test series were loaded by a combination of bending and membrane action. While the stresses for both load situations are similar at the surface, the differences in stresses increase for deeper cracks. Fracture mechanics calculations, reported in (7) showed that the difference in lifetime for bending and a combination of bending and membrane action is approximately 50%.

More information concerning the tests carried out is given in (7).

6 Evaluation of the lifetime of the bridge

The finite element model of the designed bridge in figure 2, which is described in chapter 5, was used to determine the stress ranges in the decisive middle weld for the passage of the vehicles given in EN 1991-1-3 [3]. The equivalent stress range in the decisive detail was determined at 12 N/mm^2 . This stress range is lower than the fatigue limit of the design S-N curve resulting from the bridge deck stress tests. The largest stress range occurring in the decisive detail ($22,6 \text{ N/mm}^2$) is just larger than the fatigue limit. This means that the design fatigue lifetime of the bridge according to the procedure in prEN1999-1-3 [2] is unlimited. However, the path of the S-N curve for such small stress intervals was not checked in this project.

In order to give a conservative estimation of the design lifetime of the bridge, the S-N curve is extended with the same gradient as for larger stress intervals, see figure 16.

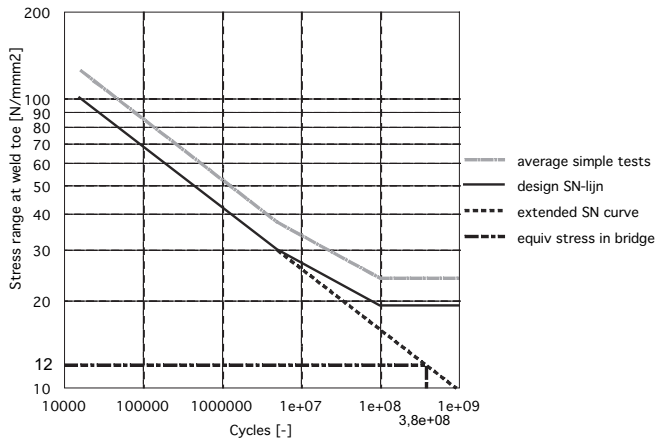


Figure 17: Conservative estimation of the lifetime of the bridge

The amount of cycles before crack initiation for the equivalent stress of 12 N/mm² was 3.8·10⁸. This corresponds to a lifetime of 211 years. Even this very conservative assumption regarding the SN curve for low stress intervals gives a sufficient fatigue lifetime.

7 Conclusions and recommendations

In this paper, the fatigue behaviour of an aluminium bridge is evaluated. A design of an aluminium bridge for heavy traffic was given. The weld in the designed bridge deck turned out to be the decisive detail for the fatigue lifetime of the bridge. However, the standard SN curve given by prEN1999-1-3 [2] was expected to be conservative for the detail considered. To determine the fatigue behaviour of this detail more accurately, constant amplitude tests were carried out on the bridge deck, resulting in an SN curve for this detail.

As these tests are a simplification of the real bridge, they are not completely representative for the fatigue behaviour of the real bridge. Therefore, two additional tests were carried out on models of the entire bridge with moving, variable amplitude tests.

Finally, a conservative estimation of the lifetime of the real bridge was given.

The bridge deck tests resulted in the following conclusions:

1. The scatter of test results was small;
2. The relation between stress interval level at the weld toe and lifetime of a deck with a weld thickness of 18 mm corresponds reasonable with this relation for a deck with a weld thickness of 15 mm;
3. The design S-N curve based on the tests is more favourable than the standard curve EC9 – 25-3.2, especially for small stress intervals;

4. The lifetime after crack initiation is relatively large.

The variable amplitude bridge tests resulted in the following conclusions:

5. The arithmetical lifetime based on the average S-N curve of the bridge deck tests corresponds reasonable with the real lifetimes resulting from the variable amplitude bridge tests;
6. The lifetime after crack initiation of the variable amplitude bridge tests was smaller than for the bridge deck tests. An explanation of this difference is the difference in load conditions applied in the test series;
7. The equivalent stress interval in the decisive detail of the real bridge is smaller than the fatigue limit. The maximum stress interval is lower than the level corresponding to $5 \cdot 10^6$ cycles according to the design S-N curve, indicating that the lifetime of the bridge would be unlimited. However, it should be noticed that the slope of the S-N curve for small stress intervals was not checked in this project.

The following recommendations were made:

1. It is recommended to determine the gradient of the S-N curve for small stress intervals (corresponding to a larger amount of cycles than $5 \cdot 10^6$);
2. It is recommended to research whether it is possible to reduce the weld throat thickness from 18 mm to 15 mm (reduction of thickness of upper flange of the extrusions from 12 to 9 mm).

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