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PREFACE

Ladies and gentlemen, dear colleagues,

Welcome to Vrnjačka Banja, to the International Scientific Conference Heavy Machinery. The first conference was held in 1993, so this is the thirtieth anniversary of the Heavy Machinery conference.

This year the Eleventh International Conference Heavy Machinery is held by the Faculty of Mechanical and Civil Engineering in Kraljevo, University of Kragujevac, from 21 to 24 June 2023.

The conference has gained a unique recognizable form of exchange of information, ideas and new scientific research. It is held in the year when the Faculty of Mechanical and Civil Engineering in Kraljevo celebrates 63 years of university teaching.

During several decades of its existence, the Faculty has acquired a specific and recognizable form in domestic and foreign scientific circles thanks to its scientific and research results.

The goal of the Conference is to make the research in the fields covered at the Faculty of Mechanical and Civil Engineering in Kraljevo available and applicable within both domestic and foreign frames. Also, our scientists will have the opportunity to learn about the results of research done by their colleagues from abroad in the fields of transport design in industry, energy control, production technologies, and civil engineering through the following thematic sessions:

- Earth-moving and transportation machinery,
- Railway engineering,
- Production technologies,
- Automatic control and fluid technique,
- Applied mechanics,
- Thermal technique and environment protection,
- Civil engineering.

The high scientific reputation of domestic and foreign participants as well as the number of papers provide guarantees that the Conference will be very successful. The papers reflect the state-of-the-art and deal with a wide spectrum of important topics of current interest in heavy machinery.

I would especially like to thank the Ministry of Science, Technological Development and Innovation of the Republic of Serbia for its support to the organization of the Conference and our efforts to promote science and technology in the areas of mechanical and civil engineering in Serbia. Also, I would like to express our gratitude to other sponsors of the Conference: Serbian Chamber of Engineers, TeamCAD d.o.o. Zemun-Belgrade, Banim reklame d.o.o. Kraljevo, Radijator Inženjering d.o.o. Kraljevo and Messer Tehnogas AD Belgrade.

My sincere thanks also go to all members of the scientific, organizing and technical committees, the reviewers, and all the participants including the invited speakers for their participation in the Conference and presentation of their papers.

Thank you and see you at the next conference in three years.

Kraljevo – Vrnjačka Banja, June 2023

Conference Chairman,

Prof. dr Mile Savković

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SESSION A: EARTH-MOVING AND TRANSPORTATION MACHINERY

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Methods for modeling bolted connections using FEM

Vladimir Milovanović[1], Miloš Pešić[2*], Rodoljub Vujanac[1], Marko Topalović[2], Milan Stojiljković[1]
[1]Faculty of Engineering, University of Kragujevac, Kragujevac (Serbia)
[2]Institute for Information Technologies, University of Kragujevac, Kragujevac (Serbia)

Abstract: In constructions with complex geometry, bolted connections are most often used to connect parts. Modeling a complete bolted connection which consists of bolt, nut and washers using 3D finite elements is either not always possible or requires a lot of engineering time. For this reason, it is necessary to approximate the bolted connection using other types of finite elements. This paper presents methods for modeling bolted connections using different types of finite elements. A complete bolted connection loaded in shear and bending was modeled using 3D finite elements. The bolted connection analysis results obtained using 3D finite elements were used as a reference. After that, the bolted connection was modeled using 1D beam finite element in combination with 3D, RBE2 and RBE3 finite elements. By comparing the results of the numerical analyses, an approximation of the bolt connection which best corresponds to the reference model was obtained. It can be concluded that the shown approximation of bolted connections gives satisfactory results and significantly saves engineering time.

Keywords: Finite element method, Bolted Connection, Beam finite element, RBE2, RBE3

1. INTRODUCTION

The successful design of heavy machinery largely depends on the way of joining the various parts used. Those parts can be made of different materials, and the method of joining those parts into a whole (construction) is of extreme importance. Bolt connections are often used to connect different parts of machines. For the detachable assembly of parts in machinery, bolts are crucial components and ensure the necessary axial or preload forces for the various parts of the machines or structures. To guarantee the security and dependability of machines, the axial force or preload of a bolt must be carefully regulated. Bolt connection failure frequently results from inadequate or excessive preload. Tightening stress in bolt must be taken into account when designing them in order not to break or overload the connection itself [1,2].

When creating finite element (FE) model of a complex structure, it takes a lot of engineering time to model a realistic bolted connection. Detailed modeling of a complete bolted connection requires the definition of contact pairs between all components. In addition to the engineering time wasted on model creation, this significantly increases the calculation time.

