SEMITRAILER CHASSIS DESIGN AGAINST FATIGUE ON THE BASIS OF FIELD TEST DATA



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Abstract

During the previous HVTT conference in Melbourne, results have been presented of a project FORWARD, including eleven different trailer manufacturers, involving testing and modeling activities to establish a practical basis for realistic fatigue assessment as a step towards an improved light-weight trailer design. The present paper describes the next step as part of the follow-up project LIFE (LIfetime Fatique Enhancement), starting with the model-based assessment of a realistic loading history for a semi-trailer. Representative loading conditions in this history, being derived from three weeks of field testing, are then used in Finite Element analyses to estimate fatigue life at a critical high loaded welded connection in the aluminum trailer chassis. Results are discussed with respect to the order of different loading cycles (Palmgren-Miner number, based on fatigue tests), 3D loading at the weld, the varying weld quality, and the impact of bonded connections in the trailer. These 'lessons learned' are interpreted, to result in improved general guidelines in light-weight trailer design.

Keywords: Tractor-semitrailer, loading history, field test, fatigue life, finite element analysis

1. Introduction

In the Netherlands, the trailer manufacturing industry consist largely of SMEs (Small & Medium size Enterprises), producing on demand in single piece or small series semi-trailers. Because of their size, the Dutch semi-trailer producers are specialized in special transport solutions for special purposes, with the end-product built and equipped to customer specification, and often with design and development realized together with the customer. Innovation is therefore important.

Clearly, the loading capacity as well as the robustness of the vehicle structure are important elements in the design of semi-trailers. A transport company aims for optimal productivity, i.e. a maximum loading capacity in combination with minimum costs in terms of maintenance, fuel and depreciation. That means that there is a challenge to reduce the trailer weight



Figure 1.: Example of cracking in the chassis

and to improve its lifetime. Traditionally, the semi-trailers were welded and built in mild-steel with large safety margins. The structural calculations were then based on static and quasi-static load cases. So far, the traditional way to connect elements of the trailer was by welding. Except for some incidental cracking problems, there were in general no significant cracking problems due to the low stress levels and materials which could be described as 'forgiving' with respect to high local strains.

In order to reduce the semi-trailer weight, one aims to use special light and at the same time high strength materials, such as high-strength steel, or aluminum. However these materials are more sensitive to fatigue, which may therefore lead to early cracking in the chassis, as illustrated with an example in figure 1.

This fatigue sensitivity requires a better understanding of the practical dynamical loading histories for semi-trailers, with consequences for local forces acting at critical locations. In addition, there is need to explore new design approaches to modify welding strategies, and the possible use of bolts and adhesive bonded connections. With this understanding, one would be able to redesign the vehicle resulting in less fatigue and therefore a longer lasting vehicle. More important, this will give more freedom in design to reduce the semi-trailer weight without compromising the vehicle lifetime, which will improve the productivity of the vehicle (more loading capacity, lower damage, lower fuel consumption).

There are various attempts to reduce semi-trailer weight by application of special materials, where we refer to examples such as the ROADLITE [4] and the ColdFeather [5] project and its successor, the GIGA lightweight semi-trailer. See also [6] where materials such as aluminum, sandwich material and high strength steel (HSS) are addressed in the context of semi-trailer design.

In close cooperation with the Dutch Chassis and Body work association FOCWA, a project, FORWARD (Fuel Optimised semi-trailer Referring to Well Assessed Realistic Design loads), has been carried out by HAN Automotive, together with eleven semi-trailer manufacturers and automotive (axle, steering system) suppliers, Delft University of Technology and the Dutch company Lightweight Structures, to derive practical load histories based on long-term field tests, and validated multi-body models (being derived for each tractor-semitrailer being part of the project FORWARD). A follow-up project LIFE (LIfetime Fatigue Enhancement) is now on its way to exploit these data to estimate lifetime for a number of selected semi-trailers,

and to explore light-weight design strategies. The total research approach is shown in figure 2. The yellow boxes in this scheme refer to the FORWARD project. Some steps were already made in FORWARD for fatigue analysis of semi-trailers, where the LIFE project will bring this further in a systematic way. Once the semi-trailer loading has been established, a representative load case, based on this loading, is used to identify the critical locations in the structure, i.e. the location where the first fatigue damage is expected due to repetitive loading. This can be done using a global Finite Element Model (FEM).



