FEM analysis of a gearbox housing, for the calculation of stress and deflection characteristics

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Abstract: Stresses and deflections developed on gearbox housing play a crucial role in the load carrying capacity of its components, as well as the durability of the gearbox itself. Building and testing actual prototypes is a procedure that requires a considerable amount of resources (i.e. personnel, time and consequently money). On the other hand, current market needs, impose short time development cycles and cost reduction. To minimize the number of prototypes built, an initial virtual model is created (CAE) and analysed for a number of analysis cases. The above procedure, leads to an increasing need for the creation of complicated models for high simulation accuracy. More and more components are included in the models while on some studies, machine elements like gears, bearings and bolts have a detailed FE representation.

In the present study, a real case automotive gearbox housing is modelled, in order to investigate stress and deflection characteristics for a number of load cases. It incorporates the FE modeling of the housing, contacts simulation, assembly and operating conditions loading. Solution results are obtained and evaluated in accordance to the design requirements. Finally, a conclusion whether to further modify the design or proceed with building a prototype for testing is reached. The study was done utilizing ANSA pre-processor and Abaqus/Standard.

Keywords: Abaqus/Standard, ANSA, Automotive, FEM, Gearbox, Powertrain.

1. Introduction

The creation of a new automotive gearbox is a complicated and demanding operation. A gearbox is designed to withstand a specific range of load carrying capacity and drive characteristics. The first step in the design cycle is to calculate the main components like gears pairs, bearings and shafts. Following the gearbox housing is calculated. One of the requirements to be met is that the housing must be stiff enough to ensure flawless operation of the gear pairs due to the elastic deflections and vibrations of the shafts and the housing. Additionally, the housing design should also guarantee optimal behavior in durability and fatigue. Finally, the gearbox should meet the size, weight and cost restrictions imposed by the engine and the car manufacturer.

Building and testing actual prototypes is a procedure that requires a considerable amount of resources (i.e. personnel, time and consequently money). On the other hand, current market needs, impose short time development cycles and cost reduction. To minimize the number of prototypes built, first a virtual model is created (CAE) and analyzed for a number of analysis cases. From the results obtained, the engineers try to optimize the behavior of the model, by continuously modifying the design and rerunning the analysis. Only after the results are satisfactory, the first actual prototype is constructed and tested.

The above procedure, leads to an increasing need for the creation of complicated models for high simulation accuracy. More and more components are included in the models while on some studies, machine elements like gears, bearings and bolts have a detailed FE representation. Preparing a gearbox-housing model for FEM analysis is a complex and tedious process that used to require a lot of man-hours from experienced engineers and usually involved the combination of different software for each step of the simulation (mesh generation, connections, loads, model built up). All these, in combination with the ever-increasing model sizes that are necessary for realistic and accurate simulation, significantly raise the complexity of the process, making it error prone and stiff. In the last couple of years many evolutions have taken place and today there are pre-processors that offer not only the majority of these functionalities, but they incorporate them in a fully or semi-automatic way, while solvers allows us to combine all the above and give us fast and accurate results.

This study, presents the modeling of a gearbox housing for FEM analysis of stresses and deflection characteristics, realized using one pre-processor and one solver. Meshing and model build up was done using ANSA, one of the leading commercial pre-processors. The model was solved using Abaqus/Standard and following, µETA post-processor was used for viewing and evaluating the results obtained.

2. MODEL BUILD UP

Table 1: Model build up phases

Geometry Handling	- CAD data input - Erase not needed parts - Check and repair geometrical errors
Mesh	- Surface meshing - Check and fix mesh quality - Volume Meshing
Model Build Up	- Contacts / Connectors - Boundary conditions - Manipulation of solver entities - Checking of the model - Solver Header
Solve	- Solve model
Evaluate Results	

The pre-processor used for the FE model creation was ANSA version v13.0.3. The process followed through the study consists of the steps summarized in Table 1. A brief description of each step is presented in the following paragraphs.

2.1 Geometry Handling

Volkswagen AG provided the CAD input files in Pro/E format. The CAD files were directly imported into the preprocessor using an application (*CAD to ANSA Translators*), which translates native CAD data to ANSA. With the use of native Pro/E data (as opposed to exporting an intermediate neutral format like iges or step and importing the latter), apart from the geometry, the meta-data that exist in the CAD file are transferred to the pre-processor. Color and layer management done in the CAD as well as all information regarding part positioning, hierarchy, multi-instantiated parts, automatically pass in the pre-processor, so both the designer (CAD department) and the analyst (CAE department) share the same model organization, resulting in an uneventful cooperation.

