Rib Design to Increase Stiffness of Housings

R. Helfrich, M. Klein, A. Schünemann

INTES GmbH, Stuttgart, Germany
www.intes.de; info@intes.de

Summary:

Crank housings and transmission housings need sufficient stiffness dependent on their operating conditions, their weight should be as low as possible, and they have to avoid oil leakage. In addition, material stresses should be not too high that cracks may occur. Because housings are offen cast, the producibility has to be guaranteed which leads to similar wall thicknesses and suitable release directions. The requirements for thin walls and low weight as well as high stiffness cause ribs on the housing. To systematically design ribs and to take into account changing boundary conditions always in the same way, is the main goal of concept driven design of housings.

The main tool for this concept design is topology optimization. A crank housing as part of a full engine model with pretension and temperature loading is taken as an example to demonstrate the rib design under weight and stiffness conditions. Procedure and achieved results are presented on the following pages.

Zusammenfassung:

Kurbelgehäuse von Motoren und Getriebegehäuse sollen je nach Funktion eine gewisse Steifigkeit haben, dabei so leicht wie möglich sein und einen flüssigen Inhalt wie Öl am Austreten hindern. Darüber hinaus dürfen Materialspannungen nicht so hoch sein, dass es zu Rissen kommt. Da die Gehäuse häufig gegossen werden, ist außerdem die Herstellbarkeit zu gewährleisten, was zu einigermaßen ähnlichen Wandstärken und zur Berücksichtigung von Auszugsrichtungen führt. Die Anforderungen an kleine Wandstärken bzw. geringes Gewicht sowie hohe Steifigkeit führen zu einer Verrippung der Gehäuse. Das Rippenbild systematisch zu entwerfen und dabei die wechselnden Randbedingungen immer gleichartig zu berücksichtigen, ist eine konsequente Forderung der Konzeptfindung.

Als zentrales Hilfsmittel bei dieser Konzeptfindung kommt die Topologie-Optimierung zum Einsatz. Am Beispiel eines Kurbelgehäuses als Teil eines gesamten Motormodells mit Vorspannung und Temperaturlastfällen wird so das Rippenbild unter Gewichts- und Steifigkeitsrandbedingungen ermittelt. Vorgehen und erzielte Ergebnisse sind Gegenstand der folgenden Darstellung.

1 Introduction

Topology optimization is an important tool for the analyst to prove existing design concepts and to develop alternative designs (see [1], [5], [6]). To use this tool for rib design on housings requires a number of basic decisions:

- The manufacturing process has to be known in advance. In case of casting the producibility of the housing with ribs has to be used to specify additional topological conditions like release directions and wall thicknesses.
- For the definition of the design space, the maximum height of the ribs has to be fixed in advance.
- Additional mass is required for the ribs. More mass can result in higher stiffness. The limit has to be defined in advance or it depends on the final stiffness which has to be achieved by the design.
- The distribution of the mass depends on the loading. The identification of the relevant load cases has to be done in advance or different designs have to be compared using different load cases.
- Beside stiffness, maximum stress also could be an important design constraint. Because the evaluation of stresses in the design space is not very reliable, the stress constraints could be taken from the non-design space. Alternatively, the stresses will be derived after the rib design has been fixed and an appropriate Finite Element (FE) model has been set up.

Some of the parameters are not independent but depend on others. E.g. the achievable stiffness depend on the available mass which depends on the thickness and height of the ribs.

To improve stiffness, there are two available strategies which will usually result in different designs:

- A global criterion is the compliance of the structure. This criterion can easily be specified and does not need to know more about the displacement field.
- If certain displacement limits are known for a housing, these limits can be used as objective function for topology optimization. This criterion is a local one and does not necessarily lead to global stiffness improvement.

