Aluminium in Infrastructures

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Abstract

Aluminium alloys are used in infrastructures such as pedestrian bridges or parts of it such as handrail. This paper demonstrates that aluminium alloys are in principle also suited for heavy loaded structures, such as decks of traffic bridges and helicopter landing platforms. Recent developments in fatigue research is discussed and future research, required for full application of aluminium in heavy loaded structures is identified. The paper ends with a number of examples of heavily loaded infrastructures composed of aluminum alloys.

Keywords: Aluminium alloy; bridge; fatigue; fracture; helicopter landing platform.

1. Introduction

Around the world pedestrian bridges have been built using aluminium alloys as structural material. Other examples of frequently observed aluminium infrastructures are lighting poles and traffic gantries. Figure 1 shows examples of such structures in The Netherlands.

Figure 1. Examples of light loaded aluminium infrastructures.

The number of heavy loaded infrastructures such as traffic bridges and crash barriers, however, is limited. The question is whether or not aluminium alloys are suited for use as load bearing material in these structures. In this respect – as with every material – a number of advantages and disadvantages can be mentioned. Clear and well known advantages are the large strength to weight ratio of alloys in combination with the tight oxide layer and therefore good resistance against uniform corrosion of many alloys – especially those in series 5xxx and 6xxx. For most infrastructures the latter aspect implies that these do not have to be coated. The first aspect makes aluminium a suited material for large span systems such as bridges. It also eases transport and erection. A reduced erection time may provide important economic gain by shortening the traffic disruption for example in the case of deck or bridge replacement. Compared to many non-metallic structural materials the large ductility and ease of joining can be mentioned. A positive aspect in comparison to steel – especially in areas subjected to low temperatures – is the fact that the fracture toughness does not reduce with temperature. Whereas steels become brittle at low temperatures, this tendency is not observed for aluminium alloys.

There are also disadvantages. The ratio between the modulus of elasticity, E, and the strength is lower as compared to conventional structural steels. For bridges this may imply that the deformation, vibration, and buckling, govern the structural design – or at least are more decisive than for steel. The remedies are clear: in many cases it involves increasing the second moment of area, I, by altering the geometry of the structure, so that the stiffness ($E \cdot I$) is sufficiently large. The fact that aluminium alloys generally are not very noble means that care must be taken to prevent crevice corrosion or galvanic corrosion when in contact with other metals. This requires special attention at joints. Some solutions are presented at the end of this paper.

A final, important drawback is the relatively low fatigue resistance. To demonstrate this, Figure 1 presents the fatigue design strength of aluminum versus that of steel for various detail types according to the European standards, as compared in [1]. The cross-marked bar should not be considered since it is believed to be due to an error in the aluminium standard. The figure indicates that the fatigue strength of aluminium parent metal and bolted joints in shear is approximately 50% of that of steel and that of conventional (MIG) welded joints in aluminium is approximately 30% to 50% of that of steel, depending on the detail type. A fatigue design strength for friction stir welded joints has not yet been implemented in the European standard. Literature indicates that the fatigue strength of such joints is high as compared to MIG welded joints, but that the production tolerances to obtain a well performing joint are small. Hence, fatigue is an important design driver for heavily loaded aluminium infrastructures.

