Automated systematic strength calculation of high duty bolted joints

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FE modeling of high duty bolted joints, such as those found in wind-turbines, is in many aspects a very complex task. On the one hand, the bolt analysis must comply with standardized guidelines, such as VDI 2230. On the other hand, FE models are usually highly detailed and contain a large number of bolt connections. This makes the whole design process error-prone and cumbersome for the FE engineer, since modeling all these connections by hand usually takes a large amount of time and diligence.

Schaeffler Bolt Studio comprises a set of tools, which supports FE Engineers in the design process. With the Abaqus kernel interface, an integrated tool for the automated creation of bolt connections has been developed, which is based on recent research at the Schaeffler Group and the above mentioned guideline. The tool operates on standardized data and offers the possibility of creating bolt connections and all the necessary load cases in a minimum of time, making the model ready for strength analysis. Furthermore, several post-processing tools help the engineer to interpret the results and perform further calculations with the data gained from FE.

1. Introduction

Since the Schaeffler Group is one of the largest suppliers of the automotive and industrial sector, innovation is an important part of the corporate identity. Today, the Schaeffler Group not only acts as a component supplier, but also as a development partner, offering calculation services which cover the complete system. Of course, this also requires a high level of expertise concerning the design and calculation process of various connecting elements. In particular, the calculation of high duty bolted joints such as those, found in wind turbines, is a very complex task.

The guideline VDI 2230 Part 1 is an internationally recognized standard work for the systematic calculation of high duty bolted joints. It provides the engineer with a systematic procedure for the design process of bolted joints in accordance with ISO. While this procedure is sufficient for simple bolted joints, as shown in Figure 1, the calculation of more complex bolted connections requires the use of FEM. The recently published guideline VDI 2230 Part 2 covers this topic and explains how to use FEM to complement the calculation steps presented in Part 1.

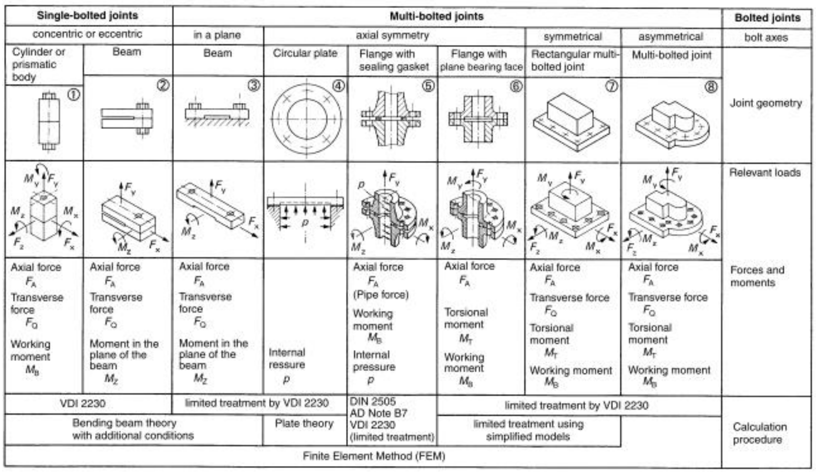


Figure 1. Overview of bolted joints [1]

Within the Schaeffler Group, several tools have been developed to standardize the design process of multi-bolted joints according to both parts of the afore mentioned guideline. While all analytical calculations are based on the recommendations of Part 1 of the guideline, the toolset also comprises an Abaqus plug-in, which automates the creation of multi-bolted connections for Abaqus FE models. The Plug-in is based on Part 2 of the guideline.

The toolset is known as “Schaeffler Bolt Studio” within the Company and, will also be referred by this name in this paper. Schaeffler Bolt Studio also contains a standalone program with a preprocessing module (“Analytical Module”) and a post processing module (“Calculation Module”) - Figure 2 gives an overview of the program modules.