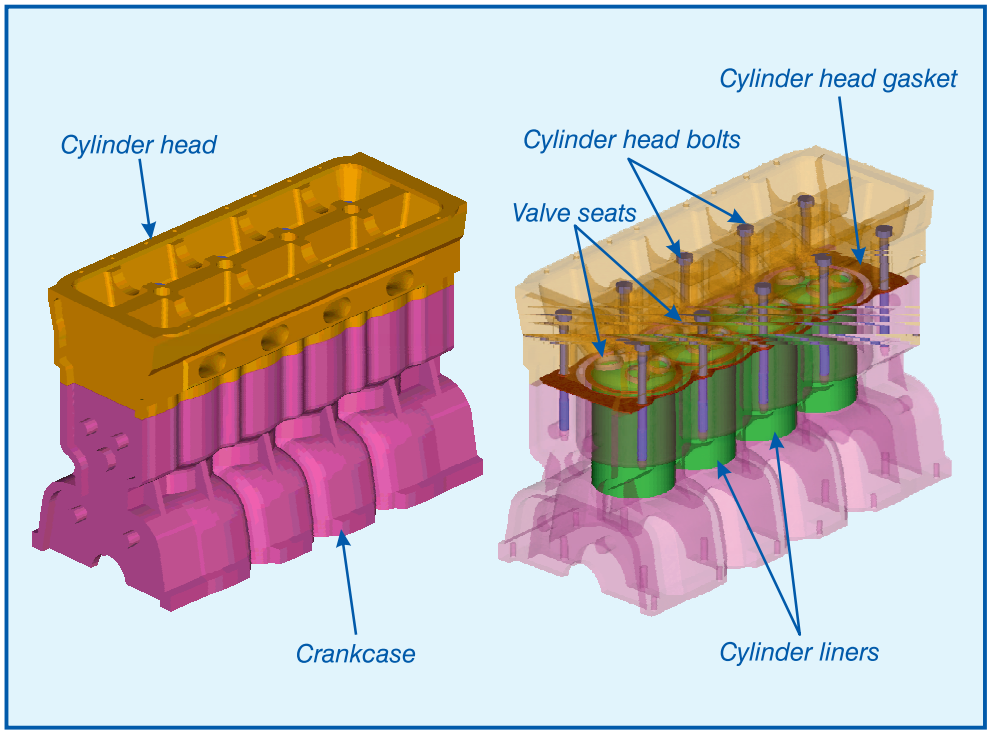

Fig. 1: Example model of an engine

The load cases used for rib design should be taken from realistic loading. So, different analysis types should be usable with topology optimization:

- In the simplest case a linear static analysis can be used.
- If contact is present in the model or nonlinear material behaviour, then nonlinear static analysis should be applied during topology optimization.
- In case of dynamic constraints like certain eigenfrequencies or amplitudes from frequency response analysis, the dynamic analysis has to be used for topology optimization.

In the following sections, the example model of an engine is introduced which is analyzed by nonlinear static analysis taking into account contact and nonlinear material behaviour in the cylinder head gasket. Different load cases and objectives are used to demonstrate their effect on the rib design.

Optimization modeling and post-processing is performed using VisPER (see [4]) and PERMAS is used to do the topology optimization (see [2], [3]).

2 Example Model

The model has the following typical components (see Fig. 1):

- Cylinder head,
- Crankcase,
- Cylinder head bolts,
- Cylinder head gasket with nonlinear pressure-closure curves,
- Cylinder liners,
- Valve seats.

