Load capacity evaluation for single lap joints applied in the railway vehicles

T Zadorozny1*, M Szczepanik2

1Alstom Konstal S.A., Engineering Department, Metalowców 9, 41-500 Chorzów, Poland
2Silesian University of Technology in Gliwice, Faculty of Mechanical Engineering, Institute of Computational Mechanics and Engineering, Konarskiego 18a, 44-100 Gliwice, Poland

*Corresponding author’s e-mail: zadorozny.tomasz@gmail.com

Abstract. The article will present a comparison performed for two different approaches based on the application of Finite Element Method used to overlap joints "HUCK BOM" modeling. For the given geometric form of the joint two different numerical models will be presented and their load capacity will be determined for each of the modeling methodologies. The first methodology where a simplified joint model using beam elements and rigid elements of the RBE2 type will be compared with the second where the initial tension and the influence of friction on the joint load capacity are taking into account. Finally, a comparison of the results obtained with reference to the time of connection modeling and computation will be given.

1. Introduction

The method of joining elements using "HUCK BOM" fasteners is very efficient and ensures high repeatability due to the use of dedicated tools. For these reasons, those fasteners are widely used in structures exposed to high static and dynamic loads (bridges, towers, trains, etc.). Such structures (and especially serial-produced ones) require calculations that allow obtaining a compromise between the load capacity of the lap joint and the number of fasteners used. Modeling structures composed of thousands of fasteners requires modeling each fastener, which is an extremely tedious process, which is why the right choice of modeling is a key issue. There are various ways of modeling this type of connection in the FEA environment. The most commons are the use of 1D elements for mapping fasteners and 3D modeling, which is much more time-consuming. This study aims to compare the above-mentioned methods in terms of the obtained results and the time needed to solve the task. This paper is an introduction to further research aimed at carrying out real tests to determine the consistency with numerical calculations, taking into account the influence of various factors on the load capacity of the joint (e.g. the accuracy of making holes). HyperWorks (one of the commercial programs using the Finite Element Method (FEA)) was used to solve the problem defined above.

2. Description of samples

The tested joint (fig. 2) consists of 12mm thick steel sheets and 8mm thick aluminum sheet, "HUCK BOM" fasteners with the R20 designation were used to connect the plates. Table 1 presents the basic dimensions of the fastener (fig. 1). Holes are made in steel sheets and then a tensile force is applied evenly on the cylindrical surface [6,7].
Figure 1. Clamped HUCK BOM fastener [6]

Table 1. Dimensions of the clamped HUCK BOM fastener [6]

| R [mm] | S [mm] | T [mm] | U [mm] | V [mm] | W [mm] |
|--------|--------|--------|--------|--------|--------|
| 2      | 8      | 11.1   | 26.1   | 18.3   | 32.2   |

Table 2 presents material data:

Table 2. Material properties

| Material   | Young's modulus [MPa] | Density [g/cm³] | Poisson's ratio | Yield [MPa] |
|------------|------------------------|-----------------|-----------------|-------------|
| S355       | 2.1·10³                | 7.85            | 0.3             | 355         |
| RAP6082    | 7·10⁴                  | 2.6             | 0.3             | 260         |

The load capacity of the joint in a given load case is determined by the surface pressure between the aluminum plate and the fastener on the cylindrical surface of the hole. The analytical capacity of the lap joint is calculated below, implying the lap is perfectly stiff and the influence of friction between the connected elements is nonexistent. Due to surface pressures, the calculations are carried out assuming that the force pressing fastener against the wall of the hole acts on the surface of a projection fastener shaft on a surface perpendicular to the direction of the force [2,3].

Section area:

\[ A = D \cdot t_a = 17.5 \cdot 8 = 140mm^2 \]  

Permissible stress (safety factor is n=1.15):

\[ \sigma_a = \frac{R_e}{n} = \frac{260}{1.15} = 226MPa \]  

The maximum value of force extending the lap joint:

\[ F \leq \sigma_a \cdot A \cdot 4 = 226 \cdot 140 \cdot 4 = 126.56kN \]  

where:

\( \sigma_a \) – Permissible stress for aluminum sheet  
\( D \) – Diameter of the hole for the fastener HUCK BOM  
\( t_a \) – Thickness of aluminum sheet  
\( n \) – Safety factor
3. Determining load capacity of the lap joint using 1D elements

In the first attempt, the connection was modeled using CBAR beam elements that were connected to the steel and aluminum sheets using rigid RBE2 elements. Figure 2 shows the layout of the lap joint and basic dimensions, the steel plate is marked yellow, and the aluminum sheet purple. The model does not take into account the friction contact between the connected elements and the pretension, all forces are transferred directly through the 1D elements. The numerical model consists of 66138 elements and 87140 nodes.