In this paper, different types of finite elements were used for the bolted connection modeling in order to determine their influence on the final results. The aim of this paper is to simplify the bolted connection model by applying different types of finite elements, reduce the model creation time and the duration of numerical calculations, while obtaining results that correspond to the results of the verification model. The verification FE model represents a complete bolted connection created by applying 3D finite elements and defining contact pairs. This FE model is loaded in shear and bending. After that, the bolted connection FE model is simplified by applying 1D, RBE2 and RBE3 finite elements. Initially, simplified models were created without washers. Then, washers were modeled and their influence on the calculation results was considered. By comparing the results obtained by using different types of finite elements with and without considering washers, the combination that gives the results closest to the verification model was determined.

2. BOLT CONNECTION

In the bolted connection, a certain axial force is created already in the state of rest, when the bolt is tightened. After settlement, the prestressing force occurs. This represents the static loading of the bolted connection, which causes static stress and associated elastic deformations in it. During the exploitation of the connected components, the bolted connection is affected by an additional load in the form of constant or variable working force. As a result, there is an additional elongation of the screw and a partial relief of the previously clamped washer. It is very important to determine the clamping force in order to maintain the structure or machine properly [3].

In addition to joining two or more components, bolted connections are also used for tensioning, regulation, measurement, and movement transmission. The basic elements of bolt connections are a bolt and a nut, where the bolt has an external thread, and the nut has a corresponding internal thread. The nut can be an independent part of the bolt connection, or it can be replaced by a part of the connected machine part, in which the internal thread should then be made. Since the bolt and nut are the most commonly used machine parts in all areas of technology, their shape, size, and material are standardized.

When it comes to modelling bolted connections using FEM, there are many publications in which FEM analyzes of bolted joints are discussed in order to analyze stress distribution and stress concentrations, contact pressure distributions, load sharing of the bolted joint components [4,5,6]. Modeling complete bolted connections requires a lot of engineering time, so it is necessary to simplify the model of the bolted connection. Many publications can be found in the literature that consider how it is possible to simplify bolted connections and significantly reduce the duration of calculations and

*Corresponding author: Jovana Cvijića bb, 34000 Kragujevac, Serbia, e-mail: milospesic@uni.kg.ac.rs

modeling time [7,8,9]. These approximations of bolted connections are most often reduced to the neglect of certain components of the bolted connection and the introduction of different types of finite elements. Within this paper, a comparative analysis of approximations of bolted connections using various types of finite elements with and without modeling washers is given. By comparing the results of the approximated models with the completely modeled bolted connection, the approximation that best corresponds to the real bolted connection was determined.

3. VERIFICATION MODELS

3D eight-node hexahedral finite elements were used for modeling the FE mesh of the verification model. The FE mesh in the contact regions is created so that the nodes of the different parts coincide ("node to node") in order to obtain the most reliable results and achieve a better convergence of numerical calculations. The numerical analysis of the bolted connection was performed in the Nastran software, while the pre and post-processing is carried out in Femap software [10].

The FE mesh of the verification model is shown in Figure 1. The assembly is formed of: upper plate, lower plate, upper washer, lower washer, bolt, and nut. The verification FE model, was modelled with 26912 3D hexahedral eight-noded finite elements and it is shown in Fig. 1.

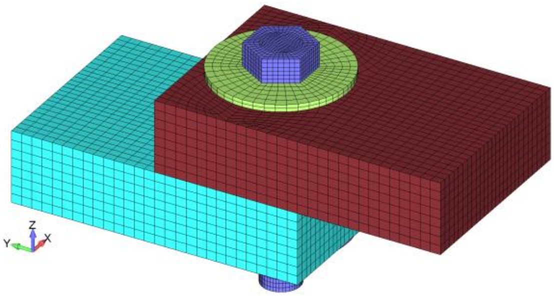

Figure 1. Verification 3D model

The characteristics of steel s355 were adopted for the material of the bolted connection assembly. Within this paper, two cases of the bolted connection loading were considered - shearing and bending (verification models 1 and 2, respectively), which is shown in Fig. 2 and Fig. 3. The boundary conditions of the model are set so that the upper plate of the assembly is fixed, while bending/shearing forces of 30 kN are applied to the lower plate. On all FE models, a bolt tightening force of 60 kN is defined.

