Distortion management in railway vehicle construction

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1 Introduction

The avoidance of shape deviations and material changes due to welding is an interesting and challenging issue, which often leads to difficulties to solve in practice. With welding simulation it is possible to calculate welding distortion, residual stresses and microstructural changes in advance. Welding assembly often takes place in several stages. For multi-stage weld assemblies, the deformations from previous sub-assemblies must also be taken into account in the simulation. This extends the welding simulation to a manufacturing simulation. The FabWeld software was developed by Dr. Loose GmbH to calculate the multi-stage assembly. Figure 1 shows the three-stage assembly using the example of a frame structure made of aluminum profiles.

In welded constructions, several questions arise that can be answered by simulation. Distortion management is about adjusting the welding distortion so that the geometry of the finished structure is within required tolerances. Simulation allows the analysis and design of manufacturing at an early stage of the design planning of components and assemblies. This makes it possible to identify manufacturing challenges at an early stage and to plan and implement necessary improvement measures in good time.

The goal is to save resources, especially raw materials, personnel, time and thus costs. This can be achieved through simulation, as production can start without errors, without loss of time or run-in loops.

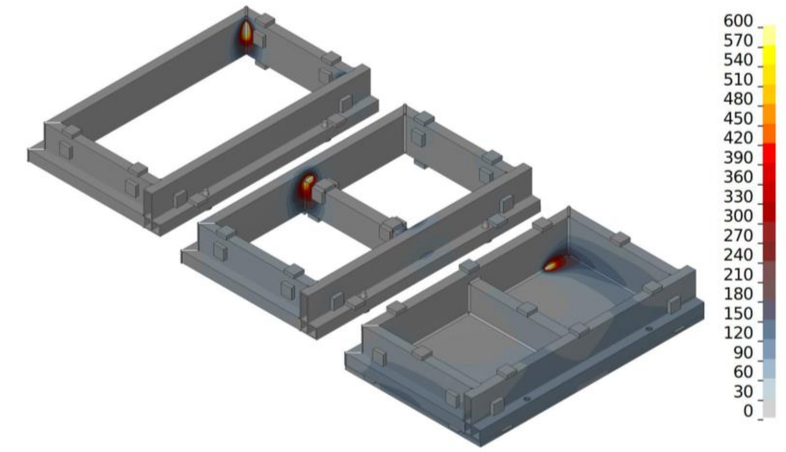

Figure 1: Multi stage assembly of welded frame structure made from Aluminium Alloys

2 Validation of weld structure simulation

The weld structure simulation as a special application of the finite element method considers the effects from welding on the entire component. The input variable is the heat input from the welding heat source. This is applied in the form of a so-called equivalent heat source. This means that any fusion welding process can be modeled, regardless of how the fusion heat is generated. Of course, all boundary conditions must be taken into account in the model. This includes the clamping device, heat dissipation through clamping or cooling jaws and tacking.
Results from the weld structure simulation include the geometry change due to welding, weld distortion, residual stresses and plastic strains, and if the microstructure transformation calculation is included, the microstructure state after welding and the resulting changing yield strength.

Goldak Technologies Inc, Dr. Loose GmbH and TIME - Technology Institute for Metal & Engineering have demonstrated the predictive accuracy of weld structure simulation in a joint research project. For this purpose, an orthotropic plate 1200 mm x 600 mm was chosen, onto which two longitudinal stiffeners and 3 transverse stiffeners were welded. (fig. 2) The stiffeners are fixed with a total of 17 tack welds. The slab is supported in a statically determinate manner and supported at three corners. The fourth corner remains free. This is the corner where the greatest distortion occurs during welding. The corner opposite the free corner on the long side is chamfered so that the corners of the plate can be clearly assigned. While the tack welds are being welded, the plate is supported at the center transverse stiffener on each outer side with a punch. Without support, the plate deflects under its own weight to such an extent that an excessive gap is created between the plate and the stiffener. After tack welding, the support is removed. This leads to a lowering of the plate at the unsupported corner. In the simulation, the removal of the support is mapped realistically.