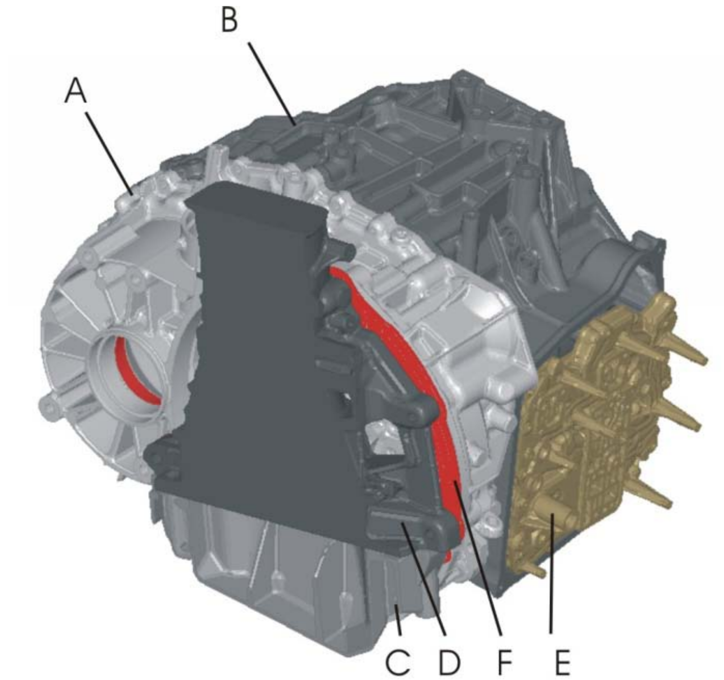

Figure 1: Parts participating in model analysis.

In the present study, only the parts that contribute to the housing stiffness are used. These are, the two cases of the gearbox (parts A, B), the engine parts where the housing is mounted (parts C, D) and some auxiliary parts bolted on the gearbox (parts E, F), Figure 1. All remaining parts were neglected alongside with the geometrical definition of the different kind of bolts. Bolts were modeled with a combination of rigid and beam elements with specific characteristics.

The last step of the geometry handling was to ensure that there was no geometrical error due to an incomplete design of a part in CAD. A check for initial penetration of the parts was also performed in case some parts had been wrongly positioned or intersected each other. In latter case, erroneous parts were either correctly positioned, or modified to ensure an intersection-free assembly.

2.2 Meshing

As mentioned earlier, in the virtual prototype development cycle (CAE cycle), after the evaluation of an analysis results, slight design modifications may be introduced to some parts to improve their behaviour. The new design must be re-evaluated and therefore the FE-model must be updated to accommodate all design changes. Furthermore, there are cases that some parts might be meshed using different set of mesh specifications. For this reason it is significant for the engineer to be able to keep track of the parts versions and the different meshes used in the model.

To maintain compatibility with the PDM system, part id and version is automatically transferred in ANSA during the CAD translation phase. Furthermore, utilizing a number or the preprocessor's features, (ANSA Data Management) [1], it is possible to monitor each part's versioning and automatically update the assembly when a new component becomes available. The product structure with all related meta-data is directly accessible, giving the user an overview of the model in-hand (parts used, versions, mesh specification), Figure 2.

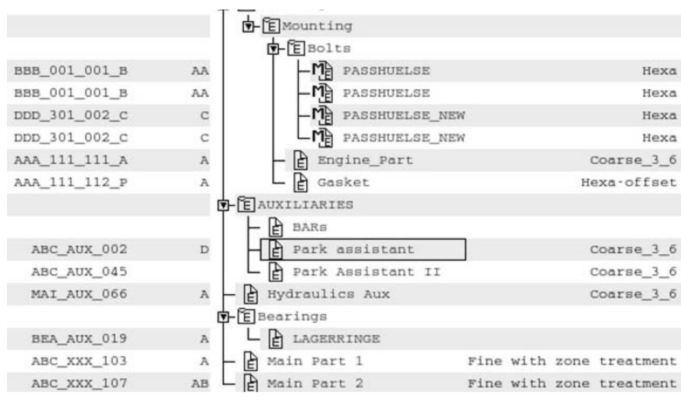

Figure 2: Model organization (*ANSA Part Manager*).

As mentioned previously, the parts included in this analysis are presented in Figure 1. Depending on the part and its position in the assembly, components were meshed using three different mesh parameters. To better simulate the gearbox housing and get more detailed results, the model was meshed with second order solid elements. To create a solid mesh of high quality, it is imperative to start from a surface mesh of also high quality. The main parts of the gearbox housing (part A, B) were surface meshed with second order triangles with a mean element length of 3.5 mm. In order to keep the total number of elements low, parts C, D and E that only contribute to the stiffness, and we are not interested in the stresses developed on them, were meshed with second order triangles with target element length of 4.5 mm. Gaskets and pins were meshed using hexahedral elements. The different mesh types used in the analysis are summarized in Table 2.