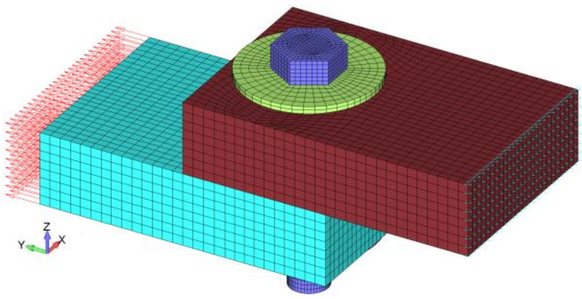

Figure 2. Boundary conditions and loading of verificatiom model 1 – shearing

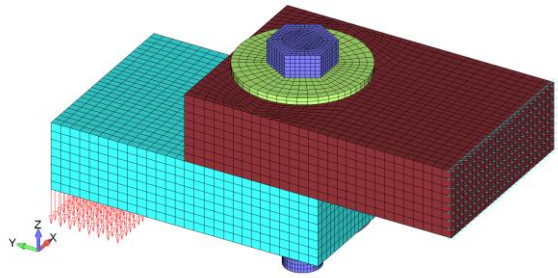

Figure 3. Boundary conditions and loading of verification model 2 – bending

Figure 4 shows the von Mises stress distribution field of the numerical analysis for the verification model 1 loaded in shearing. Results are shown in the plates which are interconnected by a bolt connection. Maximal value of von Mises stress is 147.38 MPa.

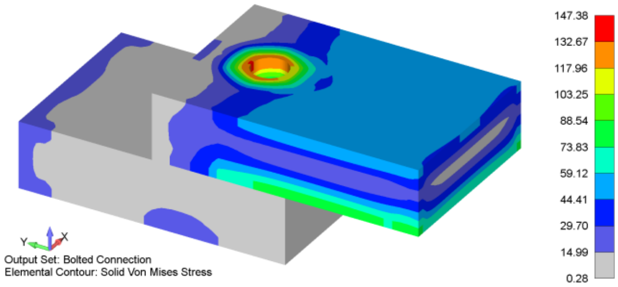

Figure 4. Von Mises stress – shearing

The total displacement field in the plates which are interconnected by a bolt connection is shown in Figure 5. Maximal value of total displacement is 0.32 mm.

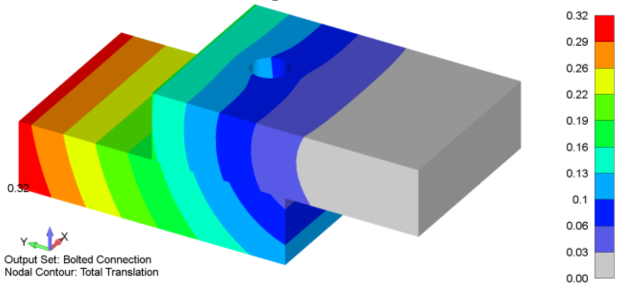

Figure 5. Total displacement – shearing

Figure 6 shows the von Mises stress distribution field of the numerical analysis for the verification model 2 loaded in bending. Maximal value of von Mises stress is 382.89 MPa.

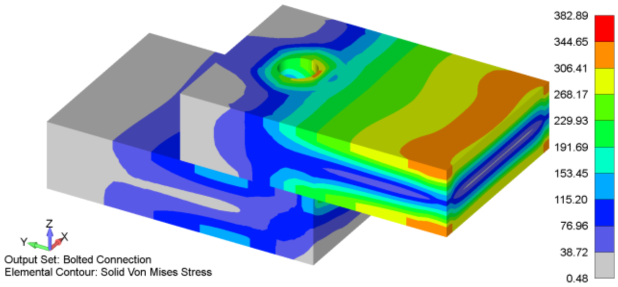

Figure 6. Von Mises stress – bending

The total displacement field in the plates is shown in Figure 7. Maximal value of total displacement is 1.80 mm.

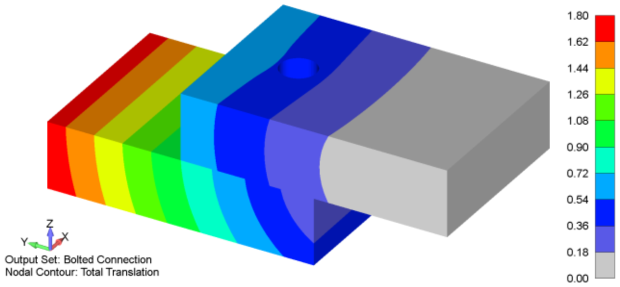

Figure 7. Total displacement – bending

4. FE MODELS WITHOUT WASHER

4.1. Approximate FE models loaded in shearing

In this chapter, the shear loading case of a bolted connection as shown in Fig. 2 is considered. In all approximate models, the bolt is modeled using a 1D beam finite element. The nut and washers were not modeled, and instead RBE2, RBE3 and 1D beam finite elements were used to connect the plates to the bolt as shown in Figure 8.