Figure 2.: FORWARD and LIFE projects

The local structure at the critical location can then be subjected to constant amplitude fatigue testing, to derive an S-N or F-N curve, giving the relationship between stress/force amplitude of the load cycle, and the maximum number of cycles until failure (defined here as a maximum crack length in the weld).

The Palmgren - Miner rule then states that the total damage for an arbitrary order of cycles with different amplitudes can be determined by superimposing the individual conributions of the cycles. This was adopted using a more refined FEM for only a part of the chassis, describing the local behavior and loading near the critical spot. However, this Palmgren-Miner rule appears to be unreliable, and may underestimate or overestimate the lifetime depending on the order of cycles, as indicated in the ASM handbook [7]. For that reason, additional in-door fatigue tests have been carried out on the same local structure subjected to the real load spectrum derived using the global FEM. The maximum number of cycles obtained was then compared to the Miner based (cumulative) lifetime assessment. This resulted in a correction of the

predicted lifetime with a factor less than 1 (for the investigated weld in our specific semi-trailer structure, this factor was about 0.26, i.e. a significant reduction). The final step would be to redesign the chassis, in order to redistribute the local force transfer in the chassis or to make the chassis more resistance against fatigue damage. Possible ways would be to use other materials,



Figure 3.: Tractor-semitrailer combination

to change the local weld configuration or weld quality (resulting in a different F-N curve and/or different Miner Number), or to replace welds by bolts, by adhesive bonded connections, etc. Changes in design will, in general, change the performance of the vehicle to road disturbances, and during cornering, braking and driving - situations. Using the validated dynamic multi-body model, the impact of such conditions on the semi-trailer-loading and the loading transfer within the semi-trailer can be determined without additional tests. This loop can then be followed several times until the design has been sufficiently improved.

The approach of figure 2 has been applied to a semitrailer, designed and produced by the company "van der Peet and Zn", with a self-carrying body of sandwich panels, bonded to a welded aluminum beam structure. This semitrailer. named "Kolibri", is used to transport bulk cargo, specifically potatoes. The cargo is unloaded through a conveyor belt. The vehicle is shown in figure 3.

The paper is structured in agreement with figure 2. In the next section, the load history is discussed, starting from the field test and based on a validated multi-body model. In section 3, a representative load case is used in a global FEM shell-model to determine the critical locations in the chassis. First fatigue analysis and lifetime assessment are discussed in section 4 using a more refined FEM model. As indicated earlier, the Palmgren-Miner rule can be questioned for large variation in cycle amplitudes, being the topic of section 5. Real load history tests are discussed resulting in a correction of the Palmgren-Miner based fatigue lifetime assessment. Conclusions are drawn in section 6, addressing also the variation in weld quality (with better quality in the trailer compared to the test specimen) and its effect on the lifetime correction. In addition, some discussion is given on the adhesively bonded connection in the trailer, which is expected to allow more deformation in the global chassis model and therefore a local force variation being different from the case where this connection is taken perfectly rigid.

2. Representative loading history

From 2009 until 2011, the project FOR-WARD has been carried out, with the aim to derive representative load cases for analysis of mainly fatigue in order to contribute to a reduction of semi-trailer mass, see [1] for more information on FORWARD. For that purpose, seven different tractor-semitrailer combinations have been subjected to field tests during a period of at least three weeks, where more than forty measurement channels were used to collect data on accelerations and angular velocities of trailer chassis and tractor (using the 3D GPS-based motion tracking system X-Sense), vertical accelerations at the axles, wheel speeds, steering angle, air spring pressures, spring displacements, and strains at some locations of the chassis. The field test



Figure 4.: Field test routes

route for each vehicle combination has been monitored using the GPS-data. The routes for the self-carrying semitrailer 'Kolibri', covering 60 hours of driving under normal transport

conditions, are shown in figure 4. This field test route means that practical braking, driving and cornering conditions as well as road disturbances have been experienced, for different loading situations. As mentioned before, this semitrailer is aimed to carry bulk (potatoes), where therefore two major loading situation could be distinguished, full load and unloaded. This loading situation is very specific. Other tractor-semitrailer combinations being investigated, such as a double floor trailer, showed more variation in loading.