Table 2: Mesh specifications used

No	Mean Length	Surface Mesh	Solid Mesh	Parts
Fine	3.5 mm	Triangles (STRIA65)	Tetras (C3D10M)	A, B
Coarse	4.5 mm	Triangles (STRIA65)	Tetras (C3D10M)	C, D, E
Hexa	3 mm	Quads (S4)	Hexas (C3D8)	F

In order to obtain the best ratio of quality versus time spend, surface mesh of all parts was performed using ANSA automatic mesh creation tool (Batch Meshing) [2]. With Batch Meshing the user specifies the required mesh characteristics and the quality criteria that the resulting mesh has to meet and ANSA automatically generates a mesh of the prescribed quality. Since no fully automatic procedure is able to guarantee a result with zero elements violating the quality criteria, after batch mesh is finished, the generated mesh is inspected and any remaining violating elements are automatically isolated and manually corrected. This is necessary because most solvers accept a limited number of elements below a quality threshold and in the case that this number is exceeded the solver either stops completely or the calculated results are of poor quality.

Having finished with the surface mesh improvement, the next step is the generation of the solid mesh. Since all parts have a 3D geometrical definition, the definition of the volumes, and the generation of the solid elements are made automatically. As a last step any violating solids are corrected by the user, to comply with the mesh specification imposed by the solver and analysis type. The total number of elements per part and the time spend for the automatic creation of the mesh is summarized in Table 3.

Table 3: Element per part and time needed for automatic creation of the mesh

Parts	Surface	Solid	Automatic (h:min)	Manual (h:min)
A	199 998	757 560	0:12	1:30
B	237 028	627 478	0:15	1:45
C	25 962	167 034	0:02	0:10
D	16 184	37 776	0:01	0:10
E	4 425	4 425	0:01	0:30
F	31 112	52 348	0:06	0:05
Total	~516 000	~1 515 000	0:37	4:10

2.3 Bolt Modelling

In the gearbox assembly, all parts, except the bearings, are connected using bolts. The bolts are modeled using a combination of beams and rigid elements. For the thread length of the bolt in contact with the hole thread, as well as the bolt head, rigid elements (*MPC) are used. The free body of the bolt, the part between the head and the thread rigid elements, is modeled with a beam combination (three B31 beams). These beams have section characteristics imposed from the actual bolt while a pre-tension entity (*PRE-TENSION SECTION) is also applied in one of the beams to correctly simulate the bolt connection. The beam characteristics and pre-tension values, for each bolt type, are summarized in Table 4.

Table 4: Bolt characteristics

Bolt type	Radius (mm)	Pretension (N)
M6 (9 pcs)	2.53	9 000
M8 (26 pcs)	3.41	17 361
M10 (3 pcs)	4.30	25 526
M12 (5 pcs)	5.18	41 400

Creation of the bolts presented two difficulties. The first was that the model had four different bolt types at 43 various locations. The second was that during the various phases of the analysis some parts had to be replaced by new or updated versions. The bolt connections representation would have to be recreated and adapted to the new design every time there was a part update.

The above problems were solved using a number of automatic features of ANSA. For each bolt type an ANSA Connector Entity [3] was created. The characteristic of such entities is that they hold information regarding the connected parts, the “representation” element to be generated and the “interface” elements; i.e. the intermediate elements between the representation and the connected parts. In this application the representation elements was the beam and the interfaces were the rigid elements. Each ANSA Connector Entity created consists of two parts. One part creates the rigid element that represents the thread in contact and the other creates the bolt head MPC, connects it using the beam elements to the MPC of the thread and applies the desired pre-tension to the beam. In this way, the user has to only define a Connector Entity for each bolt type. Following, the defined connector is copied to all the needed positions either manually or via a script (that reads a list with the locations coordinates) and in the end all connectors are automatically realized. During realization, ANSA identifies for each connector the proper nodes from the participating parts and creates the desired connection representation. The resulting bolt modelling is presented in Figure 3. At this point it must be noted that the creation of the ANSA Connector entities is done only once during the initial model creation.

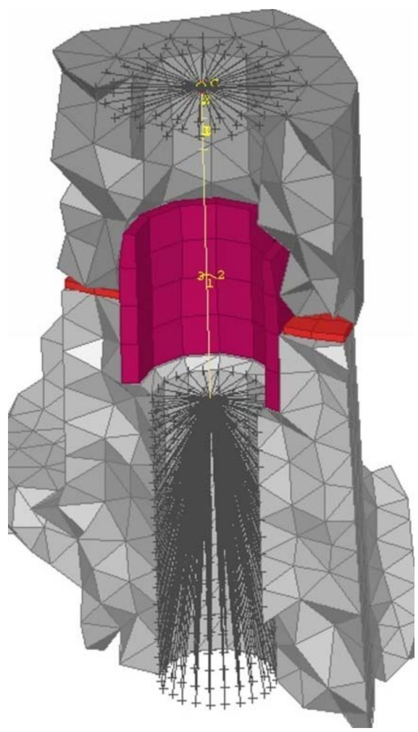

Figure 3: Bolt representation

2.4 Contact definition

To correctly simulate the behaviour of the bearings that are pressed in the bores of the housing, tie contacts (*TIE) have been created between each bore and the corresponding bearing.
A tie contact is a boundary condition used by solvers to connect nodes from one surface to elements of the other in order to restrict any movement between them. The tie contact as shown in

Figure 4 is defined between the outer solid face of the bearing and the solid face of the housing bore.