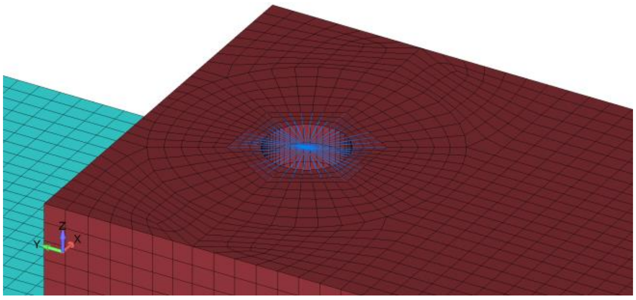

Figure 8. Aproximated FE model without washer

The FE model 1 was created using the RBE2 finite element type for the bolt to plate connection. This type of finite elements represents the so-called "rigid elements" that adds (infinite) stiffness to the structure. To create this type of finite element, the nodes at both ends of the beam element (bolt) is selected as an independent node, while the nodes on the plates at the contact with the bolt head or nut are selected as dependent nodes.

The FE model 2 was created using the RBE3 finite element type for the bolt to plate connection. This type of finite elements is created in a similar way as in FE model 1. The difference is that RBE3 finite elements represents interpolation elements that serve to "distribute forces" around the connected nodes, without adding any stiffness.

The FE model 3 was created using 1D beam elements for bolt to plate connections. A new property has been created in which new beam finite elements are defined. The cross-section of these elements is defined so that by combining these elements, the surface of the bolt head, i.e. the nut, is covered. The material of these elements is defined as completely rigid.

A comparison of these results for shearing load is given in the form of a von Mises Stress – *x* coordinate dependence diagram in the finite elements marked in Figure 9.

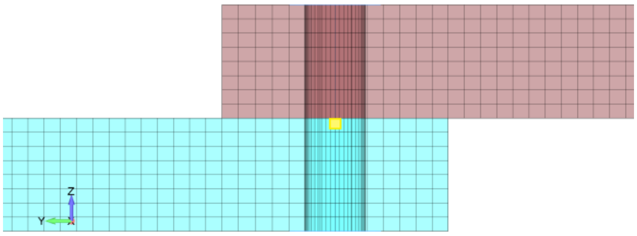

Figure 9. Finite elements for displaying results

Figure 10 shows the diagram of the dependence of the von Mises stress on the x coordinate.

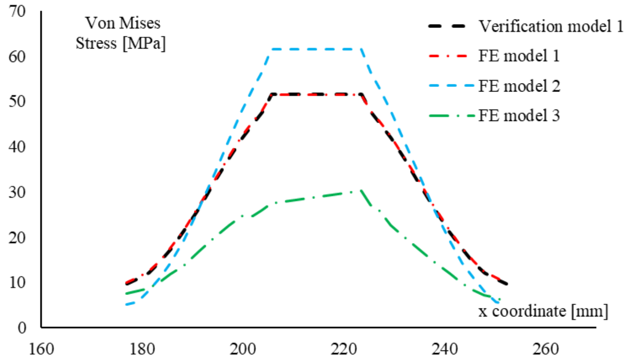

Figure 10. Von Mises Stress – x coordinate diagram

Comparison of the maximum von Mises stress values in both plates for FE models 1, 2, and 3 with verification model 1 is given in Fig 11.

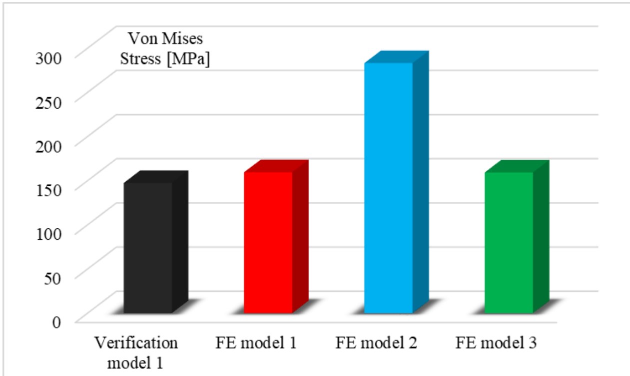

Figure 11. Maximum von Mises Stress values in plates

Table 1 shows a comparison of the maximum values of total displacement for FE models 1, 2, and 3 with verification model 1 loaded in shearing.

Table 1. Comparison of total displacement max. values

FE models	Total displacement [mm]
Verification model 1	0.32
FE model 1	0.32
FE model 2	0.33
FE model 3	0.32

As can be seen from the results above, FE model 1 (model created by combining the beam finite element and the RBE2 elements) has the best matching of the maximum von Mises stress value, stress distribution, and total displacement value compared to the verification model 1. It can be observed that FE model 2 (combination of RBE3 finite elements with a beam finite element) gives the worst matching results with the verification model 1. Also, FE model 3 (combination of beam finite elements) gives good matches of maximum von Mises stress value, while stress distribution in the model is significantly different from the verification model 1.

Fig. 12 and Fig. 13 show von Mises stress field and total displacement field for FE model 1, respectively.