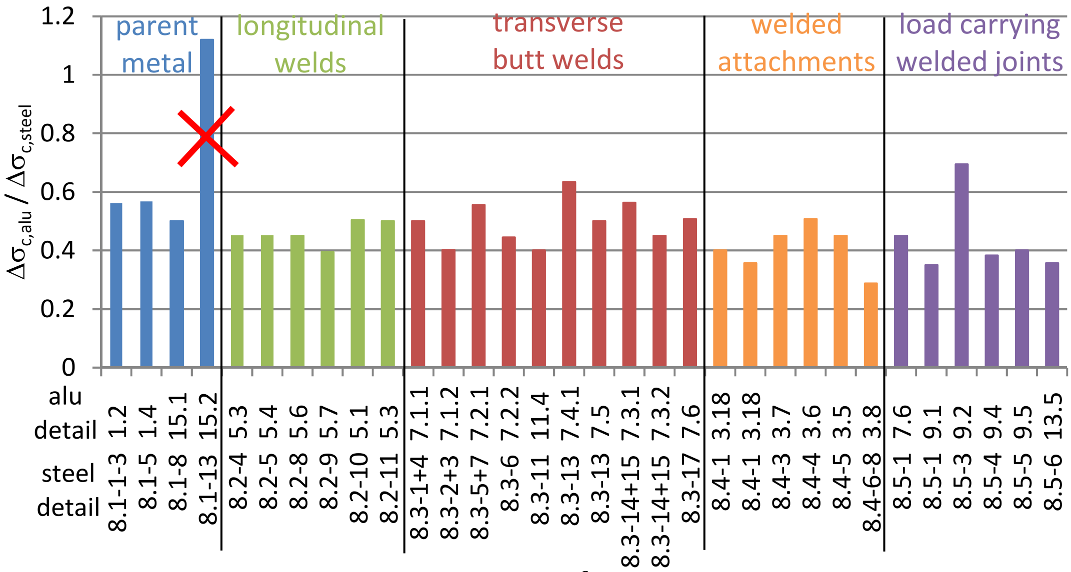

Figure 2. Ratio of fatigue strength at $2 \cdot 10^6$ cycles in the Eurocode for aluminium structures [2] and the Eurocode for steel structures [3] (number on horizontal axis refer to the detail tables in the standards), Ref [1].

Fatigue resistance is therefore the main focus point of this paper. Past, present, and future research activities at Eindhoven University of Technology and at TNO into the fatigue resistance for heavily loaded infrastructural applications are mentioned. A number of realized projects are described in order to obtain some insight into the behavior in practice of these structures.

2. Past Research Activities

2.1. Design and development of a bridge deck

Around the world and especially in Europe a large portion of today's bridges have been constructed in the second half of 20^{th} century. Since then, the number of heavy vehicles has increased tremendously – more than anticipated in the design. Since approximately two decades fatigue cracks have appeared in deck structures of steel bridges in a number of countries, [4 - 6]. Especially the steel orthotropic bridge deck concept – shown on the left hand side of Figure 3 – has shown a number of fatigue problems which can be attributed to the many welded joints, local stiffness variations, and direct loading by truck tires.

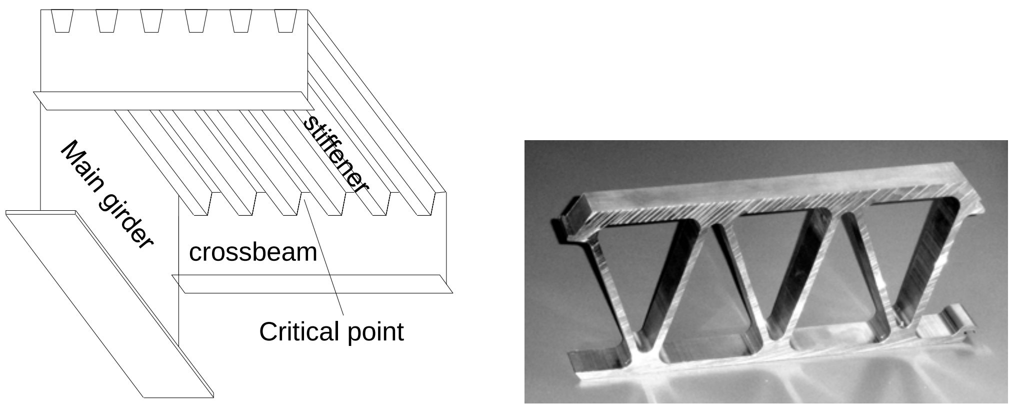

Figure 3. Structure of a steel orthotropic bridge deck and aluminium alternative.