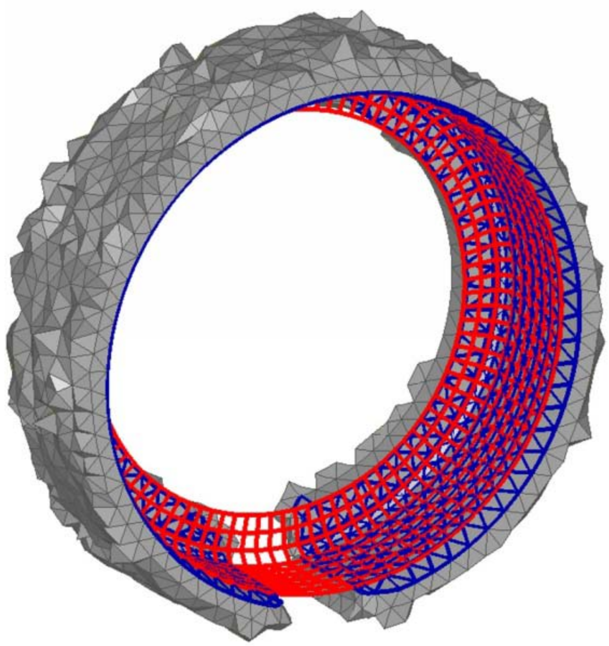

Figure 4: Tied definition between bearing and hole.

For the part pairs connected by bolts, contact definitions are created (*CONTACT PAIR), Figure 5. Contact definitions prevent the penetration of elements of one part into elements of the other, due to deflection. A friction model was also defined for the contact to represent the friction developed during sliding between the two parts. In the present study a simple friction model was used with a constant friction coefficient value of 0.1. Even if during the meshing phase the model was checked and fixed for initial penetrations a clearance value (*CLEARANCE) was also specified in the contact pairs to ensure no penetrations are present at the beginning of the simulation.

During model built up the user must be careful how to use contacts definitions or tie since it greatly influences model solution. For example, in reality part F (a gasket) is used to prevent direct contact of the gearbox (part A) to the engine (parts C and D), is kept in its place due to the pretension of the bolts that hold parts A and C together. If this is simulated via two contact definitions then solution will stop since part F at the beginning of the simulation will be considered as not connected to the rest of the model. To overcome that, these cases were modeled using a combination of one tie and one contact definition. The tie connects one side of part F to part A (ensuring that part F is not free) and the contact definition is used to prevent intersections between F and parts C - D. The above was used for the retaining pins, and the gaskets / flanges.

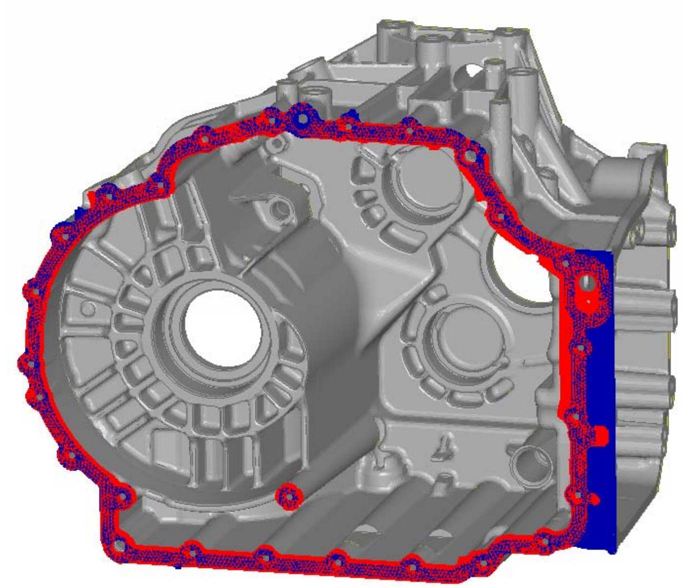

Figure 5: Contact definition between the two main parts.

2.5 Boundary conditions

Figure 6 shows the mounting boundary conditions of the gearbox housing. The housing is fixed at five positions, which represent the mounting of the gearbox to the engine. At each of the five positions an edge is selected and all the nodes on that edge have their translational (x, y, z) degrees of freedom fixed (*BOUNDARY) during solution, Figure 7.