Figure 2. Lap joint with fasteners designed using 1D elements

Figure 3 presents the boundary conditions and the numbering of the connectors. The model was fixed in one of the technological holes and the force determined by the analytical method equal to 126.56 kN was applied to the hole on the opposite side, simulating the tensile effect of the sample.

Figure 3. Boundary conditions
Table 3 presents the values of forces in 1D elements representing the fasteners, and the stress values determined on their basis. The stress results obtained from the numerical analysis are similar to the results obtained by the analytical method, differences of less than 2% are caused by the deformation of the joined elements. Figure 4 shows how the force values in the 1D fasteners were read.

![Forces in 1D elements](image)

**Figure 4.** Forces in 1D elements

**Table 3.** Forces and stress values for HUCK BOM fasteners at a load of 126.56kN

| L.p. | \(F_y\) [N] | \(F_x\) [N] | \(F_w\) [N] | \(\sigma\) [Mpa] |
|------|--------|--------|--------|--------|
| 1    | -948.17 | -31117 | 31 131.4 | 222.4  |
| 2    | 948.16  | -31117 | 31 131.4 | 222.4  |
| 3    | 966.55  | -32183 | 32 197.5 | 230.0  |
| 4    | -966.54 | -32183 | 32 197.5 | 230.0  |
| 5    | 966.54  | 32183  | 32 197.5 | 230.0  |
| 6    | -966.53 | 32183  | 32 197.5 | 230.0  |
| 7    | -948.17 | 31117  | 31 131.4 | 222.4  |
| 8    | 948.16  | 31117  | 31 131.4 | 222.4  |

where:

\(F_y\) – Force acting in the direction of the Y axis  
\(F_x\) – Force acting in the direction of the X axis  
\(F_w\) – Resultant of forces  
\(\sigma\) – Maximum stresses determined on the basis of forces in 1D elements

Figure 5 shows the displacement distribution on the deformed model in the 2:1 scale, the maximum displacement value is 8.76 mm.
Figure 5. Displacement distribution in the 2:1 scale for a tensile force of 126.56kN [mm]

Knowing the results presented above, the lap joint capacity corresponding to the maximum value of force \( F_z = 124.03 \text{kN} \) (fig. 6) was determined so that the maximum stresses do not exceed the permissible stress.

Figure 6. Point of application of \( F_z \) force, determining the maximum load capacity of the joint

In order to check numerically, table 4 presents the values of forces in elements 1D for the sample loaded with force \( F_z = 124.03 \text{kN} \). The determined stresses do not exceed the permissible value.

Table 4. Forces and stress values for HUCK BOM fasteners at a load of \( F_z = 124.03 \text{kN} \)

| L.p. | \( F_y \) [N] | \( F_x \) [N] | \( F_w \) [N] | \( \sigma \) [Mpa] |
|------|------------|------------|------------|--------------|
| 1    | -929.2     | -30495     | 30 509.2   | 217.9        |
| 2    | 929.19     | -30495     | 30 509.2   | 217.9        |
| 3    | 947.22     | -31539     | 31 553.2   | 226.0        |
| 4    | -947.21    | -31539     | 31 553.2   | 226.0        |
| 5    | 947.21     | 31539      | 31 553.2   | 226.0        |
| 6    | -947.2     | 31539      | 31 553.2   | 226.0        |
| 7    | -929.21    | 30495      | 30 509.2   | 217.9        |
| 8    | 929.19     | 30495      | 30 509.2   | 217.9        |
4. Determining load capacity of the lap joint using 3D elements modeled for fasteners

In the second test, the load capacity of lap joint with fasteners modeled using 3D elements was examined. Friction contact was modeled between the fasteners and plates on the head surfaces and cylindrical surfaces. The model also includes pretension \( N_u = 24 \text{kN} \). The coefficient of friction used is \( \mu = 0.2 \). The friction contact in this case also prevents the penetration of joined elements. The numerical model consists of 75954 elements and 99804 nodes (fig. 7).