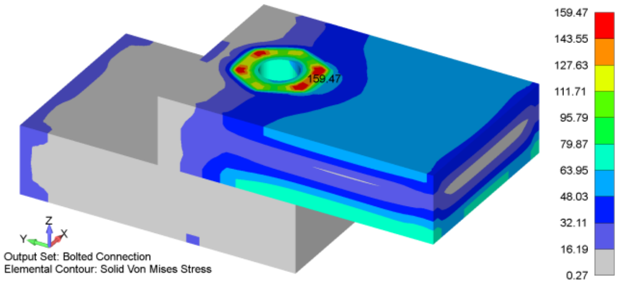

Figure 12. Von Mises stress field distribution for FE model 1

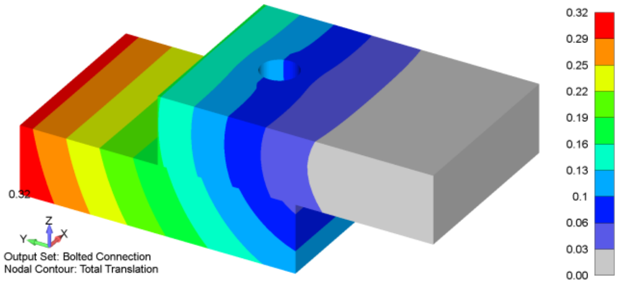

Figure 13. Total displacement field distribution for FE model 1

4.2. Approximate FE models loaded in bending

The approximate FE models used for the case of the bolted connection loaded in bending are the same as for the shear case (FE models labelled as FE models 4, 5 and 6 correspond to approximation FE models 1, 2 and 3 respectively loaded in bending.). The boundary conditions and loads are set to correspond to the bending load case of the bolted connection as shown in Figure 3.

A comparison of results is given in the form of a von Mises Stress – *x* coordinate dependence diagram in the finite elements marked in Figure 14.

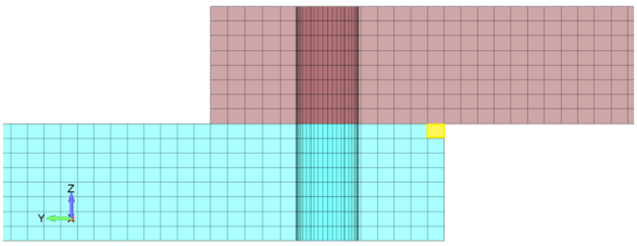

Figure 14. Finite elements for displaying results

Figure 15 shows the diagram of the dependence of the von Mises stress on the x coordinate.

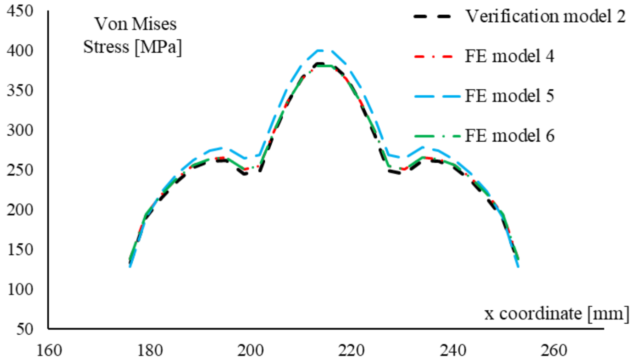

Figure 15. Von Mises Stress – x coordinate diagram

Comparison of the maximum von Mises stress values in both plates for FE models 4, 5, and 6 with verification model 2 is given in Fig 16.

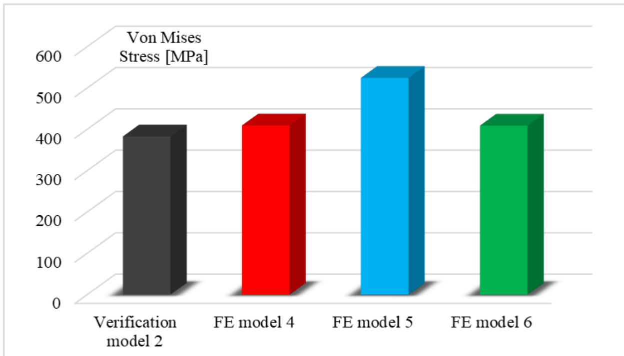

Figure 16. Maximum von Mises Stress values in plates

Table 2 shows a comparison of the maximum values of total displacement for FE models 4, 5, and 6 with verification model 2 loaded in bending.

Table 2. Comparison of total displacement max. values

FE models	Total displacement [mm]
Verification model 2	1.80
FE model 4	1.74
FE model 5	1.81
FE model 6	1.74

Based on the results above, it can be concluded that for the case of bending, best match of the results with the verification model 2 gives FE model 4 (combination of beam and RBE2 finite elements). It should be noted that, although FE models 4, 5, and 6 give good matches for the maximum stress values, the locations where the maximum values occur are not the same.