Anticipating on this problem, we started 15 years ago with developing an aluminium alternative for these bridge decks. One of the finally selected variants is presented in the right hand side of Figure 3. The continuous top and bottom flange result in a closed section which provides a larger and more uniform stiffness as compared to an interrupted bottom flange as in case of the orthotropic steel deck. The extrusion process enables optimization of all dimensions, including radii at geometric discontinuities in order to prevent fatigue crack initiation at these points, an optimized weld shape, a small span and therefore low stresses at the critical top flange weld, and variation in thickness where required. The dimensions are determined and optimized for static and fatigue loading according to relevant European standards using the finite element method and the fatigue strength was further validated by testing. Outer dimensions are 300 mm in width and 150 mm in height.

At the time of design, practical experience with friction stir welding was still limited as well as the number of companies with friction stir welding equipment so that MIG welding was applied to weld the extrusion sections. Nowadays, we would use snap joints for the bottom flange and friction stir welded joints for the top flange.

2.2. Demonstrator: large scale test

A number of steps had to be taken to demonstrate the final applicability of the bridge deck into practice. Especially for fatigue there were concerns despite of the successful small scale tests because of the following reasons, [7]:

- Rolling wheels can create other stress distributions – including possible multiaxial fatigue – in comparison with fixed loading positions used for the small scale tests;
- The small scale tests were performed with constant amplitude loading. More realistic variable amplitude loading is known to sometimes retard and sometimes accelerate crack growth and the results may thus differ from those of constant amplitude loading.
- The translation of test results with relatively high stress range levels and small number of cycles to failure to more realistic levels introduces uncertainty.

A demonstration project was selected and a large scale test was carried out to simulate the real loading conditions as close as possible. The test was performed on two bridge replicas with deck and girders constructed from aluminium. A set of eight actuators loaded the replicas – Figure 4. Actuator no. 7 and 8 introduced global bending in the replica resulting from the entire vehicle weight and actuators 1 to 6 were loaded in sequence and simulated crossing of a wheel, [7].

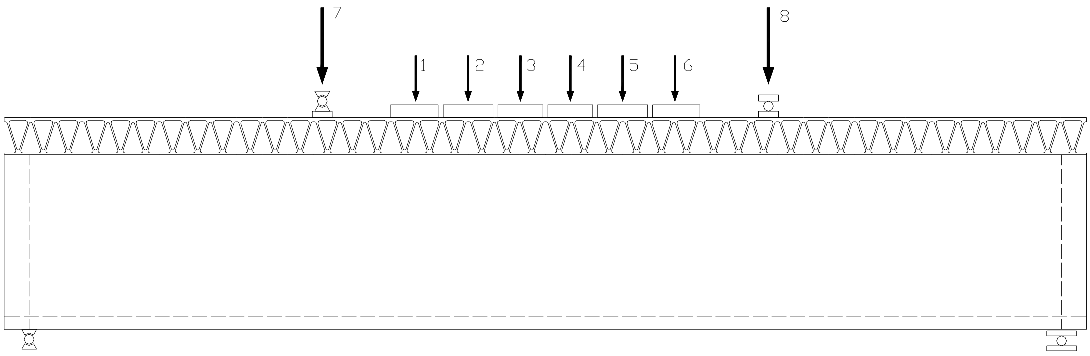

Figure 4. Actuators in the bridge fatigue demonstrator test. Ref [7].