Figure 5.: Multi-body model of the tractor - Kolibrie semitrailer combination

These field test data have been transferred to load data at all separate wheels and king-pin in all directions (longitudinal, lateral, vertical), using a SimMechanics Multibody model, see figure 5.

The model included torsional stiffness of the chassis. The coupling between truck and trailer was chosen such that revolute motions in yaw and roll direction were allowed. The (swing-arm) axles were modelled individually, with left and right part connected via a prismatic-revolute joint, allowing separate roll stiffness per axle. For the modelling of the tyres we have used the nonlinear tyre model TNO/Delft Tyre, see [2]. This model was validated with extensive testing on the DAF proving ground at St. Oedenrode, the Netherlands.



Figure 6.: Lane change model validation (left) and vertical force in swing arm while passing a trapezoid shaped threshold

In contrast to the field tests, these validation tests included special cases such as severe deceleration (braking) and acceleration (also in combination with cornering), driving over obsta-

cles, steady state cornering, double lane change, and low-speed maneuvering starting with a 90 degrees king-pin angle. As explained in the next section, the critical location was a welded connection between the outer chassis beam and a lateral connecting floor beam. Especially the vertical dynamic force variation resulted in a local force at the weld being responsible for fatigue. That means that cornering conditions (leading to low frequency load transfer) and road disturbances were the dominant load cases for the lifetime analysis. The high local shear loading at low speed maneuvering for high king-pin angle has been omitted in the fatigue analysis. An example of the model validation for a double lane change, and the axle suspension vertical force while passing a special threshold are shown in figure 6.

In addition to the force data, the field tests have been used to determine representative load histories (number of cycles) for this vehicle. This is done using the accelerations in lateral, longitudinal and vertical direction multiplied with the relevant masses and subsequently subjected to rainflow counting.

3. Critical location (weld) and FEM analysis

The Kolibri semi-trailer consists of sandwich panels in combination with a welded construction of extruded aluminum beams. A FEM analysis has been carried out, based on Shell elements with an element size of 1 mm, to identify the welded connection with the highest stresses. The welds between transverse beams and longitudinal beams carry the potato cargo, with this load being increased by dynamic effects.



Figure 7.: Critical welded connection

The most critical location is determined to be the welded connection just between the axle support and the support legs. It appears that stress concentrations arise at the end of the weld due to bending of the transverse floor beam (as a result of the dynamic cargo weight), leading to a tension stress in the upper flange of the welded beam. The bending of the longitudinal beam has an increasing effect on the stresses around the welding seam. A close-up of the welded connection between transverse floor beam and longitudinal chassis beam is shown in figure 7. Observe the stress concentrations at the weld ends in figure 8, based on the FEM analysis using shell elements. The same local part of the chassis has been modeled in solids (hex elements plus tetrahedrons for the welds), in order to have a better understanding of the local stress concentration near the weld which is effectively a 3D weld (see figure 9).



Figure 8.: FEM analysis of the shell model showing stress effects (von Mises) at weld ends

Because the dominant loading in the trailer creates a tension stress in the flange of the welded beam, the local structure can be considered equivalently as an isolated structure being supported at the longitudinal beam and loaded by a representative calculated tension force along the transverse beam. Local rounding of welds (toes) have not been taken into account, which is acceptable if the so-called hot-spot stress method is used. This method uses an extrapolated stress at the weld toe, derived from stresses at some distance from this location, see figure 10 and also [8] for more information on this method and design curves and rules for fatigue analysis.

4. Fatigue analysis and lifetime assessment

With the extrapolated stress from figure 9, and assuming this stress to result from a fixed amplitude variation of loading, the fatigue life can be estimated using the design rules in [8], leading for aluminum to a FAT value (fatigue class) of 40. Each FAT value corresponds to a fatigue resistance S-N curve, i.e. describing the maximum number of cycles N for given stress amplitude S. Other options for estimating the fatigue lifetime are the effective notch stress method (in which the roots and the toes of the weld have to be modeled with an assumed fictive notch radius of 1 mm, see [8]), and the



Figure 11.: Fatigue machine and test specimen

Verity mesh – insensitive Equivalent structural stress method, see the book of John Draper [9], and being originally developed by Dong, [10]. The Verity method uses a single S-N curve for all welded geometries, plate thickness and type of loading and is insensitive to the finite



Figure 9.: FEM analysis of the solid model with the 3D weld description (von Mises stress)



Figure 10.: Linear extrapolated stress at weld toe

element density and element type. It is our objective to evaluate this method for the welded joint, as described above, in our semi-trailer.