Fig. 17 and Fig. 18 show von Mises stress field and total displacement field for FE model 4, respectively.

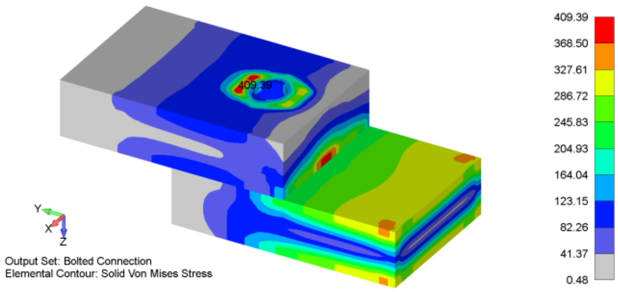

Figure 17. Von Mises stress field distribution for FE model 4

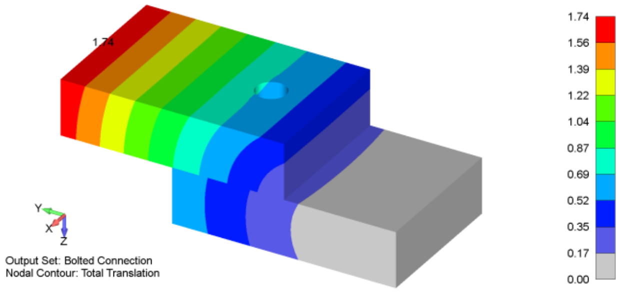

Figure 18. Total displacement field distribution for FE model 4

5. FE MODELS WITH WASHER

5.1. Approximate FE models loaded in shearing

Based on the results from the previous chapter, in models without washers, it can be observed that higher stress concentrations occur at the place of washers. This occurs as a result of connecting the plates and the beam finite element (bolt) with rigid elements. For this reason, approximate FE models with washers are considered in this chapter (Fig. 17).

As in the previous chapter, in all approximate models, the bolt is modeled using a 1D beam finite element. The nut is not modeled. RBE2, RBE3 and 1D beam finite elements were used to connect the plates to the bolt. Approximate FE models labelled as FE models 7,8 and 9 correspond to FE models 1,2 and 3 respectively with added washers.

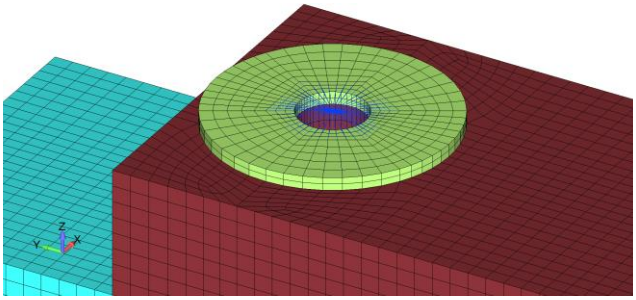

Figure 17. FE model with washer

The boundary conditions and loads are set to correspond to the shearing load case of the bolted connection as shown in Figure 2.

A comparison of results is given in the form of a von Mises Stress – *x* coordinate dependence diagram in the finite elements marked in Figure 9.

Figure 18 shows the diagram of the dependence of the von Mises stress on the x coordinate.

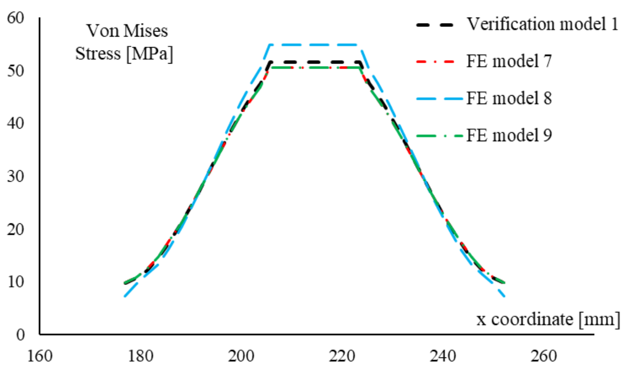

Figure 18. Von Mises Stress – x coordinate diagram

Comparison of the maximum von Mises stress values in both plates for FE models 7, 8, and 9 with verification model 1 is given in Fig 19.