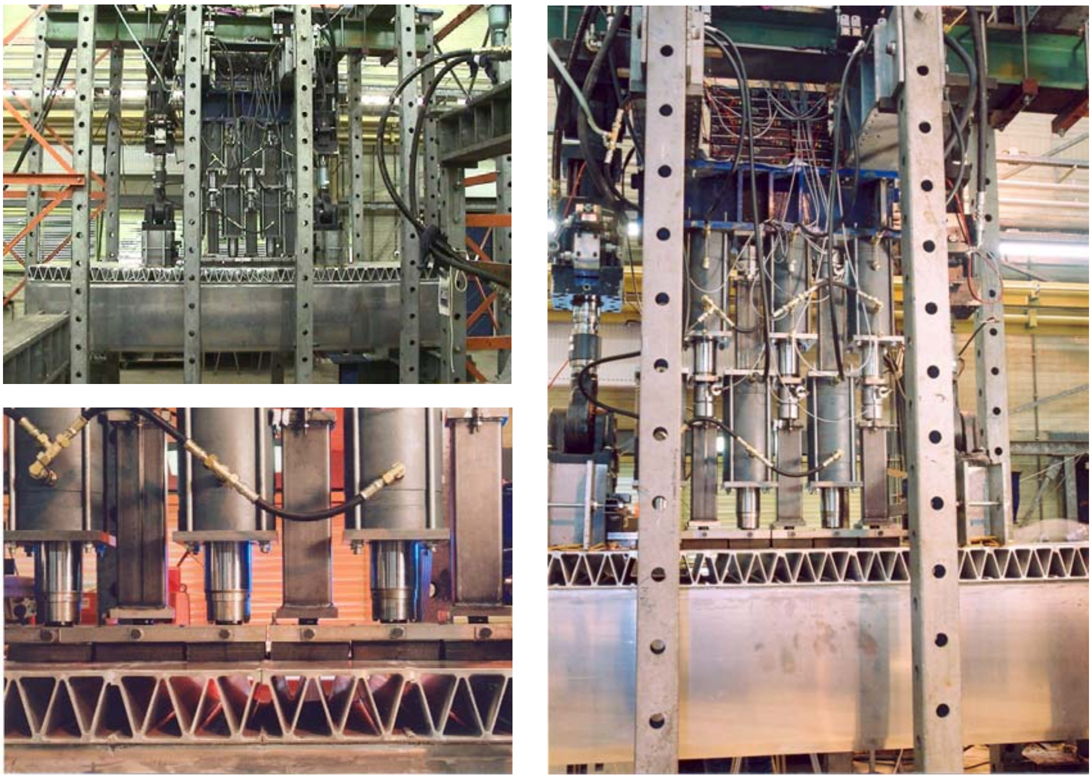

Figure 5. Test set-up of the bridge fatigue demonstrator test. Ref [7].

The loads of each simulated vehicle was varied so that a realistic variable amplitude load spectrum resulted. The mimicked vehicle loadings were obtained from the European standard on traffic loads but factored with a factor of 4 (first test) and 4.5 (second test) in order to reduce the testing time. Figure 5 provides the test set-up. The test results were 'translated' into a design life of the bridge, applying conservative assumptions such as absence of a fatigue limit. For the demonstration project, this resulted in a design fatigue life of over 200 years, i.e. more than the required life of 100 years. The demonstrator has resulted in the application of a number of heavy loaded aluminium bridges and bridge decks, examples of which are given in Section 5.

3. Current Research Activities

3.1. Simulation models for crack initiation

Crack initiation dominates the fatigue life of aluminium parent material and of bearing material in case of bolted or riveted shear joints. For welded joints the crack initiation period is relatively short and crack propagation is more important, however, even for welded joints crack initiation is more important for aluminium than for steel, [3].

Crack initiation is relatively difficult to predict and model. Testing is the standard option to determine the initiation life but a prediction model would be welcome, especially for variable amplitude and / or multiaxial loading cases and for the transition between low cycle and high cycle fatigue. We are currently working on a simulation model using the finite element method and Lemaitre's two scale model in order to predict initiation, [8 - 9]. In the model the development of damage on the microscale is implemented through elementary equations and its interaction with stiffness change on the macroscale is described through finite elements. The parameters of the model are determined using simple one-dimensional tensile tests and constant amplitude low cycle fatigue tests. The sequential load cycles are applied and the model predicts the number of cycles to crack initiation for low, intermediate, and high cycle fatigue under variable amplitude loading. The results of the model are in good agreement with test results (difference in the order of 15 % of the life). With current computer capacities, the simulation time is very large and for this reason we expect that its domain will be the academic world for the coming years.

