SPACEBOLT™: FASTENER VERIFICATION SOLUTION FOR THE SPACE INDUSTRY

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ABSTRACT

Threaded fastener joints are commonly used in spacecraft components. Their design and verification in accordance with the relevant standards is a labour-intensive task prone to human errors. Thus, the efficiency and usability of the verification tools play a crucial role. This paper presents the fastener verification tool SpaceBolt™ created specifically for the needs of the space industry.

User-friendly interface, validated verification procedures, direct import of the FEA results, comprehensive reports, and integrated means of the problem mitigation boost the engineer's productivity and correctness of the results.

1. INTRODUCTION

Bolted joints are one of the most common connection methods in structural engineering. Verification procedures are presented in the number of normative documents (VDI-2230 [1], EN 1993-1-8, NASA-STD-5020, ECSS-E-HB-32-23A [2] etc.) A common approach is to implement relevant calculations in spreadsheets and reuse them for the next projects. Experience shows this approach is not robust: the spreadsheets are poorly validated and can become inconsistent due to constant modifications required to adapt them to new projects. In addition, results of such spreadsheet analyses are often difficult to check for an independent reviewer. To overcome these problems, it is beneficial to use specialized tools for the bolt calculations.

The ECSS handbook ECSS-E-HB-32-23A provides the guidelines for the fastener verification and recommended for the European space industry projects. This handbook addresses each failure mode related to the threaded fasteners by the corresponding margin of safety calculation. Special attention in the space structures verification is dedicated to the slippage and gapping failure modes.

VDI-2230 is one of the most widely applied bolt verification standards in mechanical engineering in Europe, therefore there is a number of commercially available tools on the market which implement the VDI-2230 procedure. Despite the fact that the ECSS handbook is mainly based on the VDI standard, adaptation of the pure VDI-2230 procedure to the space projects requires significant efforts due to specific safety factors philosophy and margin of safety calculations.

SpaceBolt™ was initially created as the internal tool at Space Structures GmbH specifically for the space projects needs and, therefore, based on the ECSS-E-HB-32-23A and VDI-2230 standards. The top-level requirements for the software are:
- Compliance with ECSS-E-HB-32-23A.
- User friendly graphical interface with database functionality for standard data and parameters.
- Import of bolt forces from NASTRAN PUNCH files, CSV tables or direct user input.
- Analysis of several bolt groups in a single session.
- Comprehensive documentation of the results.

After very positive internal feedback, it was decided to offer this tool as the commercial product. After an internal evaluation process [5], SpaceBolt™ procured by ESA. Successful cooperation with ESA resulted in the development of additional modules for the bolts verification under the vibration loads and fracture analysis data generation compatible with NASGRO™ [3].
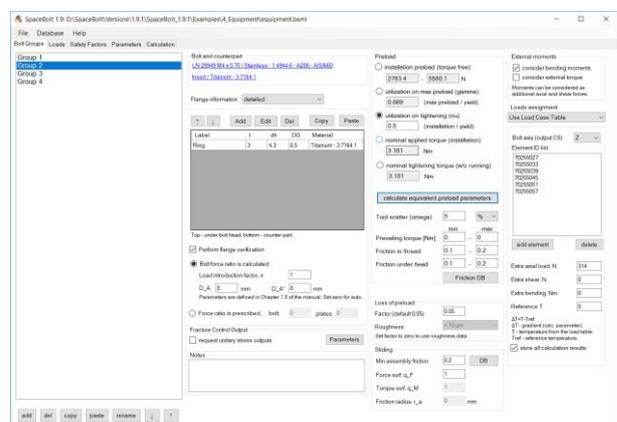

Figure 1. Main window

Today, SpaceBolt™ helps engineers in a number of companies to design MGSE, electronic and optical units, and satellite structures spanning from CubeSats to large spacecrafts. All customers, and most significantly Airbus Defence and Space, have reported the tool helps to significantly improve the bolt calculation process and increase productivity. The feedback from the community is continuously implemented in the software for its further improvement.

2. MAIN ASSUMPTIONS

Main assumptions in SpaceBolt™ (v.1.9):
- Only concentric joints are considered
- The flanges are considered to be cylindrical
- The chamfers are ignored
- The material parameters are assumed to be temperature independent

These assumptions are valid in most real life applications without significant penalties in accuracy. In order to address the loading eccentricity, the bending moments are transformed into the additional axial bolt force:

$$F_{A,upd} = |F_A| + \left| \frac{M_B}{0.5 D_K} \right|$$

where
- $F_{A,upd}$ – resulting axial force
- M_B – bending moment
- F_A – axial bolt force
- D_K – diameter of the compression cone.