As an alternative to the use of handbook S-N fatigue resistance curves using FEM-derived equivalent stress levels, we have derived an F-N curve for the welded joint by fatigue testing of a number of welded specimen. This testing was done on the 1000 kN MTS fatigue machine of the Structures & Materials Laboratory of Delft University of Technology. Specimen and test facility are shown in figure 11. To assure as less scatter as possible in order to keep the number of required tests low, the welds were of a more simple type compared to the semi-trailer, all made using a welding robot. The predicted fatigue life using these tests is therefore expected to be exceeded by the fatigue life of the semitrailer for the same loading. In accordance to the dominant tension stress in the flange of the welded beam, the specimen was tested with a calculated tension force. To verify representative stresses and geometrical similarity between test specimen and trailer, the FEM analysis of the loaded specimen was compared with the FEM analysis of the same part of the trailer chassis. The FEM model of the specimen using



Figure 12.: Comparison of strains from speckle tests and FEM

digital image correlation). Experimentally obtained strains and FEM results are compared in horizontal and vertical direction, along a

norizontal and vertical direction, along a line parallel to and at some distance away from the weld. See figure 12 for these comparisons, which show a satisfactory correspondence.

Constant amplitude fatigue loading tests were carried out on the fatigue machine, with a stress ratio of 0.05 (ratio of minimum force and maximum force), with test specimen assumed to have failed at a crack length of 15 mm. A slope of the obtained curve according to the Basquin relation

$$F^k . N = C$$



Figure 13.: F-N curve, from fatigue tests

for some constant C, was found to be k = 3.115. A value of about 3 was expected from the Paris crack growth relation (see [8] and [9]). Welded joints contain crack-like defects, produced during manufacturing, which will also grow at small loads below the fatigue limit. Ear-

ly in the life of the weld, the defect is too small to be propagated by cycles with small amplitude. Large amplitude cycles will cause the defect to propagate such that its size finally becomes sufficient to allow small amplitude cycles to contribute to the crack propagation process as well. As a consequence, all cycles have to be considered and the F-N curve has to be extended over the full cycle range. According to [3], this can be done with the so-called Haibach approximation beyond $N = 10^7$, which means that the fatigue resistance curve is extended according to the relationship:

$$F^{2.k-1}.N = C_0$$

for some constant C_0 . The resulting F-N curve is shown in figure 13. The Basquin curve is determined from regression through the fatigue test results, also indicated in figure 13. The Haibach approximation starts at 10^7 cycles. With this curve, the total fatigue life can be determined using the Palmgren-Miner rule, which means that each separate cycle with index i in the representative load history (determined by rainflow counting) with a force amplitude F_i contributes to the fatigue life according to the expression:

$$\sum_{i} \left(\frac{n_i}{N_i} \right)$$

with n_i the number of cycles and N_i being the number of cycles at failure for amplitude F_i , using the curve in figure 13.

5. Reliability of lifetime assessment at welds.

According to [7] the Miner rule is fully unreliable for comparing the severity of different load spectra. We quote: As a simple illustration, compare a load spectrum to a modification of that spectrum obtained by adding a small number of high-load cycles. According to the Miner rule the addition should lead to somewhat shorter fatigue lives, whereas in general it leads to significant life improvements. In our case, the loading is not a constant amplitude cycle, which means that the above Palmgren-Miner rule needs to be corrected. We have determined the correction factor (referred to as the Palmgren-Miner number) by repeating the tests with the test specimen, but this time for a load spectrum according to the real load history, derived from field tests using the multi-body model described in section 2. Determining the number of cycles until failure (15 mm crack length) and comparing this with the number of cycles for which the Palmgren-Miner rule gives a value of 1, allows us to find this factor. These tests have been repeated with three test specimen in total. It resulted in a correction factor of 0.26, which means that the fatigue life of this weld under realistic loading conditions is 26 % of the value being predicted according to the Miner rule. This may also be affected by poor weld quality. Different test specimen appeared to have different types of weld leading to different crack initiation and propagation. However all cracks started from the weld ends. The geometry of the "weld start" and the "weld stop" are expected to have great influence on the low Miner Number. This requires more detailed and repeated tests, with more variation in the weld (-ends). As mentioned before the welds in the test specimen are of a different geometry and probably less quality compared to the real welds in the Kolibri semi-trailer.