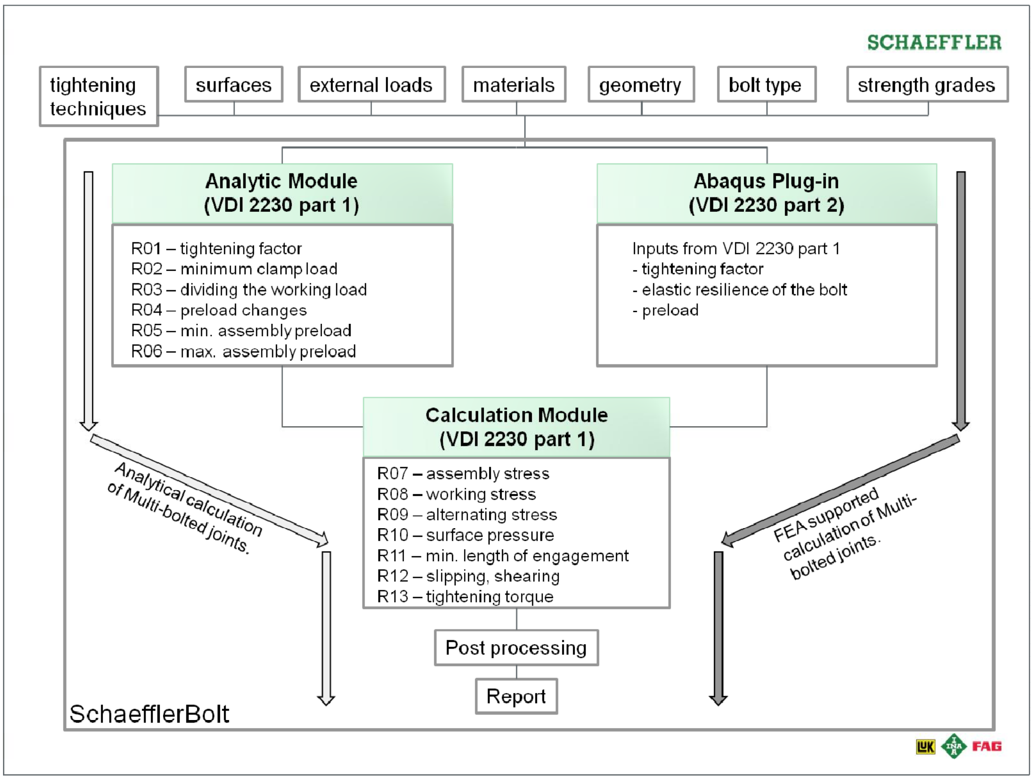


Figure 2 Program overview of Schaeffler Bolt Studio

2. Theoretical background

2.1 Calculation steps

The VDI 2230 Part 1 guideline lists 14 calculation steps which cover the assembly process as well as the working case, including strength verifications. Schaeffler Bolt Studio covers these calculation steps, which form the basis of the design process of bolt connections.

R0: nominal diameter, limiting measurement d, G

R1: tightening factor α_A

R2: minimum clamp load F_{Kerf}

R3: dividing the working load/load factor F_{SA}, F_{PA}, ϕ

R4: preload changes $F_Z, \Delta F'_{ZVth}$

R5: minimum assembly preload $F_{M\,min}$

R6: maximum assembly preload $F_{M\,max}$

R7: assembly stress $\sigma_{red,M}$, F_{Mzul}

R8: working stress $\sigma_{red,B}$, S_F

R9: alternating stress σ_a , $\sigma_{ab,}$ S_D

R10: surface pressure p_{max} , S_P

R11: minimum length of engagement $m_{meff\,min}$

R12: slipping, shearing S_G , τ_{Qmax}

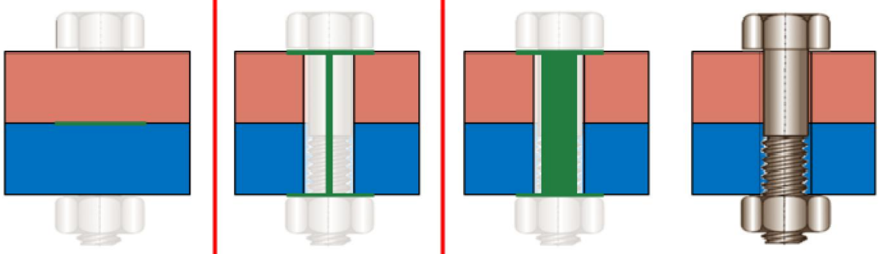
R13: tightening torque M_A

2.2 Usage of FEM

The usage of FEM allows a wider range of application, since it avoids many limitations of the VDI 2230 guideline Part1 such as gaping and size limitations of the interface area. Furthermore, nonlinearities concerning boundary conditions, material behavior and geometry can also be taken into consideration.