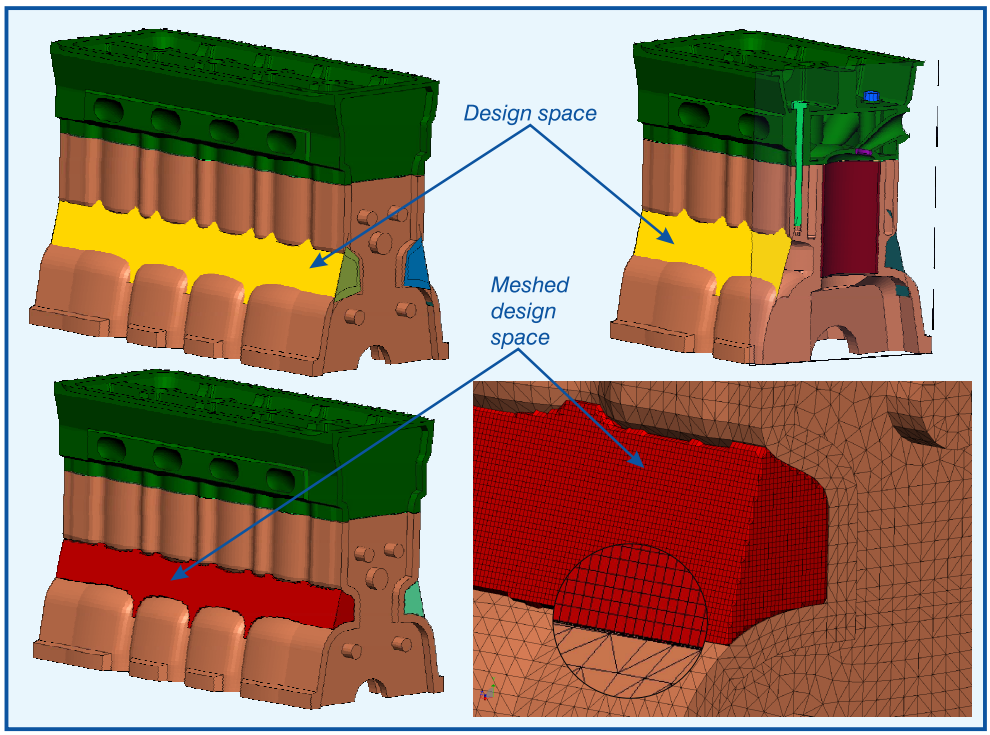

Fig. 2: Design space definition and meshing of design space

The boundary conditions are build as kinematic minimum support at the crank shaft bearings in order to avoid any constraint forces from the supports.

The original model (see Fig. 1) shows a number of ribs between the cylinder area and the crankcase. These ribs are erased before the design space is specified. This design space is defined by the surface of the crankcase and a plane as shown in the upper images of Fig. 2. The meshing is automatically performed using hexahedron elements giving a rather fine mesh (see lower images of Fig. 2). The coupling between the crankcase surface and the fine mesh of the design space is made using incompatible meshes which couple the displacements by projection and interpolation with shape functions like elements.

The analysis performed is a nonlinear contact analysis with nonlinear material behaviour of cylinder head gasket (i.e. nonlinar gasket loading and unloading curves which represent the relationship between pressure and closure of the gasket elements).

The typical engine loading consists of bolt pretension, temperature loading, and pressure on cylinders in a predefined sequence. The rib design is seen as mainly dependent on bolt pretension and thermal analysis. So, we used two load cases, one for bolt pretension and one for bolt pretension and temperature loading.

The temperature loading is interesting, because intake and exhaust side show different temperatures (see Fig. 3) which lead to a bending of the crankcase around a vertical axis (y axis, see Fig. 4). Our expectation was that the temperature loading is more critical for the overall stiffness of the engine than the bolt pretension.

The total mass of the engine model is 21.3 kg. The mass of the ribs in the original model was 348 g. Therefore, this mass is used as a weight constraint for the new rib design. For the objective function, the following conditions were applied:

- Compliance as a global stiffness parameter.
- To minimize relative displacements in the lateral direction of the engine. This condition tries to reduce the bending at the crankshaft main bearings.

In order to facilitate rib design, a release direction is specified perpendicular and outwards to the wall of the engine (like the ribs in the original model in Fig. 1).