3.2. Simulation models for crack propagation

We are also working on models that predict the crack propagation life. Main focus point is an accurate prediction of load sequence effects, i.e. crack growth retardation and acceleration resulting from variable amplitude loading. Most experts believe that these sequence effects are a result of plasticity induced crack closure, [10], and this was the starting point of our research. Models are already available that are able to predict the effect of a single large stress peak, a large stress valley, or a blocks of stress ranges with a different amplitude in a further constant amplitude load spectrum. The prediction of a real variable amplitude spectrum has proven to be much more difficult. In our research, we combine a constitutive damage model acting at the crack tip with a plasticity model for the material around the crack tip and in the plastic wake. We started with a cohesive zone model for the crack tip damage model, [11], but are now developing a new method that requires less model parameters to be fixed. Again, results are compared with experiments. The research is in a too early stage to be able to draw conclusions on whether we succeed in predicting the crack propagation life for variable amplitude loading.

3.3. Safety margins and added value of inspections

Because fatigue is a degradation process that advances in time, possible damage may be detected and repaired before the detail or structure fails. Many heavy loaded metal infrastructures therefore rely on inspections in order to meet the required safety level for fatigue. Since fatigue cracks grow progressively, it is important that inspection methods be used that are able to detect cracks when they are small. Visual inspections are frequently used but are known to be not very reliable, [12]. Eddy current or ultrasonic based inspection techniques may be more suited.

Apart from requirements on the inspection techniques, a number of structural or material aspects are important for inspections to be effective. The European standard for fatigue of steel structures, EN 1993-1-9 [3], therefore specifies for damage tolerant design:

"Selecting details, materials and stress levels so that in the event of the formation of cracks a low rate of crack propagation and a long critical crack length would result."

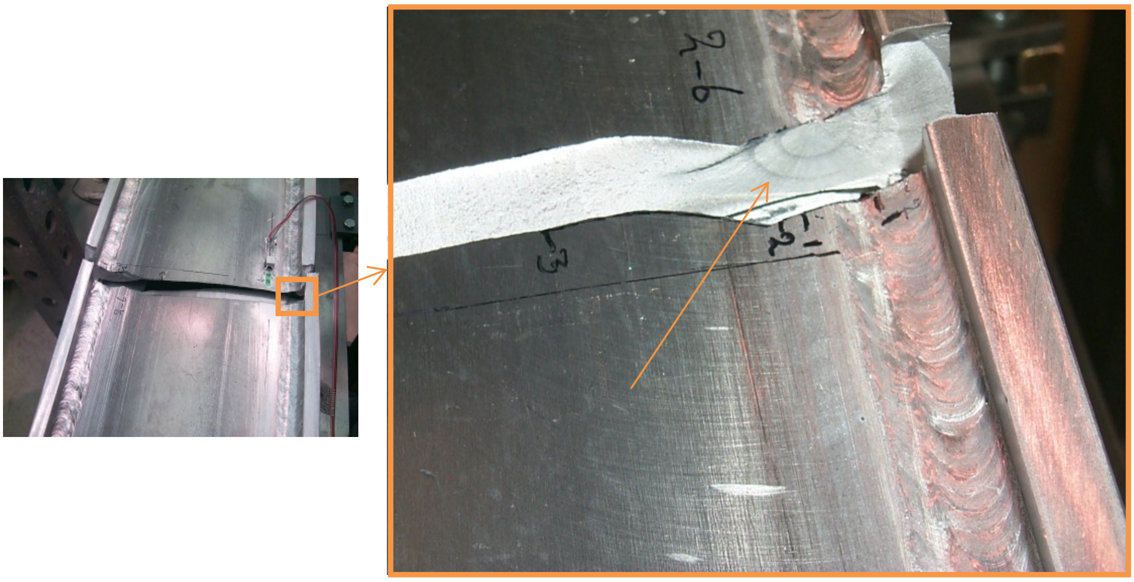

Figure 6. Aluminium beam after fatigue testing.

This is an issue for aluminium structures. The material crack growth rate is relatively high. In Section 1 it is already mentioned that aluminium alloys are not subjected to embrittlement at low temperatures as in case of steel – which is an advantage for aluminium. However, the 'basic' level of toughness of many aluminium alloys is relatively low. The effect of the latter is visible in Figure 6. The figure shows a beam that fractured at the end of a fatigue test carried out in TNO's laboratory. The portion of the fracture surface consumed by fatigue is visible by the beach marks – "rings" – in the insert of the figure – indicated by the arrow. The final fatigue crack – after 10^5 stress cycles – is only slightly larger than the largest beach mark visible on the figure – i.e. a few centimeters in width and thickness. Then, the entire specimen fractured in only two or three cycles. Such a small fatigue crack is difficult to detect especially in case of visual inspections outside.