2.3 Bolt model

The VDI 2230 guideline Part 2 proposes four model classes, which can be used according to the necessary level of detail of the study (see Figure 3). An extensive benchmarking study between the four model classes has been carried out. As a result, model class II was selected as a standardized bolt model, since this class provides the best results in terms of calculation effort and results quality. The parameters required for this model, such as the tightening factor or assembly preload, can be calculated analytically with the Schaeffler Bolt preprocessor module according to the calculation steps R0-R6.



	model class I	model class II	model class III	model class IV
Idealization	Screw and interface are ignored (preload force is not taken into account)	Screw will be modeled as a beam. (Preload an contact in the interface can be considered)	Screw will be modeled as a substitute volume. (Preload an contact in the interface can be considered)	Screw will be modeled in detail. Inclusive thread, preload and contact in the interface.
Output	Reaction loads in the interface will be use as input for a calculation according VDI 2230 Sheet 1.	Section loads of the beam will be use as input for a calculation according VDI 2230 Sheet 1.	Section loads and stress of the substitute volume will be use as input for a calculation according VDI 2230 Sheet 1.	Section loads of the bolt. Local stress at the bolt ard clamped area.

Figure 3 Model classes according to VDI 2230 Part 2 [2]

3. Schaeffler Bolt

Figure 4 gives an overview of the different calculation tools and the corresponding calculation steps. The toolset consists of an Abaqus Plug-in and a standalone program with modules for the pre and post processing and the results export.

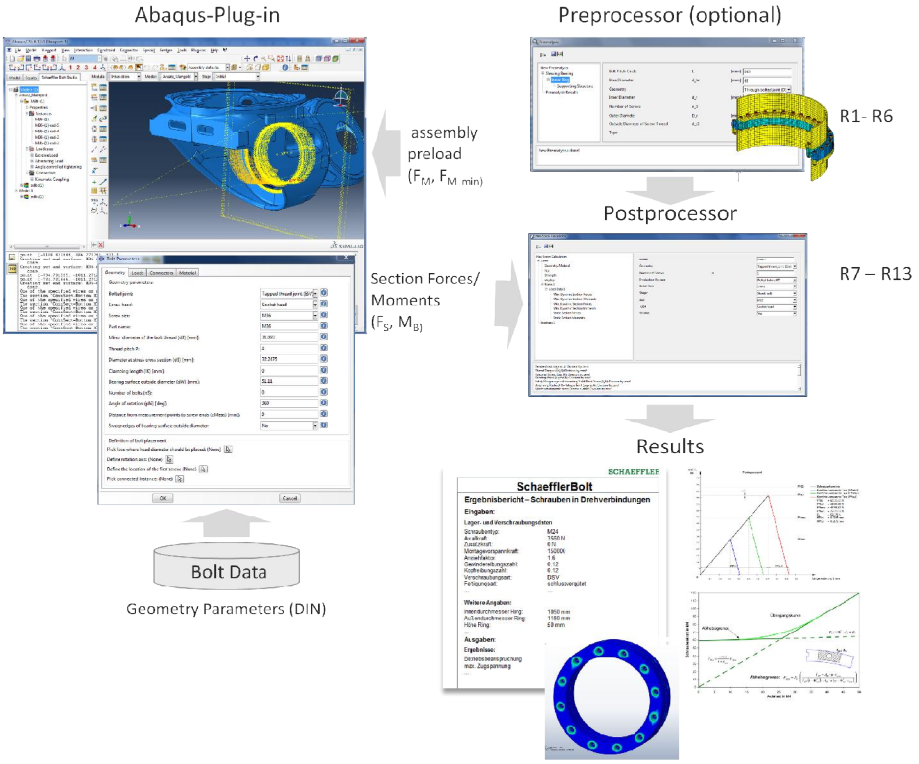


Figure 4 Schaeffler Bolt overview

The calculation steps R0 – R6 are covered by the preprocessing module. The calculated assembly preload serves as an input for the Abaqus Plug-in.