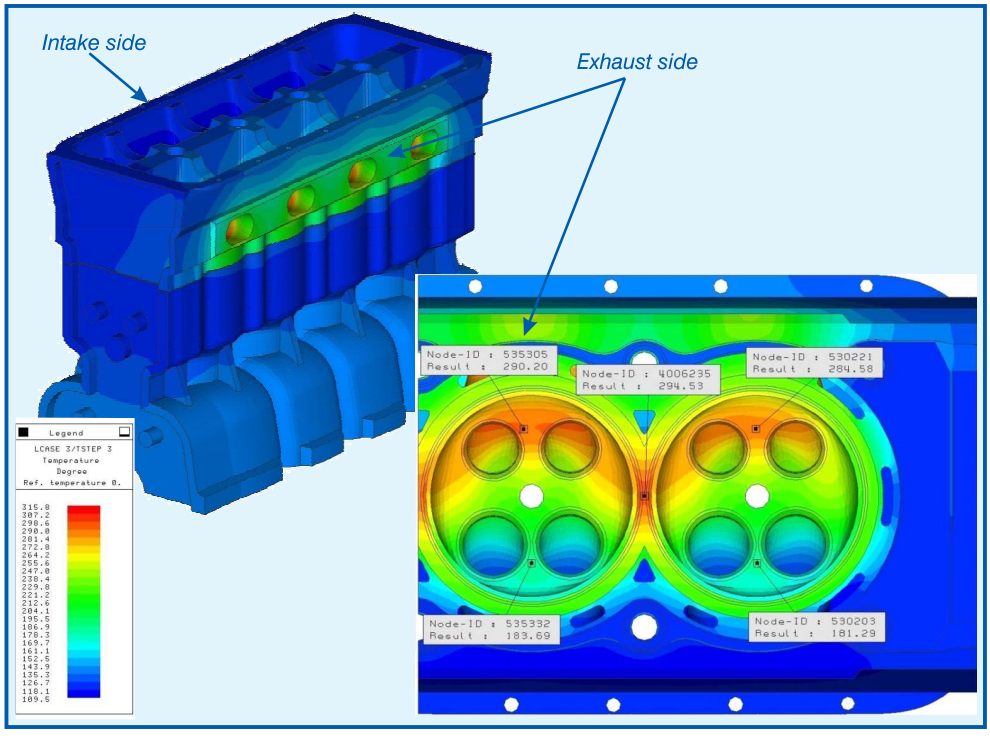

Fig. 3: Temperature distribution in the engine

3 Bolt Pretension with Compliance as Objective

The rib design under bolt pretension for compliance as objective function is shown in Fig. 4. The result were not only ribs but just systematic reinforcements below the bolts. The ribs at both ends of the design space are related to the effect of the bolts at the end of each bolt row. These bolts are not symmetrically loaded as the other bolts and would lead a bending of the engine along the lateral direction (x direction). The generated ribs work against this bending effect.

The weight constraint history show that the weight limit was not reached, i.e. the result was achieved with less weight than the original ribs.

The result shown in Fig. 4 is generated on the basis of the element filling ratio which represents the primary result of topology optimization. In addition, this result is smoothed before the image was generated.

Usually, a certain filling ratio is used to select the remaining elements. Here, it is worth mentioning that topology optimization is able to clearly generate values 0 or 1 for the filling ratio. So, the images are looking the same with both values of 0.1 and 0.9 for the filling ratio.