Figure 2: Validation test TIME plate

Then the longitudinal seams are first welded on the outside as a two-layer seam with 3 weld beads. All other 17 seams are executed as single-layer fillet welds. During welding, the movements normal to the plate are measured at five points with cable tension transducers. At the same locations, the vertical distortion is evaluated from the simulation. Fig. 3 shows an example of the result of the validation test on displacement transducer 4. The graph compares the vertical deformations measured with cable wire transducers with the calculated vertical deformations. It can be seen on the graph that the deformation jump caused by removing the center bearings after tack welding is accurately represented by the simulation. The vertical distortion during the entire welding process is also calculated correctly. This proves that the applied calculation method of the weld structure simulation is able to accurately reproduce the deformation behavior during the entire welding process. This finding is new, since previously only final results, i.e. the condition after welding and cooling, were used for validation. In order to fully use weld structure simulation to analyze welding, the simulation results must also be accurate throughout the process. For example, this comes into play when the gap formations during welding are to be investigated in order to check the clamping or tacking concept.

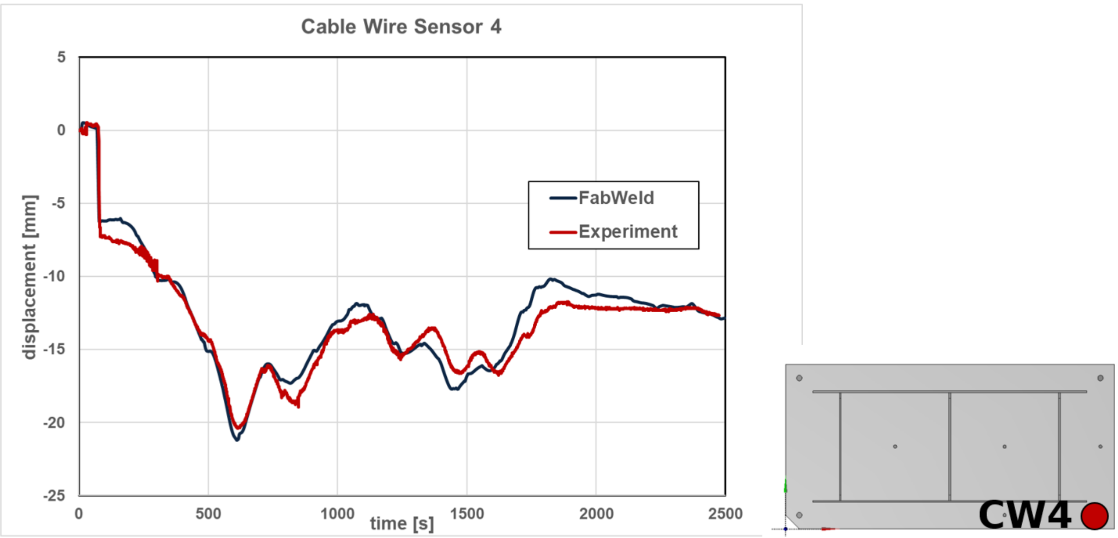

Figure 3: Validation result. Calculated deformation vs. measured deformation

3 Simulation of the weld assembly

In order to obtain accurate results when simulating the welded assembly, the clamping process with the resulting distortions must be mapped correctly. If individual components or subassemblies already deviate from the nominal geometry, clamping distortion occurs when they are clamped in the fixture. Welding generates the thermal distortion. When the clamping forces are released during unclamping, unclamping distortion occurs, which represents springback. All distortion components together result in the final distortion. The clamping process must be mapped realistically in the simulation in order to achieve exact calculation results.

The simulation of the assembly requires a multi-stage simulation. In the simulation, as in reality, components or subassemblies are added, clamped and welded from manufacturing station to manufacturing station.

Fig. 4 and Fig. 5 show a bottom structure in the 2nd manufacturing stage, where the subassemblies cross member and bottom plate are added. Both pictures show the longitudinal distortion in the X-direction. Fig. 4 represents the situation before insertion and clamping of the cross members. The bottom plate shows deformations in the X-direction. During clamping, the cross members are pressed onto the bottom plate and deformed in the process due to the imperfection of the bottom plate. During welding, this deformation component is frozen (Fig. 5).