3. CALCULATION ASPECTS

A comprehensive description of the calculation procedures implemented in SpaceBolt™ is provided in the reference manual [4]. In this paper some space related aspects are addressed.

3.1. Preload

SpaceBolt™ allows calculation of the bolts tightened using the torque wrench and the torsion-free methods. Since the preload plays a dominant role in the bolt verification process, there are several methods of the preload control available in the tool:
- Bolt material utilization on tightening
- Bolt material utilization on max preload
- Applied torque (with or without consideration of the prevailing torque)

Preload definition interface depicted in Fig. 3 allows quick assessment of the applied torque and the resulting preload force. Details about the calculated preload are summarized in the analysis report generated by the tool (Fig. 2).

Bolt group	Tightening torque (w/o running) [Nm]		Prevailing (running) torque [Nm]		Installation torque (with running) [Nm]		Preload [N] (room, w/o embedding)		Actual Preload [N] (embedding+thermal)			Max utilization	
	Nominal		Min	Max	Nominal	Tolerance	Min	Max	Min	Max	Nominal	Max preload	Tightening
Group 1	N/A		0.00	0.00	81.85	±5.00%	29696.12	60528.30	26868.71	60528.30	39676.83	0.72	0.85
Group 2	N/A		0.00	0.00	3.18	±5.00%	2783.37	5580.13	2504.36	5580.13	3588.42	0.67	0.80
Group 3	N/A		0.00	0.00	10.58	±5.00%	6418.40	12879.05	5774.44	12879.05	8277.43	0.67	0.80
Group 4	N/A		0.00	0.00	6.37	±5.00%	4519.32	9122.99	4063.17	9122.99	5840.72	0.68	0.80

Figure 2. Preload definition interface

Figure 3. Preload definition interface

3.2. Batch (load table) calculations

Bolt verification for a typical space structure is associated with the large set of calculations due to the following:
- The structure usually includes a number of bolt groups (e.g. for the satellite structure the number of bolt groups can reach several hundred)
- The structure needs to be verified for the set of environments resulting in the multiple load cases (often thousands of load cases).

The bolt forces are recovered from the NASTRAN PUNCH file (either static SOL101 or dynamic SOL111) containing MPCFORCE or ELFORCE output for CBUSH elements. Alternatively, CSV table can be used as the input ensuring compatibility with any FEA solver. The tool also allows superposition of the forces using the load factors tables.

Margins of safety

Parameter	Value	Element	LC
Tightening yield	0.43	111	101
Tightening ultimate	0.61	111	101
Sliding (min preload)	-0.13	114	126
Sliding (nominal preload)	0.24	114	126
Gapping	38.19	115	114
Thread pull-out (external load)	39.05	115	114
Thread pull-out (total load)	3.51	115	114
Shear load yield	7.66	114	109
Shear load ultimate	7.79	114	109
Axial load (applied) yield	14.91	115	114
Axial load (applied) ultimate	13.96	115	114
Axial load (total) yield	0.59	115	114
Axial load (total) ultimate	0.69	115	114
Combined load yield	0.56	115	106
Combined load ultimate	0.66	115	106

Figure 4. Margin of safety summary for the bolt group

In the session file the user defines the bolt groups and association between the groups and the elements in the FEM. SpaceBolt™ performs the calculation for each requested element and each load realization and aggregates the worst-case results indicating the worst-

case element leading to the minimum margin of safety and corresponding load case as shown in Fig. 4.

This calculation approach helps to significantly reduce the efforts during the verification while reducing the conservatisms or possible mistakes during the loads enveloping traditionally performed during these tasks.

In case the calculation results for all bolts in the particular bolt groups are required, SpaceBolt™ generates the CSV table with all loads and corresponding margins of safety for each bolt and load cases for the bolt groups selected by the user.

3.3. Sliding

The majority of the interfaces in the space structures work as a friction grip carrying the shear load. Therefore, sliding verification is an important aspect during the bolt verification. Margin of safety on sliding is calculated using the following equation:

$$MoS = \frac{(F_V - (1 - \Phi)F_A) \cdot \mu_S \cdot q}{F_Q \cdot SF} - 1$$

Where
- F_V – preload force
- Φ – bolt force ratio
- F_A – axial bolt force
- μ_S – assembly friction
- q – number of shear force transmitting interfaces
- F_Q – shear force
- SF – safety factors.