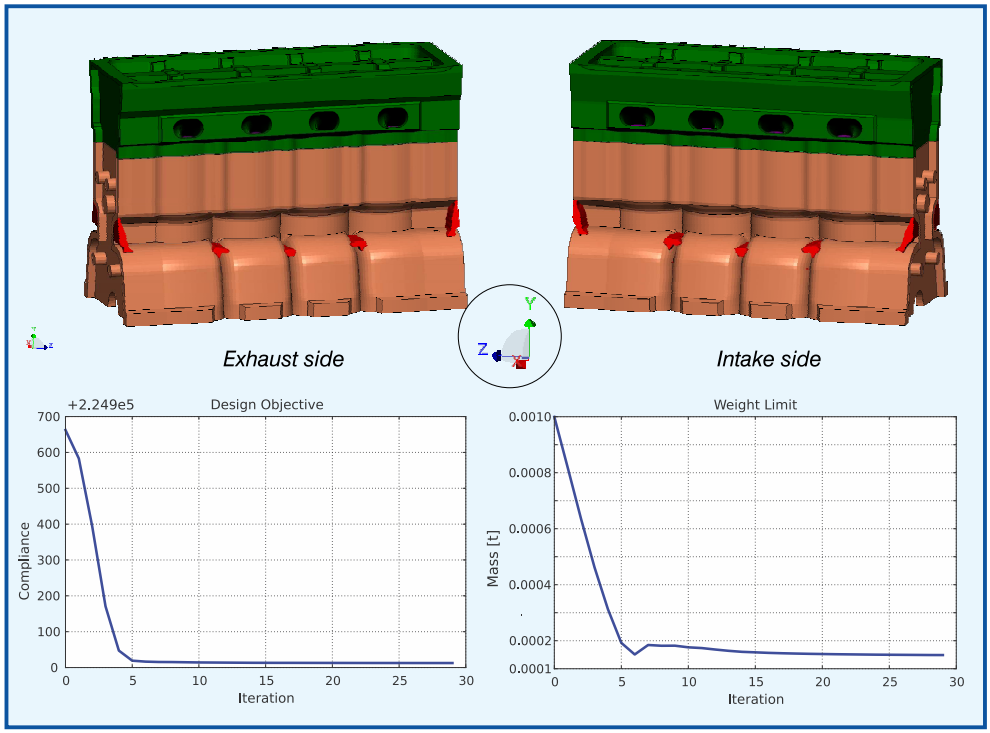

Fig. 4: Rib design under pretension with compliance as objective

4 Bolt Pretension and Temperature with Compliance as Objective

The rib design under bolt pretension and temperature with compliance as objective function is shown in Fig. 5. The result shows three ribs on the exhaust side together with similar reinforcements than with bolt pretension only. The weight constraint history shows that the weight limit was already reached, i.e. the maximum available weight has been spent to minimize compliance.

The first observation is that there are no ribs. Local reinforcements lead to a sufficient solution which fully exploits the mass which is available for the new design.

The second observation is that the resulting rib design is not the same on both sides of the engine due to different temperatures. The design is almost symmetric along one side of the engine, because bolt pretension and temperature field are almost symmetric.

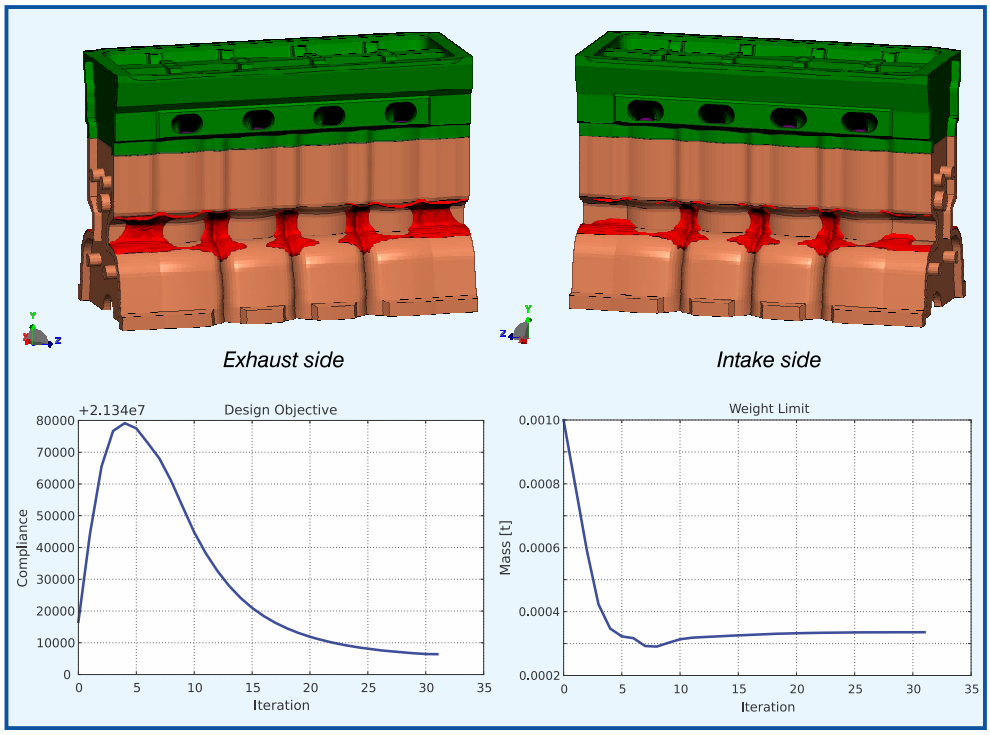

Fig. 5: Rib design under bolt pretension and temperature with compliance as objective

The displacement field of this rib design compared with the original model is shown in Fig. 6. A significant reduction of displacements is visible.