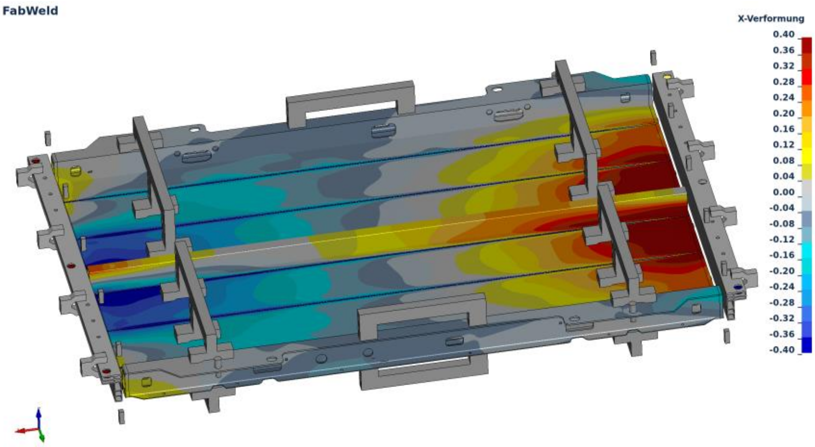

Figure 4: Longitudinal distortion of floor assembly structure before clamping of the cross members

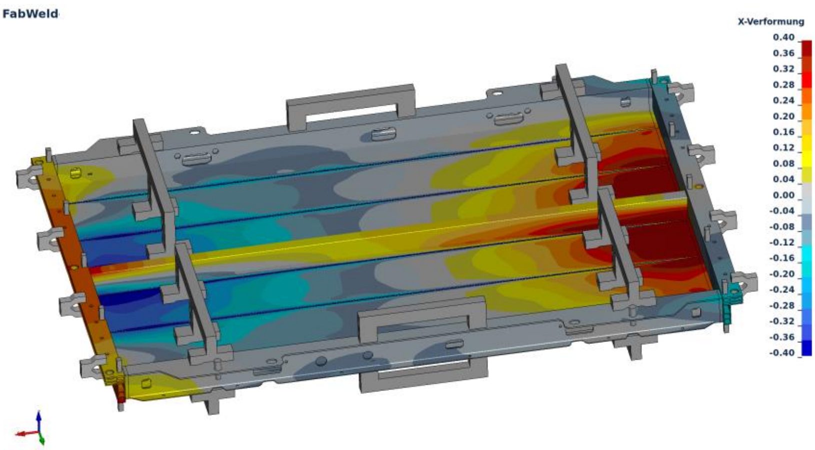

Figure 5: Longitudinal distortion of floor assembly structure after clamping of the cross members

Since distortion-free welding is not possible for many welding tasks, suitable measures must be taken to ensure that the geometry complies with the required tolerances after welding. In addition to the design of the clamping device or the tacking concept, suitable measures include compensation measures:

- Addition to welding shrinkage
- angular allowance
- Pre-oval of circular cross sections
- Pre-stamping of inverse welding distortion
- Geometry adjustment on the component to counteract welding distortion
- Stiffness modification on the single component counteracting the welding distortion

Just as the distortion during weld assembly can be calculated in advance, the compensation measures can also be entered into this calculation. This makes it possible to numerically validate the compensation measures. This is the case if the calculated welding distortion, taking into account the compensation measure, is within the permissible mold deviation tolerance.

4 Simulation-supported distortion optimization using the example of a floor assembly

A floor assembly is manufactured from extruded aluminum profiles. An MSG cold wire process is used. Assembly takes place at three stations with one substation:
Station 1: Assembly of the base plate
Substation 1.1: Subassembly of bushings to outer cross members
Station 2: Assembly of base plate with outer cross members
Station 3: Assembly of inner cross members
For this battery beam, the distortion that occurs during the welding assembly is calculated. As described above, the deformations from the previous welding station are taken into account in this simulation. Figure 6 shows the battery beam during welding station 3.