Inspection experience from aircraft industry cannot be straightforwardly applied to infrastructures because the joining techniques in infrastructures are different, the plate thicknesses are much larger, different alloys are used and the environment in which the inspections take place as well ass the accessibility are much more difficult.

The risk of fracture not preceded by warning of aluminium structures may be mitigated by designing structures with multiple load paths, by using alloys that have a reasonable toughness and by designing for moderate stress levels. Using probabilistic theory, we are currently determining the structural reliability and safety level of metal infrastructures subjected to fatigue loading. In this research, the effect of inspections on the safety levels is quantified, inspection intervals are set, and the required safety margins with and without inspections are determined.

4. Required Research Activities for Future

To further enhance the position of aluminium alloys for use in heavy load bearing infrastructures, this section identifies required future research into fatigue and fracture.

A simple and cheap testing method related to material fracture toughness should be developed. Existing reliable fracture toughness tests such as CTOD or KJC tests are expensive. For steel, a cheap and approximate alternative is a Charpy notch impact test. Correlations are available for steel between the Charpy value and the fracture toughness expressed e.g. as stress intensity factor. Charpy testing may or may not be suited for aluminium alloys, however, a correlation between Charpy value and fracture toughness has not been investigated for aluminium alloys. As a result, to date a Charpy value for an aluminium alloy cannot be compared with standardized values for steel and cannot be translated to the material fracture toughness. In the end it is unknown whether Charpy testing is suited for aluminium. A different type of test may have to be developed.

Models that provide more reliable and accurate information on the growth and failure of large cracks than current state of the art should be developed. The growth rate of relatively small cracks – size of a few millimeters – is reasonably known because of extensive test data available from literature. This is different for larger cracks. Aspects such as load shedding effects, combined normal and shear loading, changes in residual stresses and the yield and fracture criterion for components with cracks are very structure dependent and require large scale specimens. Available data is therefore limited. Existing models aiming at predicting the growth of large cracks and the moment of fracture should be improved so that conservatisms in the existing design procedures can be reduced.

A design value of the fatigue strength of friction stir welded aluminium joints for implementation into standards should be derived from tests. This value should be accompanied by fabrication requirements. Test results available in literature or provided by suppliers may not always be useful for this application because these may be resulting from trial and error procedures to obtain optimized fabrication parameters for a certain application. Such trial and error procedures may not be suited for infrastructures without or with little repetition. European research groups are now in the process of evaluating existing fatigue test data in order to propose strength values and requirements.

Finally, for structures such as crash barriers, it is important that models be developed that predict the behavior of a structure for impact loading. Applications such as aluminium lighting poles, explosion walls in offshore platforms and military bullet resistant vehicles have demonstrated that aluminium is a suited material for impact loading at a variety of strain rates. However, in all these applications an approval test is required on the finalized product in order to check the behavior under actual impact loading conditions. For infrastructures with low repetition, final testing may be expensive – especially if the test demonstrates insufficient resistance – and therefore reliable simulation models are important.

5. Practical Examples

5.1. Example from offshore: helicopter landing platform

Let us first take a brief look into a well established aluminium application in another type of industry. There are many similarities between infrastructures and offshore structures e.g. with respect to design methods, joining techniques, plate thicknesses, robustness, safety requirements and load levels. For over 30 years, aluminium structures have been successfully applied in offshore. Nowadays, aluminium alloys are the most used materials for offshore helicopter landing platforms. We have determined the load bearing resistance of a type of deck section that is regularly applied for these platforms. The deck consists of extruded sections that are 450 mm in width, 150 mm in height, and have a weight of less than 20 kg/m. Snap joints are used to join the extrusions to each-other and to the supporting beams. The resistance was first determined using the finite element method. Because simulating the resistance of snap joints with the finite element method is not straightforward – the deformation at which the joint fails under loading is not easy to model – a full scale test was carried out to check the model, Figure 7. The resistance against crash landing of a deck spanning 5 m between the beams was more than 250 kN. This is the resistance for loading by one wheel. Would this section with this span be used in bridges, the static resistance to axle loading would have been (two wheels) 2 x 250 kN = 500 kN. The required resistance for traffic bridges in most European countries is only slightly larger. This demonstrates that it is possible to use a comparable structure for bridges. Note that fatigue loading is not an issue in helicopter deck applications.