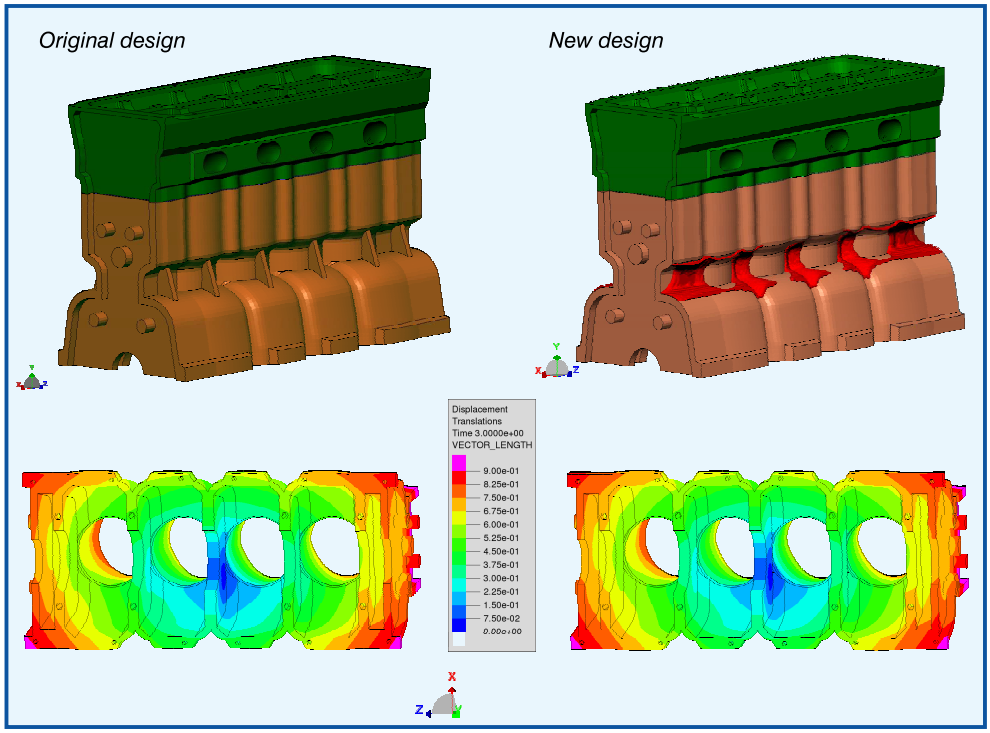

Fig. 6: Comparison of displacement field under bolt pretension and temperature with original model

A non-symmetric rib design will only be produced in case of very strong reasons. So, it is usual to expect a symmetric rib design for this symmetric engine model. Fig. 7 shows the symmetric design which is achieved using a symmetry definition by specifying the symmetry planes.

Here, the observation is that the compliance achieved with the symmetric design is somewhat higher than with the non-symmetric design. So, the stiffness of the engine with the symmetric design is not as high as the non-symmetric design. The result was expected, because additional constraints usually give a minor optimum.

The conclusion for this temperature-dominated load case is that ribs are not optimal to reduce bending due to different temperature on intake and exhaust side. Therefore, the resulting design does not show any rib.