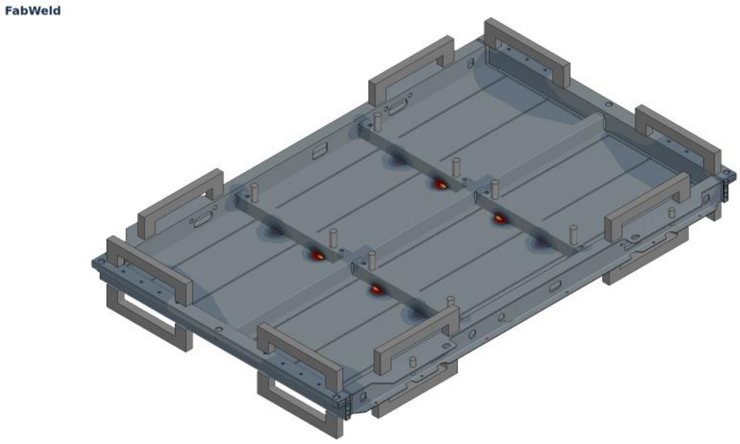

Figure 6: Floor assembly carrier, welding of the third and final station

For the center section, there are the design variants shown in Fig. 7. Variant 1 represents the original design. The center section is designed with the bottom section as an extruded section. This profile is welded to the other profiles in station 1 to form the base plate. Variant 2 represents the optimized construction. The profile is divided into a floor profile and a longitudinal member profile. The bottom profile is installed in station 1, while the longitudinal member profile is not added until the third and final station.

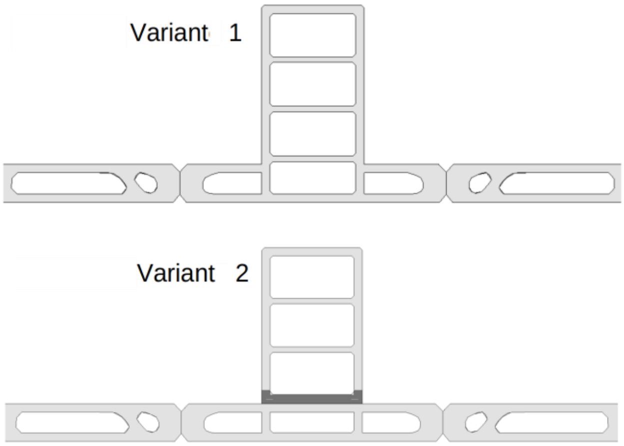

Figure 7: Versions of the center section. Variant 1 as a single profile and variant 2 as a split profile.

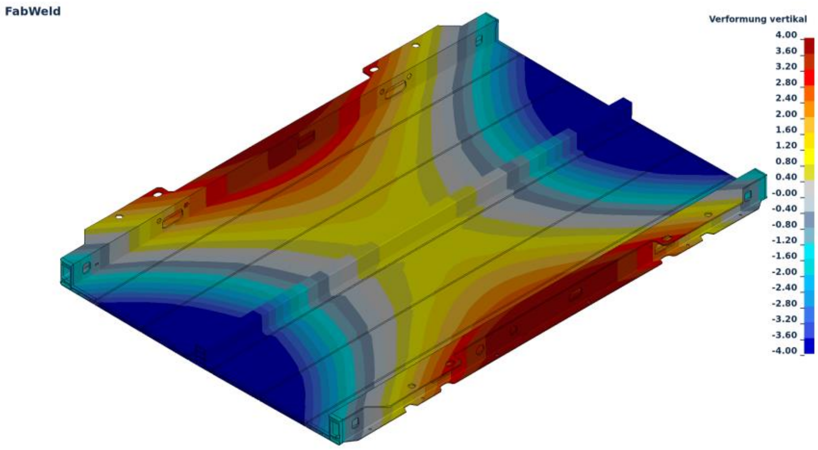

Figure 8: Vertical distortion variant 1 after station 1

From the multi-stage assembly simulation, the station where the greatest distortion occurs can first be determined. In our example, this is station 1 with the welding of the floor profiles. Fig. 8 shows the vertical deformation of variant 1 after unclamping and intermediate cooling shortly before clamping in station 2. The station at which the greatest deformation occurs is also the station at which the compensation measures are most effective. The distortion that occurs with the warping of the plate is explained by the eccentricity between the center section gravity line and the longitudinal welds. The improvement of variant 2 is based on the fact that the longitudinal welds are now arranged symmetrically to the center line of gravity. Fig. 9 shows the vertical distortion of variant 2 after station 1. A clear distortion minimization can be seen. The improvement in station 1 has a direct effect on the total distortion. Fig. 10 shows the vertical deformation after complete cooling for variant 1 with unsplit center section and Fig. 11 for variant 2 with split center section.