6. Conclusions and discussions.

We have presented an approach to derive fatigue life assessment for semi-trailers on the basis of field test data. These data are transferred into a realistic loading spectrum, which is then used to derive critical spots in the chassis and a fatigue life estimate. The approach has been applied to a semi-trailer with a self-carrying body of sandwich panels, bonded to a welded aluminum beam structure. This semitrailer, named "Kolibri", is used to transport potatoes. Similar studies are on its way for other semi-trailers. More than half a year of field test data has been derived in the past years, being now applied to fatigue analysis and light-weight design studies for a large variety of semi-trailers such as a multi-floor trailer, a low-loader goose neck structure, etc.

The application to the Kolibri semi-trailer revealed that the selection and derivation of fatigue properties is critical in this study. There are different ways to estimate the local stress concentration at the critical (welded) spot, such as the hot-spot stress method and the effective notch stress method, on the basis of FEM analyses of both the full trailer and a more detailed model of part of the chassis. This last FEM model was validated using optical (speckle correlation) strain measurements.

The practical approach to determine fatigue life using the hot-spot or the effective notch stress method requires a realistic S-N fatigue resistance curve, which can be taken from literature according to a certain fatigue class. We have observed that the fatigue properties depend on the weld quality, and on the order of load cycles. In order to account for these dependencies, we have described the local fatigue behavior in terms of an F-N curve instead of an S-N curve, being determined by various fatigue tests, including constant cycle tests as well as spectrum fatigue tests.

We conclude:

- The method with the obtained F-N curve gives us a good start for possible fatigue life assessment of semi-trailers.
- The investigated welds are clearly a 3D geometry problem, they cannot be simply assessed with 2D IIW handbook data. The recommended handbook methods may be used if we concentrate more on the geometry and quality of the weld. FEM should be used to investigate the local stresses. This requires more detailed tests and investigation.

We close this section with discussion on bonded connections in the semi-trailer and on the costs of fatigue analysis.

In the full chassis analysis, we neglected the bonded connections between chassis and sandwich panels, see figure 14. For bonding, such as in the Kolibri trailer, a stable 1-component elastic humidity-curing MS-Polymer-based adhesive with high green strength (high viscosity) and high tensile strength is commonly used. Its secondary function is sealing. The standard thickness of a seam is 3-4 mm. This creates a great number of flexible primary connections in the trailer construction. In FEM models like the one of the full Kolibri trailer, the normally bonded construction parts are tied together in a rigid way, which is not correct and leads to inaccuracies in the analyses results for displacements and stresses. We have started an investigation to model the flexible bonded connections in an acceptable accurate way.

In trailers, there is not just one connection being representative for fatigue life, but there are many structural details vulnerable to fatigue, all with their specific welding geometry. The F-

N method for the whole weld would make it necessary to create an F-N curve for each investigated joint. If we could use a more generic approach of a S-N curve of the weld end, we could probably limit the testing to a standard series of weld-ends, and draw up more general guidelines for the assessment of fatigue life. If the Verity-method (using a single S-N curve for all welded geometries, plate thickness and type of loading and being insensitive to FEM density and element type) could be approved to give accurate results, an even further reduction of testing could be possible. The margins in the semi-trailer industry are small compared to for example the aircraft industry were fatigue calculations and testing procedures are standard procedures. This means that reliable and accurate fatigue life prediction in the semi-trailer industry will only be feasible against acceptable low costs.



Figure 14.: An aluminum chassis and the bonded sandwich panel

This makes it necessary to improve the fatigue analysis in the sense that reliable assessments are possible with less effort, using more general guidelines. If we aim for reduced trailer weight by using special light and at the same time high strength materials also being more sensitive to fatigue, it is clear that fatigue analysis of semi-trailer will become more important in the future.

Experience with fatigue analysis along the steps, as discussed in this paper and indicated in figure 2, is an important step to fulfill this goal in an affordable way.

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