Slip resistance of the interface greatly depends on the preload force F_V, however its actual realization is not known. In case if the bolt group is composed of only one or several bolts, minimum preload shall be used for the verification. In certain situations, when the bolt group has many bolts, it is possible to reduce the conservatism by considering nominal preload for the verification. This preload is calculated assuming average friction coefficients in the thread and under the bolt head. This approach can be justified when it is demonstrated that the slippage of an individual bolt only leads to a redistribution of the total shear force but does not cause an overall interface slippage nor lead to other failure modes. In this case the verification can be performed based on the averaged total shear force. This verification is available as a module to the SpaceBolt™ which calculates the resultant shear force for each bolt group and performs the sliding verification assuming the shear force is uniformly redistributed among the bolts in the bolt group.

Bolt group	Max avg shear force		Min sliding MoS			
	Value	LC	min preload	nominal preload	EID	LC
Group 1	1402.14	1	-0.18	0.23	70001068	1
Group 2	1570.69	250	-0.28	0.09	70001009	250
Group 3	1604.30	238	-0.30	0.06	70001020	238

Figure 5. Average shear force sliding verification report

2.4. Fracture control outputs (NASGRO)

To support fracture analysis for the critical interfaces, SpaceBolt™ provides the unitary stress outputs which can be combined with the load spectrum in order to generate the fatigue stress spectrum compatible with NASGRO™. The steps are schematically shown in Fig. 6.
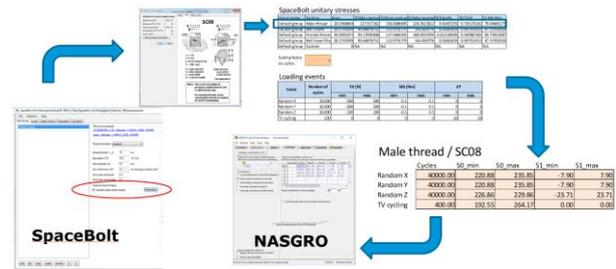

Figure 6. Fracture control output steps

Unitary stresses are generated for the following crack models (in accordance with NASGRO nomenclature):
- Bolt shank (SC07, SC14)
- Male thread (SC08)
- Female thread (SC09)
- Bolt head fillet (SC07, SC14)

3.4. Flange information and simplifications

SpaceBolt™ offers two methods of flange information input: the user can input information for each flange individually (material, dimensions) as shown in Fig. 7 or provide averaged flange parameters as shown in Fig. 8.

Figure 7. Detailed flange input

Figure 8. Simplified flange input

When the detailed flange input is provided, SpaceBolt™

calculates force ratio values and margins of safety for each flange individually (Fig. 9).

Flange configuration

Parameter		Mount	Ring	Units
Thickness	t,i	8	3	mm
Inner diameter	dh,i	6.4	6.4	mm
Outer diameter	DO,i	12	12	mm
Material		Titanium - 3.7164.1	Titanium - 3.7164.1	
Young's modulus	E,i	113800	113800	MPa
CTE	α,i	8.6	8.6	$10^{-6}\ K^{-1}$
Shear ultimate strength	$\tau_{ult,i}$	570	570	MPa
Bearing yield strength (1.5)	$\sigma_{br.y.1.5,i}$	830	830	MPa
Bearing ultimate strength (1.5)	$\sigma_{br.ult.1.5,i}$	900	900	MPa
Bearing yield strength (2.0)	$\sigma_{br.y.2.0,i}$	830	830	MPa
Bearing ultimate strength (2.0)	$\sigma_{br.ult.2.0,i}$	900	900	MPa
Limiting surface pressure	$p_{G,i}$	900	900	MPa
Min MoS bearing yield		66.55	24.33	
Min MoS bearing ultimate		60.04	21.89	
Min MoS crushing		1.46	3.19	
Min MoS shear-out		76.31	27.99	

Figure 9. Flange verification output

Such output is especially helpful when assessing the strength of the delicate materials such as INVAR.

4. CONCLUSIONS AND FUTURE WORK

SpaceBolt™ is the only commercially available software for the bolt verification according to ECSS-E-HB-32-23A. It allows significant reduction of the verification cycle duration while increasing the robustness of the process and improving the documentation of the results.

This tool is useful for a wide range of the applications: from the MGSE (mechanical ground support equipment) verification up to satellite and launcher structures verification. Features such as torque-free tightening and fracture control outputs are especially useful for the optical instrument developers.

SpaceBolt™ is constantly being developed based on the customer feedback and general needs. The main focus during further developments will be dedicated to further improvement of the user experience and the modules, allowing the engineers to investigate the problems with the fasteners faster and more effectively.

Other development vectors include further integration with ESALOAD and other packages for the optimization of the verification process, consideration of the eccentricity, and command line interfaces etc. More details about the software can be found on https://spacebolt.de/.

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