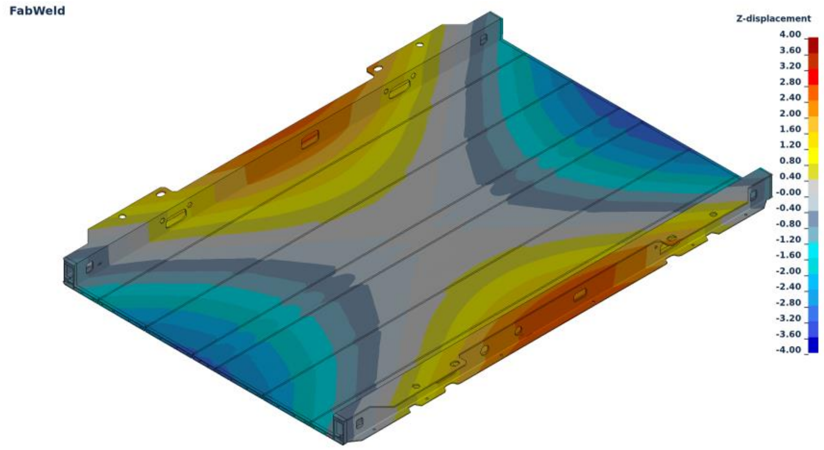

Figure 9: Vertical distortion variant 2 after station 1

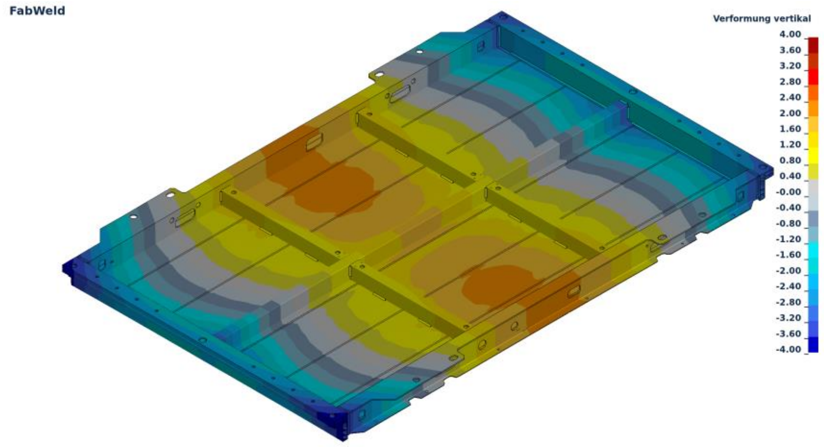

Figure 10: Variant 1, final vertical deformation

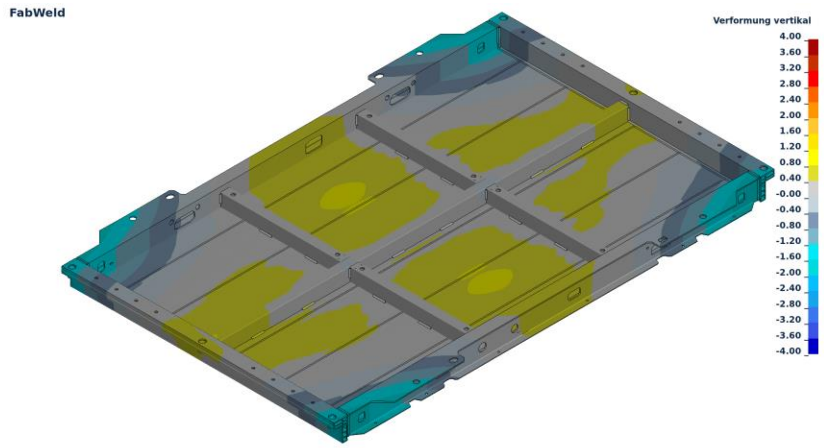

Figure 11: Optimization of variant 2, final vertical deformation

This example clearly shows how profitably assembly simulation can be used in the design phase. If the welding distortion is determined precisely at this early stage, it is possible to minimize the welding distortion efficiently with geometry changes that do not require much effort.