The theoretical friction force in the lap joint was analytically determined below:

\[
T = 4 \cdot N_u \cdot \mu = 4 \cdot 24 \cdot 0.2 = 19.2 \text{kN}
\]

(4)

Figure 7. Lap joint with fasteners designed using 3D elements

The model was loaded in the same way as in the first attempt (fig. 3). Figure 8 presents the distribution of H-M-H reduced stresses on an aluminum plate in the area of the location of the fasteners. Figure 9 presents a detailed distribution of stresses on the cylindrical part of the hole in contact with the HUCK BOM fastener. The maximum stresses in the contact area are 235.8 MPa, however, these are local stress accumulation in the nodes, that are in direct contact with the connectors. The difference of 4% in relation to the analytical calculation results comes from the deformation of the joined elements and the contact used (different contact areas in contact) on the cylindrical surfaces.

Figure 8. Distribution of H-M-H reduced stress in aluminum plate for tensile force 126.56kN [MPa]
Figure 9. Distribution of H-M-H reduced stress in cylindrical part of the hole for tensile force 126.56kN [MPa]

The real contact surfaces are shown below in figure 10, the red color marks where the cylindrical surface of the fastener closely adheres to the cylindrical surface of the hole, thus transferring the predetermined load.

Figure 10. Contact status

Figure 11 shows the displacement distribution on the deformed model in the 2:1 scale, the maximum displacement value is 8.48mm.
Figure 11. Displacement distribution in the 2:1 scale for a tensile force of 126.56kN [mm]

Like before, knowing the results presented above, the lap joint capacity corresponding to the maximum value of force $F_z = 120.63$ kN was determined so that the maximum stresses do not exceed the permissible stress.

The detailed distribution of stresses on the cylindrical part of the hole for the tensile force $F_z = 120.63$ kN is presented below. The maximum stresses (225.97 MPa) are within the acceptable range.

Figure 12. Distribution of H-M-H reduced stress in cylindrical part of hole for tensile force 120.63 kN [MPa]

5. Summary
The time needed to solve the problem using 1D beam elements is about two hours. In order to solve the same task by modeling fasteners using 3D elements, one should spend an additional hour modeling connectors that have a relatively complex geometry. In addition, one should create groups of contacts
between the combined elements and fasteners, additionally extending the time of solving the task. Table 5 provides a comparison of approximate modeling times and numerical solutions.

Table 5. Comparison of approximate times for modeling and analysis solutions

|                               | 1D       | 3D       |
|-------------------------------|----------|----------|
| Modeling of connected plates  | 90min    | 90min    |
| Modeling of fasteners         | 30min    | 60min    |
| Modeling of contacts          | -        | 30min    |
| Numerical solution of the task| 2min     | 70min    |
| **Summary**                   | **122min**| **250min**|

The results indicate that the lowest load capacity of 120.63kN was obtained using 3D elements modeling for the fastener, although the numerical model taking into account the phenomenon of friction between the joined elements. This method can be considered the most accurate because it precisely maps the joint system and its stiffness, but it is crucial to remember that the maximum stress value occurs locally, in the nodes where the contact between the aluminum plate and the HUCK BOM fastener occurs. Close attention should be paid to the fact that with the decrease of the friction force, the contact stresses will increase resulting in a reduced load capacity of the single lap joint. Modeling the fasteners using 1D elements, the joint capacity was 124.03kN. Table 6 summarizes the comparison of load capacity for each of the methods described above.

Table 6. Comparison of single lap joint load capacity, depending on the calculation method

|                   | Load capacity of the single lap joint |
|-------------------|---------------------------------------|
| Analytical method | 126.56kN                               |
| Fastener 1D       | 124.03kN                               |
| Fastener 3D       | 120.63kN                               |

Differences in the load capacity of the joint between carried out numerical analyses are insignificant, the time needed to solve the problem by modeling the fastener using 3D elements is more than twice as long. On the basis of the obtained results, it can be concluded that such slight differences indicate that for fasteners with relatively low stiffness, a simplified method of modeling connectors with 1D elements can be successfully applied to take into account the appropriate safety factor. This approach allows shortening the computation time several times, which translates into cost reductions while maintaining the safety margin.

6. References
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