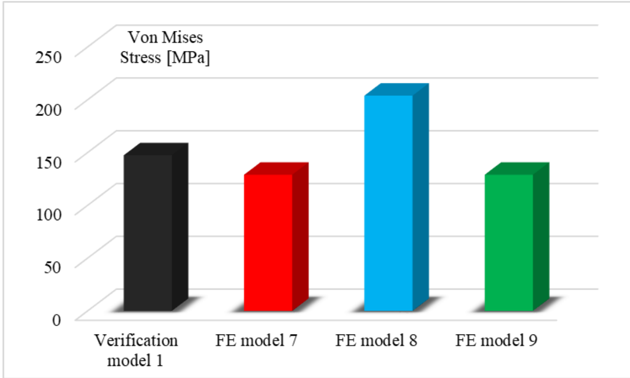

Figure 19. Maximum von Mises Stress values in plates

Table 3 shows a comparison of the maximum values of total displacement for FE models 7, 8, and 9 with verification model 1 loaded in shearing.

Table 3. Comparison of total displacement max. values

FE models	Total displacement [mm]
Verification model 1	0.32
FE model 7	0.32
FE model 8	0.32
FE model 9	0.32

Based on the results above, it can be concluded that FE model 7 (combination of the beam and the RBE2 finite elements) has the best matching of the results compared to the verification model 1. Also, as in the case of the no-washer models, FE model 8 (the combination of RBE3 finite elements with a beam finite element) gives the worst matching in results with the verification model 1.

Fig. 20 and Fig. 21 show von Mises stress field and total displacement field for FE model 7, respectively.

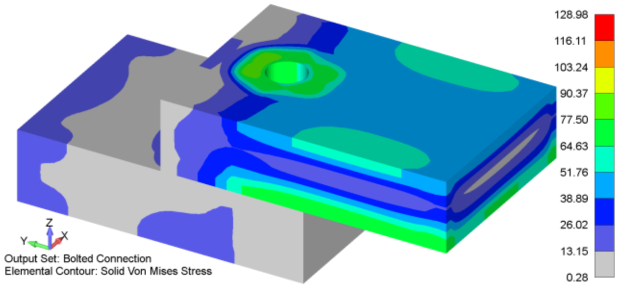

Figure 20. Von Mises stress field distribution for FE model 7

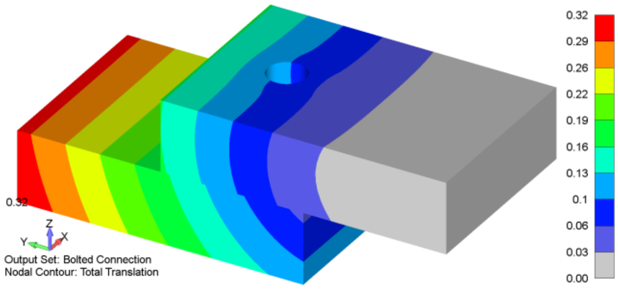

Figure 20. Total displacement field distribution for FE model 7

5.2. Approximate FE models loaded in bending

The FE models used for the case of the bolted connection loaded in bending are the same as for the shear case (approximate FE models labelled as FE models 10, 11 and 12 correspond to FE models 7, 8 and 9 respectively loaded in bending.). The boundary conditions and loads are set to correspond to the bending load case of the bolted connection as shown in Figure 3.

A comparison of results is given in the form of a von Mises Stress – *x* coordinate dependence diagram in the finite elements marked in Figure 14.

Figure 21 shows the diagram of the dependence of the von Mises stress on the x coordinate.

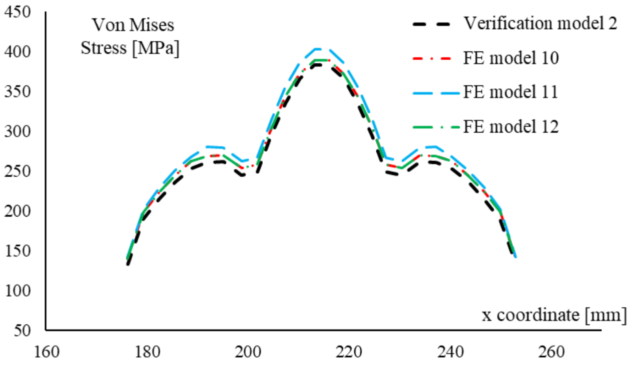

Figure 21. Von Mises Stress – x coordinate diagram

Comparison of the maximum von Mises stress values in both plates for FE models 10, 11, and 12 with verification model 2 is given in Fig 22.