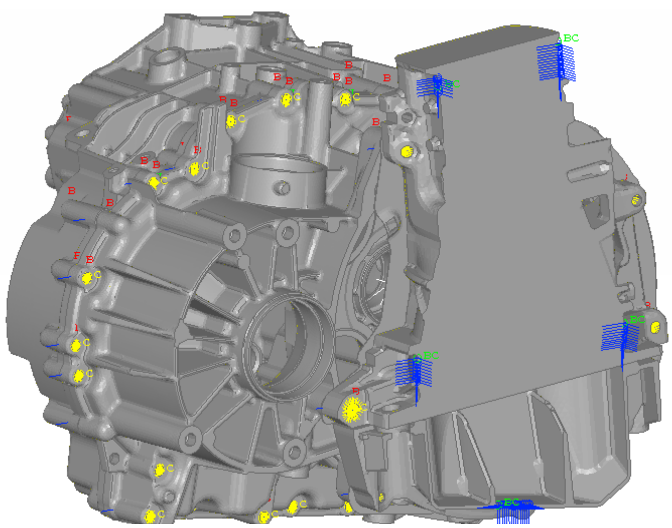

Figure 6: Mounting boundary conditions.

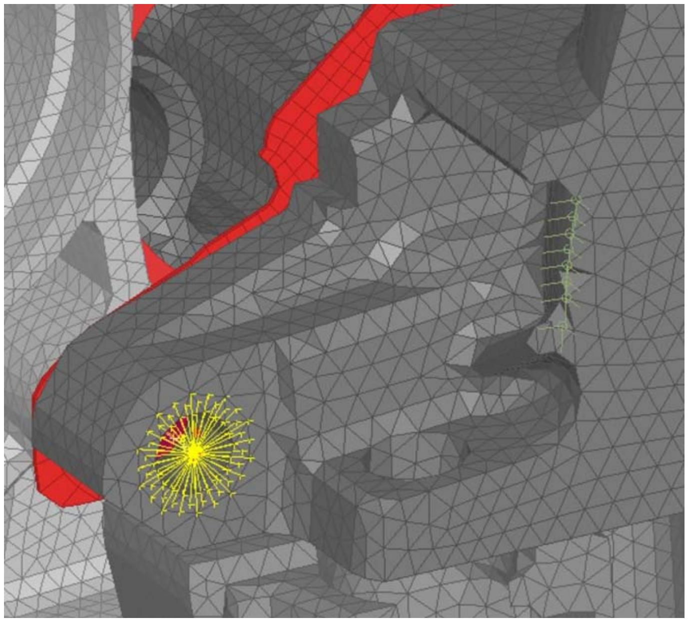

Figure 7: Fixed nodes in x, y, z directions.

2.6 Part replacement - Version Update

The development of a new gearbox is usually based on an already existing design. Old parts are re-designed in order to comply with the new requirements or completely new parts are introduced. This process is repeated many times throughout the development cycle. So, the analyst has to continually update his model with the new versions of the parts. Furthermore, when changing a part, he also has to re-apply all boundary conditions, loads, connection entities, and update previously defined grouping of entities, i.e. sets of elements that are used by contact definitions (*SURFACE). This was taken into account when the housing model was created. Connectors entities were used for bolts, while for the boundary conditions and the contacts set definition special ANSA entities were used that allow the automatic recreation of these entities if any change occurs.

When a new part becomes available, the user should execute the following steps. Start with meshing the new / updated part using batch meshing, and then continue with the manual repair of any remaining violating elements. Then, through ANSA Parts Manager replace the existing part with the new version. Any dependent entities of the outgoing component are automatically applied on the new the part. Connectors, boundary conditions (generic entity builders) [3] and contact definition sets are automatically recreated using the nodes / elements of the new part. When the procedure is over, a report of any failed operation is printed and the user knows those areas / cases that need further treatment.

2.7 Load cases

To examine the stresses and deflections characteristics of the gearbox housing, the following cases have to be investigated: For every gear pair two cases, one for acceleration and a second for deceleration. This is done for all seven gear pairs, for the reverse, as well as for parking uphill and downhill. Summing the above cases result in a total of 18 different loads cases.

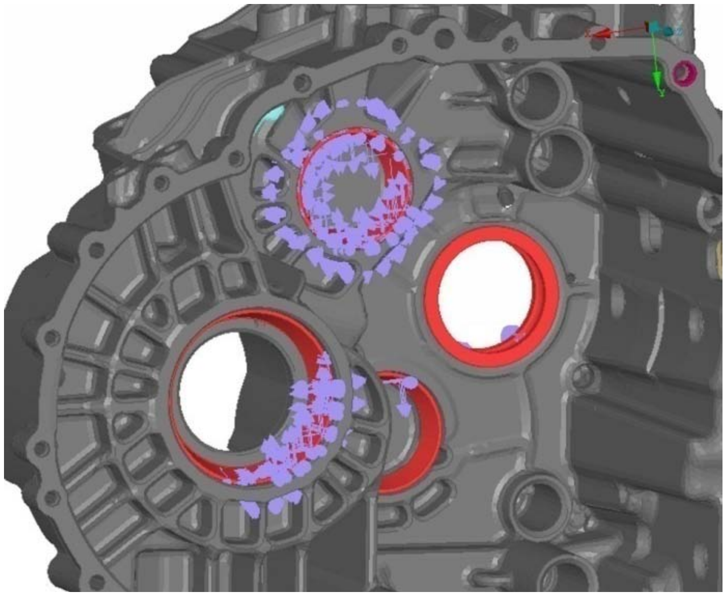

Figure 8: External forces on the bearings.