The Abaqus Plug-in automates the process of building one or more multi-bolted joints in an existing Abaqus FE model. The Plug-in also generates the necessary load cases for calculating section forces and moments. The FE results can be loaded in the postprocessor, which performs calculation steps R7 to R13. Finally, several results documents are generated by the postprocessor, containing an overview of the input data, the calculated results per screw and joint diagrams.

Additionally, the bolt results are imported and displayed in the Abaqus .odb-database as field output results.

The Abaqus Plug-in and the .odb results generator have been developed with the Abaqus Scripting and the Abaqus GUI interface, which are based on the programming language Python and the GUI toolkit FOX. The latter was also used for the pre- and postprocessor modules. The results generator has been developed with the Microsoft .Net framework.

3.1 Precalculations

The preprocessor performs the calculation steps R0 to R6. The most important results are the tightening factor α_A and the minimum and maximum assembly preload forces $F_{M\,min}$ and $F_{M\,max}$, which serve as inputs for the Abaqus Plug-in. Furthermore, the minimum clamp load F_{Kerf} is calculated, which is necessary for the calculation of the safety margin against slipping in step R12.

Additionally, the preprocessor contains a module for calculating the working diameter and eccentricity of the bolt connection for slewing bearings according to the geometry of the supporting structure of the bearing.

3.2 Abaqus Plug-in

The Abaqus Plug-In for Schaeffler Bolt was developed from the perspective of standardizing the FE analysis within the design process of bolt connections . Furthermore, the creation of the bolted joints is also automated to a high degree, which makes the design process less time consuming and error-prone.

The Plug-in is loaded automatically when starting up Abaqus/CAE. The program provides a graphical user interface, which makes it possible to define and place a new multi-bolt joint within the model. All geometry and resilience data can be loaded from a database according to the standardized bolt sizes M6 to M68 (DIN). The program user can position the bolt connection by selecting the corresponding surfaces. In addition, predefined load cases are created according to the given input parameters.

After having performed the FE analysis, the results data can be exported and loaded into the postprocessor module.

The bolt model used by the Plug-in is idealized as a beam element, which is shown in Figure 5. For through bolted joints (right) the length of the beam corresponds with the clamp length. For the modeling of tapped thread joints (left) the beam is extended by a small amount according to the thread pitch.

To reproduce the elastic resilience of the shaft correctly, a substitute diameter is calculated and assigned to the beam. Furthermore, the elastic resilience of the screw head and thread area are computed according to geometry and material information and assigned to connector elements at the screw head and thread. The connection with the surrounding structure is represented by rigid connections between the connector elements and the solid environment. All geometry and resilience parameters are loaded from the connected database, which makes the modeling process easier and safer for the program user.