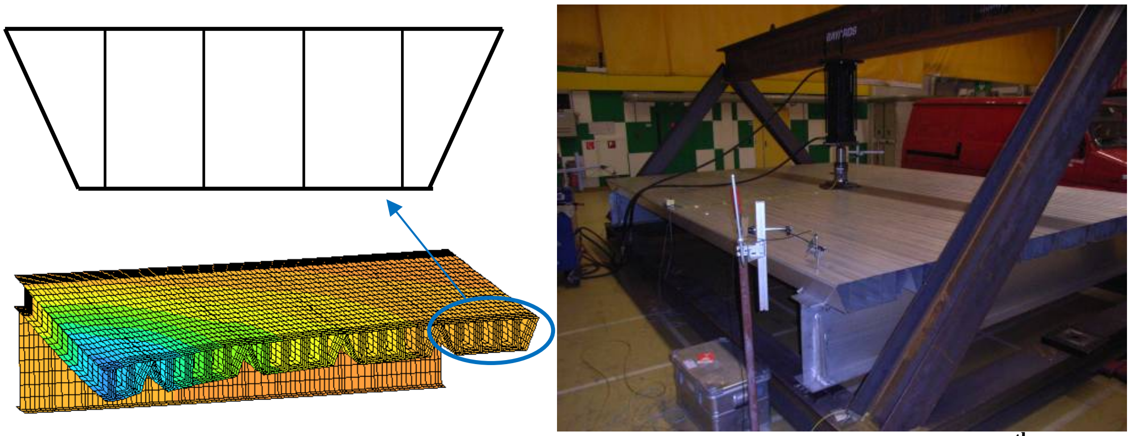

Figure 7. Resistance of a helicopter landing platform. Finite element model (1/4th of the geometry modelled) and test set-up.

5.2. Traffic bridges

The first aluminium traffic bridge in Europe was constructed in 1956 in Germany [13]. To date, 10 to 15 years of experience with aluminium traffic bridges is available in The Netherlands. Two examples of bridges in local roads are presented in Figure 8. The movable bridge - located in Amsterdam – can be lifted by a single hydraulic cylinder whereas a steel alternative would have needed a counterbalance weight.

Figure 9 shows a bridge in a motorway consisting of a steel main structure. The original timber deck has been replaced by an aluminium alternative for reasons of durability. Aluminium was the preferred material here because the mass of a steel deck would have been too large to bear for the existing steel main structure. A neoprene isolator was applied between the steel beams and the aluminium sections and they were jointed by clamps that were inspired by those used to clamp rails to crossbeams in rail transport. The clamps allow for a difference in thermal expansion between steel and aluminium and at the same time they are able to transfer breaking forces from deck to main structure. Some problems arose related to fretting of these clamps and these have been solved. The deck is loaded by approximately $1.5 \cdot 10^6$ heavy vehicles – around $6.5 \cdot 10^6$ heavy axles – per year. The deck is now around 10 years old and to date has not shown any fatigue problem.

Figure 8. Aluminium traffic bridges in local roads in The Netherlands (left-hand: Riekerhaven bridge in Amsterdam. Right-hand: bridge in Rhenen).

Figure 9. Aluminium deck of the Haringvliet bridge in motorway A29, The Netherlands.