For the gearbox housing calculation, as mentioned earlier, gear pairs, shafts and bearing's inner rings are not included in the model. The loads (*CLOAD) are applied on the inner solid face of the bearing outer rings as shown in Figure 8 and are the reaction forces developed at the bearings on each load case.

These reaction forces are previously calculated using a simulation software for the 18 load cases. This simulation software is supplied with the design characteristics of the gears, shafts, bearings, the stiffness characteristics of the participating parts as well as the external loads of the gearbox and calculates the reaction forces on bearings rings for each load case.

The fact that the shafts and all the components mounted on them are not included in the model means that the same model of the housing can be used for all 18 calculations by simply changing the applied loads (loading step).

3. Results and Discussion

3.1 Solution

Abaqus/Standard v6.8-3 [4] was used to solve the model. Solution was made into two stages (steps).

The first (STEP 1) simulates the gearbox before loading due to operation, when only bolt pretension and initial boundary conditions are present. This step is made in order to calculate the stresses and deflection of the gearbox casing due to the bolts pretension. Since this stage is common for all loadcases it was calculated only once and the results derived were used then for each loadcase. As mentioned above the model consisted of 1.5 million second order tetras (C3D10) which resulted in a 350 MB Abaqus input deck. A 16 cpus cluster was used to solve this step. The step was solved in only one increment to keep the output file as small as possible. The results were obtained after 8 hours and the size of the file was 1.4 GB, Table 5.

Table 5: Solution steps information

Step	No. of cpus	Time (hours)	Input file	Results size
Step 1 (Pretention)	16	8	350 MB	~ 1 400 MB
Step 2 (loadcase)	32	3.5	*Restart step 1*	~ 1 400 MB

Since contacts and pretensions have been established in the initial step (Step 1) restarts were made from these results, for each loadcase, resulting in a STEP for a each of the 18 different loadcases. To further speed up solution, a 32 cpu cluster was used, resulting in lowering the time needed for each step to 3.5 hours. Again the size of each result file was around 1.4 GB, Table 5.

3.2 Results

As mentioned above, the first step simulates the gearbox before loading, when only bolt pretension and boundary conditions are present. Due to the bolts pretension, stresses are developed around the bolt holes and the contact interfaces, Figure 9.

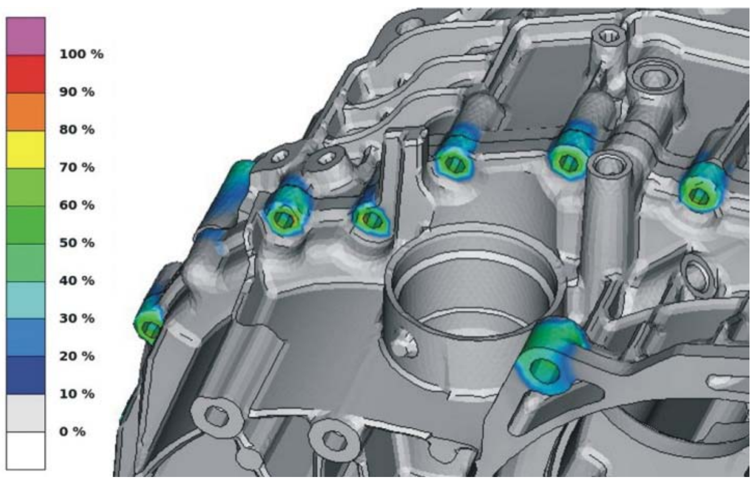

Figure 9: Calculation of the stress due to the bolts pretension (Step 1).

Following, based on the results of the first step, each loadcase is applied (loads on the bearing rings) and the calculation continues to obtain the final stresses developed on the gearbox housing, Figure 10. In this way the model better simulates the reality since the gearbox is first assembled and mounted on the engine, developing stresses due to the bolts pretension (Step 1), and finally is loaded during engine operation (Step 2).

The results presented for Step 2 are for full acceleration using the first gear pair of the gearbox.