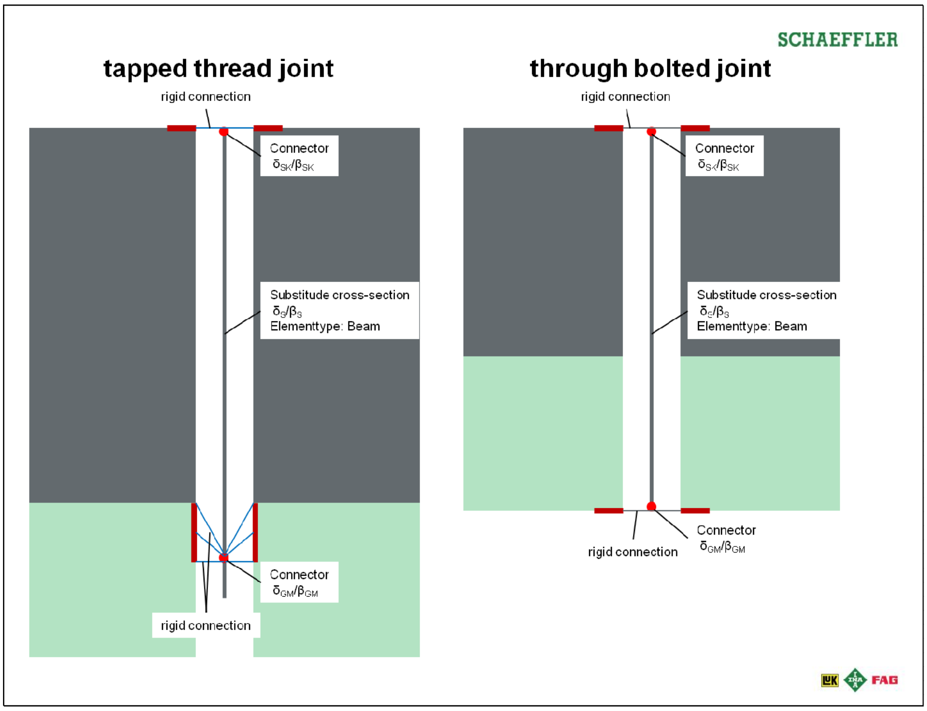


Figure 5 Bolt model

The assembly process is modeled as angle-controlled tightening. Furthermore, two load cases for simulating the working load and an alternating load are created. Both the preload distance and the elastic resilience of the bolt are taken into consideration.

After the calculation has been performed, the Plug-in offers the possibility of exporting the results to the postprocessor.

3.3 Postprocessing

The post processing module performs the calculation steps R7 to R14. Load data can either be imported from FE using the Abaqus Plug-in or from analytical calculations with the preprocessor.

The calculated results serve as inputs for the results generator, which creates standardized reports, listing the input data and the results from the calculation steps R0 to R14. The output files also contain diagrams of the joint and forces. Furthermore, the results can be imported in the Abaqus .odb-file as field output.

4. Example of use

Schaeffler Bolt is optimized for multi-bolted joints in rotationally symmetrical components such as those found in a bearing test rig (Figure 6). In particular, flange connections, which are commonly used in large bearings of wind turbines, have a significant number of screws. A number of 100 screws or more per flange is not uncommon. The automated generation and analysis of bolted joints saves an enormous amount of time and cost. Furthermore, potential errors are minimized through the automated and standardized approach.

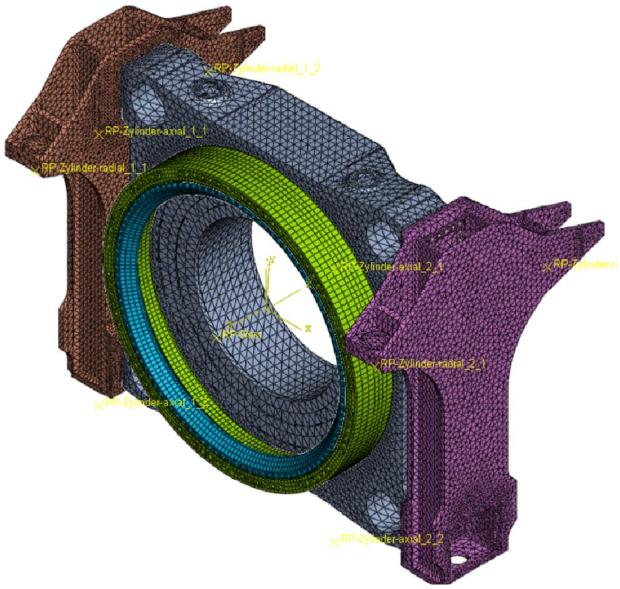


Figure 6 Sample model bearing test rig

5. Conclusion

With the developed toolset, the design process of bolt connections has been standardized and automated to a high degree. The creation of large bolt connections in Abaqus FE models can be achieved in a very short space of time instead of several hours, especially if the Abaqus Plug-in is used. Furthermore, errors are minimized by automating the modeling process and by ensuring data consistency.

6. References

1. VDI-Richtlinie 2230 Part 1, “Systematic calculation of high duty bolted joints – Joints with one cylindrical bolt”, Verein Deutscher Ingenieure, Düsseldorf, February 2003.

2. VDI-Richtlinie 2230 Part 2, (Greenprint) “Systematic calculation of high duty bolted joints – Joints with several cylindrical bolts”, Verein Deutscher Ingenieure, Düsseldorf, November 2011.