5.3. Retrofitting – joining to steel

The final example in this section is a bicycle lane on a bridge. Hence, not a heavy loaded bridge structure but discussed here to demonstrate some possibilities of joining aluminium to steel. The 5 m wide and 16 m long aluminium box structures supporting the bicycle path were mounted on the cantilever beams of an existing steel bridge and they replaced a smaller path consisting of a concrete deck, Figure 10. Aluminium was chosen because of the limited load bearing resistance of the steel cantilever. Some basic requirements apply to the joints between aluminium and steel:

- They have to transfer horizontal and vertical loads.
- They have to allow for the difference in thermal expansion – the coefficient of linear thermal expansion of aluminium is approximately twice that of steel.

– They should be design in such a way that direct contact between carbon steel and aluminium is avoided so that galvanic corrosion is avoided.
– Gaps should be avoided so that crevice corrosion is avoided.

More information on the structure is provided in ref. [14].

Figure 11 shows the joints that we designed. Stainless steel bolts with a sufficiently small potential difference with aluminium were used in all joints. The left-hand figure indicates one of the two types of joint between the steel cantilevers and the aluminium beams. The joint was equipped with slotted holes and Teflon pads were applied in between steel and aluminium in order to avoid metallic contact as well as to allow sliding of aluminium over steel. The right-hand figure shows the joints applied between the aluminium structures in length direction. Each aluminium box structure spans 16 m – two steel cantilever centre-to-centre distances. The joint applied in between the box structures allows for thermal expansion in length direction through a slotted hole at one side of the joint. The bolt is not preloaded and Teflon rings are applied, generating a sliding surface. Three bolts clamp the plate on the other side of the joint. In this way, horizontal movement is allowed whereas vertical (shear) forces can be transferred from one to the other box structure. The allowance for thermal expansion through the sliding surfaces has been checked for all joints one year after installation and the systems worked as anticipated.

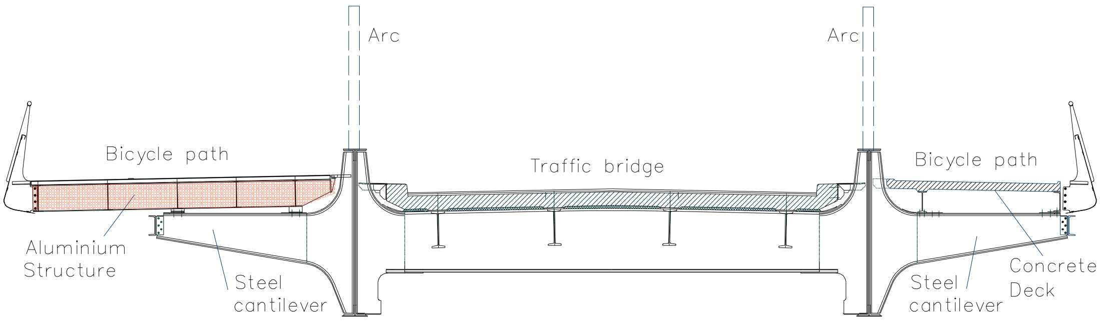

Figure 10. Aluminium structure of a bicycle path (left-hand side, in red) of Maarssensebridge, The Netherlands, Ref. [14].

Figure 11. Joints between aluminium and steel in Maarssensebridge, The Netherlands.

6. Discussion and conclusions

Aluminium alloys have been used for decades in infrastructures that are moderately loaded. This paper shows examples of aluminium infrastructures subjected to more heavy traffic loading. In The Netherlands, a major reason for applying aluminium alloys in infrastructures is their high strength to weight ratio. This makes aluminium especially suited in retrofitting projects, where increasing traffic demands require a light deck solution because the existing superstructure is already loaded to its limits. An important reason for applying aluminium in countries where temperatures can be very low is the fact that aluminium alloys are not subjected to embrittlement at low temperatures – as in the case of steels. The largest issue with respect to aluminium alloys in infrastructure is the relatively low fatigue resistance. Several research projects are run in The Netherlands in order to develop more accurate prediction models and to obtain knowledge on the consequences for the structural safety. Nonetheless, the paper shows that it is possible to design for fatigue in aluminium by applying optimized extrusion sections. To date, in The Netherlands, the heavy loaded infrastructures constructed in aluminium do not show fatigue damage.

7. References

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