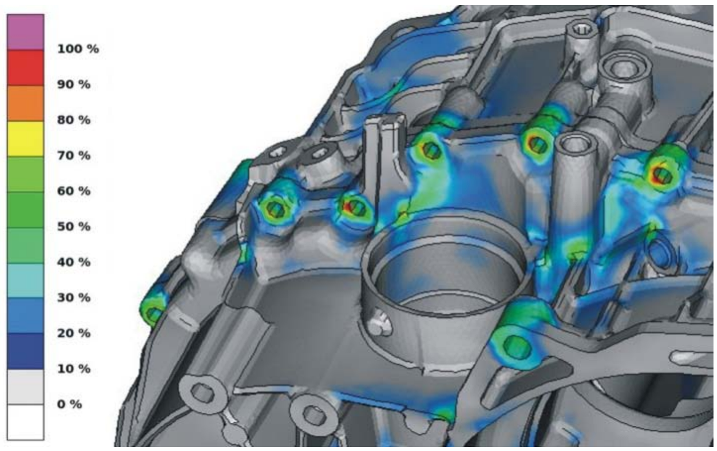

Figure 10: Von Misses stresses developed on housing (Step 2).

In Figure 11, the Von Misses stresses developed on the gearbox housing are shown. In the bigger part of the housing, stresses have a value lower than 25% of the tensile strength limit. At areas around bearing bores where usually cracks are developed due to high stresses, the values encountered are around 65% of the material's tensile strength limit (100%).

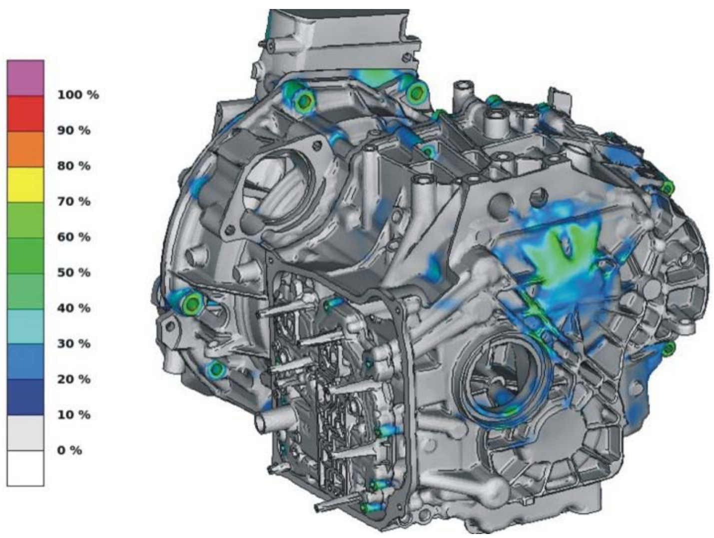

Figure 11: High stresses developed near bearing housings (Step 2).

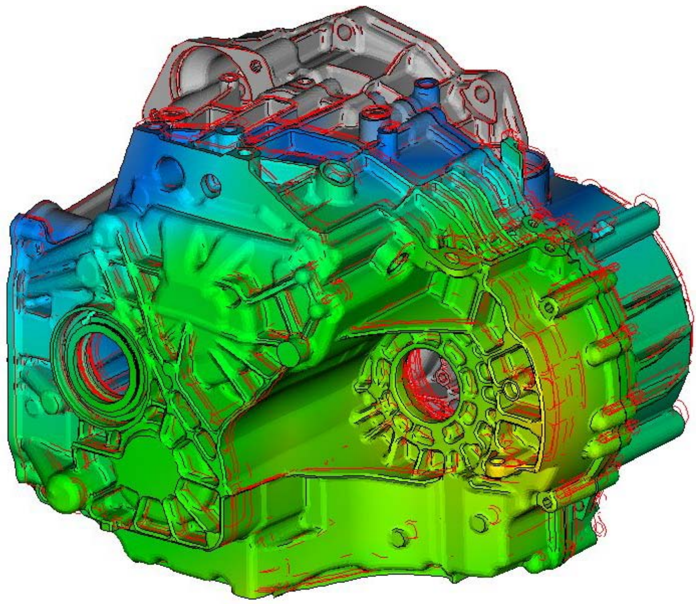

Figure 12: Deformation of the gearbox housing.