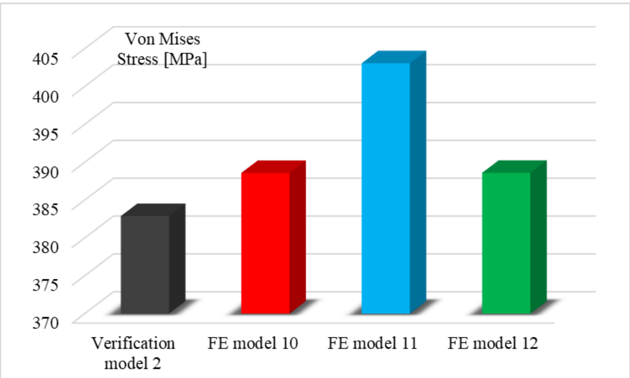

Figure 22. Maximum von Mises Stress values in plates

Table 4 shows a comparison of the maximum values of total displacement for FE models 10, 11, and 12 with verification model 2 loaded in bending.

Table 4. Comparison of total displacement max. values

FE models	Total displacement [mm]
Verification model 2	1.80
FE model 10	1.78
FE model 11	1.82
FE model 12	1.78

By analyzing the results above, it can be concluded that, for the case of bending, the best matches of the results with the verification model 2 gives FE model 10 (combination of beam with RBE2 finite elements). It should be noted that, although FE models 10, and 12 give good matches for the maximum stress values, the locations where the maximum values occur are not the same.

Fig. 23 and Fig. 24 show von Mises stress field and total displacement field for FE model 10, respectively.

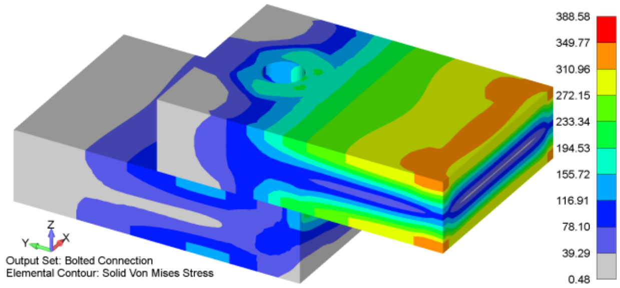

Figure 23. Von Mises stress field distribution for FE model 10

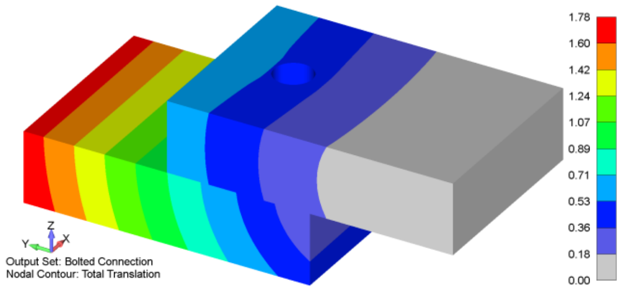

Figure 24. Total displacement field distribution for FE model 10

6. DISCUSION

In Table 5 are shown the maximum values of von Mises stress and total displacement for all FE models.

Table 5: Results of numerical analysis

FE models	Maximal stress [MPa]	Total displacement [mm]
Verification model 1	147.38	0.32
Verification model 2	382.89	1.80
FE models without washer – shearing		
FE model 1	159.47	0.32
FE model 2	283.08	0.33
FE model 3	159.28	0.32
FE models without washer – bending		
FE model 4	409.39	1.74
FE model 5	524.61	1.81
FE model 6	409.02	1.74
FE models with washer - shearing		
FE model 7	128.98	0.318
FE model 8	203.93	0.326
FE model 9	128.98	0.318
FE models with washer – bending		
FE model 10	388.58	1.78
FE model 11	403.07	1.82
FE model 12	388.60	1.78

As can be seen from the table 5, FE model 1 and 4 (the models created by combining the beam finite element and the RBE2 element) has the best match in maximum values of von Mises stress and total displacement, as well as stress distribution compared to the verification models 1 and 2, i.e. shearing and bending load cases. It is important to point out for FE models without washers that all of them show stress concentration locally at the place where washers should be inserted. Modeling both washers and specifying contact between them and the plates (FE models 7 and 10) can reduce this stress concentration in the plates, as can be seen in Fig. 20 and Fig. 23.

7. CONCLUSION

Based on everything presented in the paper, the following can be concluded:

- Modeling the bolt using beam finite element in combination with RBE2, RBE3 and beam finite elements can significantly reduce the modeling time. In addition, contact definition between all parts of the bolt connection is avoided, which significantly reduces the calculation time. On the other hand, in this way, the side contact of the bolt and the plates is not taken into account and its influence on the analysis cannot be considered.
- The best matches with the verification models for both load cases are obtained by combining the beam finite element (bolt) with RBE2 finite elements, while the worst matches are obtained by combining the beam finite element (bolt) with RBE3 finite elements.
- Approximating the bolted connection without modeling the washers results in large stress concentrations on the plates where the washers should exist. Therefore, it is recommended to model the washers to remove this stress concentration.
- In approximated FE models containing washers, the best results are also given by the combination of the beam finite element (bolt) with RBE2 finite elements.

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