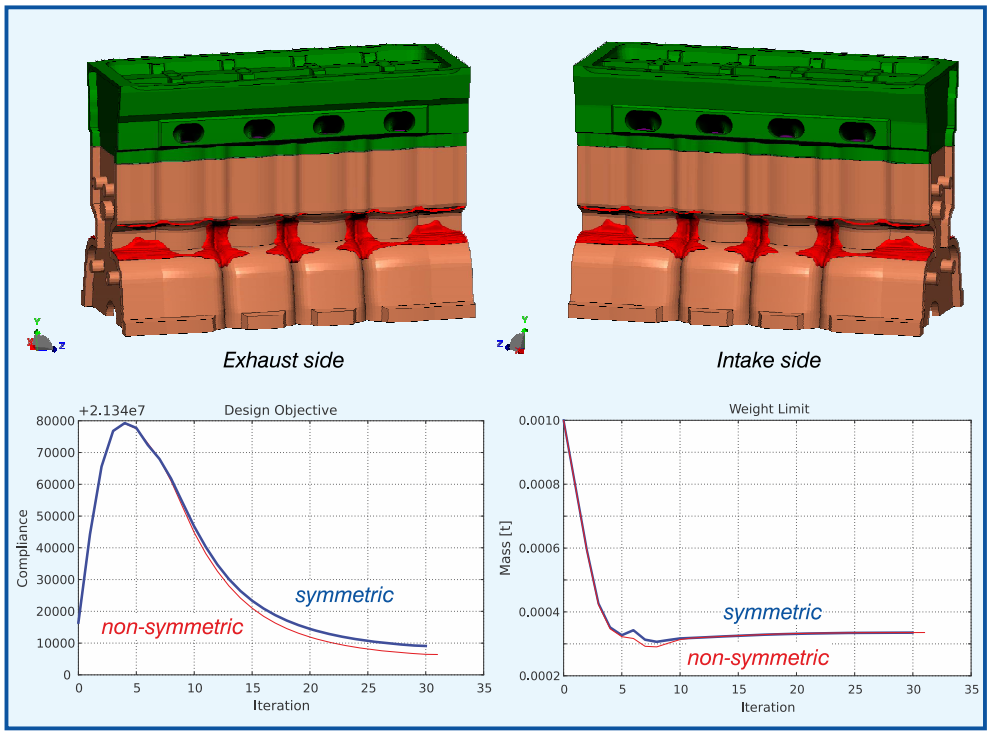

Fig. 7: Symmetric rib design under bolt pretension and temperature

5 Bolt Pretension and Temperature with Displacement as Objective

Compliance is a global criterion to describe stiffness of a structure. In case, displacements at certain nodes or relative displacements between some nodes have to fulfil given quality requirements, such local criteria could be more specific than compliance.

If we take the crankcase, one important criterion is that the center line of the crankcase remains a straight line, i.e. any bending of this center line should be reduced to a minimum. So, the objective is defined with the displacements of the five points located on the center line at each main bearing. To minimize the sum of all these displacements that is the objective of the topology optimization. Fig. 8 shows the resulting rib design. A symmetry condition was not taken into account in order to see the differences between intake and exhaust side of the engine.

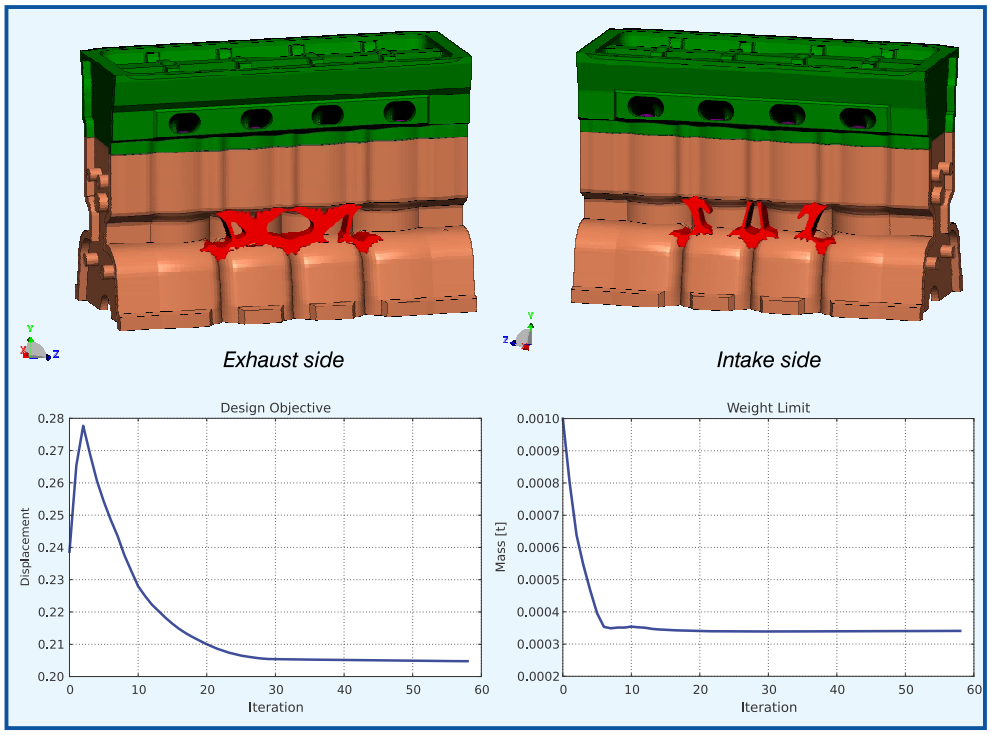

Fig. 8: Rib design under bolt pretension and temperature with displacement as objective

The effect of this rib design compared to the original design is shown in Fig. 9. There, the center line is shown in two perspectives for both designs. One perspective is looking exactly along the center line which shows the deviation from the center line. The other perspective shows the bending effect of the loading on the center line. In both perspectives, the improvements are obvious which were achieved by the new rib design.