5 Critical assembly points and gap analysis

Critical points can be analyzed from the assembly simulation. By calculating the welding distortions, it can be determined in advance whether the insertion of further components is possible or whether fit conflicts will occur. Fig. 12 shows such a fit conflict. The cross member has the length of the CAD nominal geometry. Due to the welding of the frame from the previous production stage, the side profiles have warped inward to such an extent that it is not possible to insert the cross member. Here, the simulation shows in advance that measures must be taken to enable trouble-free insertion.

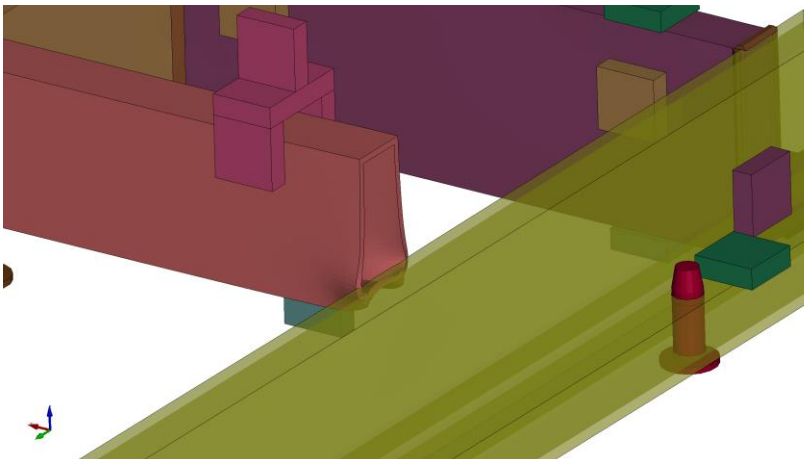

Fig. 12 Fit conflict when inserting a cross member.

The assembly simulation can be used to analyze whether critical gaps occur during production. When the bottom profiles of the battery carrier example are welded together, a gap occurs toward the end between the center profile and the adjacent profile. The gap forms in both the vertical and lateral directions (Fig. 13). The vertical gap can be significantly reduced by optimizing the clamp position.

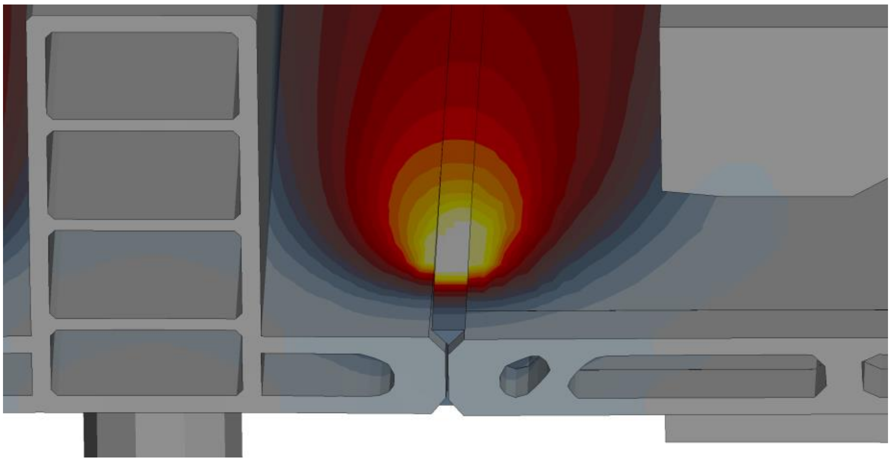

Fig. 13: Gap formation during welding of the assembly

6 Summary

With numerical analysis, it is possible to precisely calculate the deformation during multi-stage assembly of welded structures. The assembly station at which the greatest distortion occurs can thus be determined in advance. This enables the targeted planning design and numerical verification of compensation measures. Furthermore, assembly problems such as gap formation or installation constraints can be identified and eliminated in advance.

Thus, the welding production can be optimally designed in advance, even with multi-stage assembly supported by numerical simulation. This significantly saves costs in terms of time, material, energy and personnel.