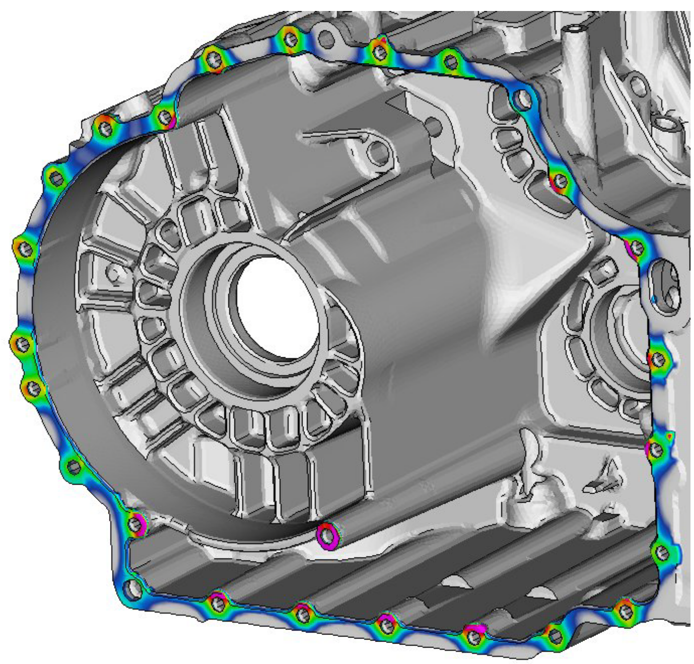

Figure 13: Contact Pressures after Step 1 (pretension).

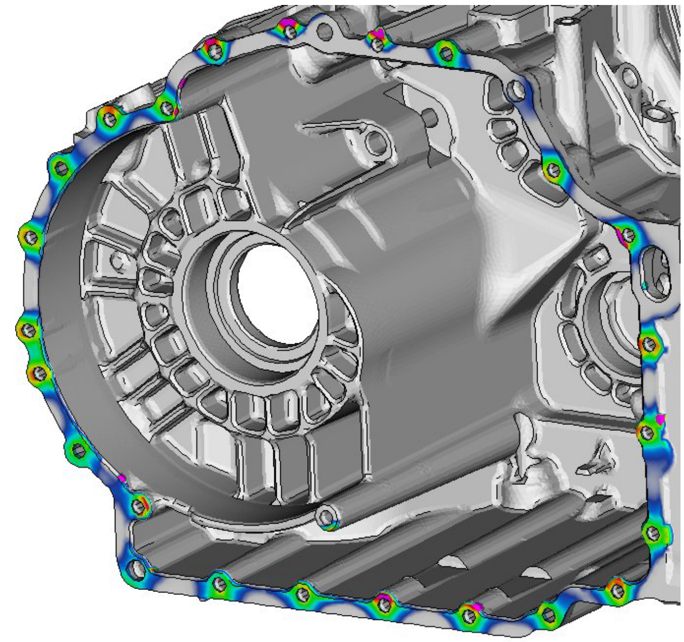

Figure 14: Contact Pressures after Step 2 (loading).

In Figure 12 the deformed over the undeformed (wire frame) housing is presented. The calculations also show that, the highest eccentricity of a pair of bearings centers, due to the housing deflections, is within the designer's tolerances.

Another problem encountered in gearboxes is that due to elastic deflection of the housing there is the chance that two parts might be separated, and let the lubricant escape. This will, eventual lead to the failing of the enclosed machine elements (gears, bearings) due to lack of lubrication. For this reason, the value of the contact pressures between the parts is very important. In Figure 13 the contact pressures developed between part A and part B are shown as a result only of the bolt pretension loading. The contact pressures are evenly distributed on the contact area getting maximum values around the bolt holes. As a result of the external loads, Figure 14, the contact pressure distribution changes. This leads to higher contact pressures in lower part of the contact area and lower pressures on the upper region. The values also show that separation of the two parts under load is avoided.

4. Conclusion

In this study the modeling of a gearbox housing for FEM analysis of stress and deflection characteristics was presented. The model was created using the ANSA pre-processing software. The model set-up was done in such a way to support fast and accurate synchronization of the CAE model with CAD updates, and easy application of the forces for the 18 different load cases.

The gearbox model was solved using Abaqus/Standard v6.83. Solution was conducted into two steps. The first simulated the pretention of the bolts. The second step simulated each loadcase. Each loadcase step differed only in the applied loads and it used the results obtained from the first step (*RESTART). Complete analysis of all 18 loadcases took 63 hours (3.5 hours x 18 = 63) for a model that consisted of 1.5 million, tetras (C3D10M), and 16 TIE orCONTACT pairs.

Stresses and deflections characteristics were calculated for all cases, while the results for the first load case (full power acceleration of the first gear) were also presented in this study.

5. ACKNOWLEDGEMENTS

The authors would like to thank Volkswagen AG for the support given throughout this work and for granting permission to publish this study.

6. References

1. Makropoulou I., Kiouptsidis K., Skolarikis K. “Capturing the best practices for the organization and analysis of crash-test simulation load-cases.” Proc of the 2nd ANSA & μETA INTERNATIONAL CONGRESS,Chalkidiki 2007
2. Saltiel S.-T., Tryfonidis M.. F2006M141: Latest Developments in CAE Process Automation: An Insight into Batch Meshing of BiW Models, FISITA 2006, Yokohama 2006.
3. ANSA v13.0.3 User’s Guide, BETA-CAE Systems S.A., 2009.
4. Abaqus/Standard version 6.8 Documentation, Simulia