The rib design reflects the usability of ribs to reduce bending distortions. A more general objective like compliance will try to improve the overall stiffness and cannot specifically improve a specific stiffness condition.

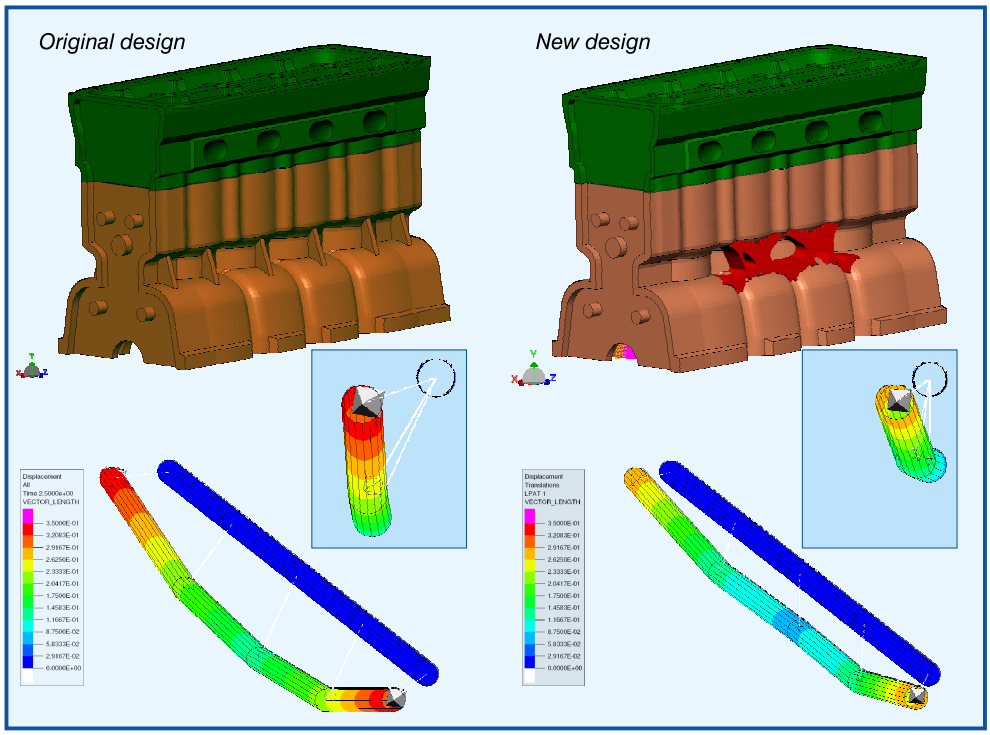

Fig. 9: Comparison of displacements at crankcase center line.

6 Conclusions

The paper demonstrates the use of topology optimization for the rib design of a crankcase in an engine model. The engine analysis takes into account nonlinear conditions for contact and nonlinear gasket material behaviour. Bolt pretension and temperature loading were taken as design loads for the rib design. Different objectives were considered like compliance and displacements.

The topology optimization used shows a very robust behaviour which clearly separates the remaining elements from the unnecessary elements. Symmetry conditions can be used to achieve a satisfactory design.

The procedure is generally applicable to other housings like transmissions. Further extensions to additional constraints like maximum or minimum member size are possible.

References

[1] *PERMAS Product Description Version 14*, INTES, Stuttgart, 2012, `http://www.intes.de/kategorie_support/download/shortdescription`

[2] *PERMAS Version 14: Users' Reference Manual*, INTES Publication No. 450, Stuttgart, 2012.

[3] *PERMAS Version 14: Examples Manual*, INTES Publication No. 550, Stuttgart, 2012.

[4] *VisPER Version 3: Users' Manual*, INTES, Stuttgart, 2012.

[5] K. Bohnert: *Development of a cockpit supporting frame from concept of design to start of production*, Proceedings 11th PERMAS Users' Conference, Heidelberg, April 2012

[6] B. Thomas, Ph. Goge, N. Rannou: *Complete optimization process on engine cooling module component*, Proceedings 11th PERMAS Users' Conference, Heidelberg, April 2012.