

Calculation of thread length installed in assemblies of threaded aluminum parts

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Abstract— In this article we present an equation for the calculation of the length of threading between a bolt and a tapped part. We approach the problem where both parts have different mechanical resistances. The equation allows us to calculate the length of the thread necessary to prevent any of the three types of failure that could appear: stripping of the part thread, stripping of the thread of the bolt or rupture of the bolt. This allows us to have more different combinations of assembly materials from the point of view of its resistance and the prevention of static failure given that there was no method to approach these cases. The equation can be applied to threaded aluminum assemblies since this is one of the materials used in the development process. The process of development consists of an axisymmetric finite element model and a criterion of rupture by damage due to located plastic deformation. This model allows us to analyze the parameters involved in the design up to conditions of failure. These parameters include characteristics of the materials and dimensions of the assembly. Also, the process of development involves a model of experiments design to determine in the given equation, the behavior of the effects in the different types of failure. Finally, the results obtained from the equation are presented and compared against the results of physical tests in laboratory proving to be very close and satisfactory.

Keywords— aluminum, stripping, threads, tapped-part, damage.

I. INTRODUCTION

In the automotive and aeronautical industry, assemblies with thread elements are very important and widely used in systems and mechanical structures including in machines of high technology, in which it is desirable to minimize the weight of their components. In an assembly of parts that involve bolts of steel and threaded aluminum parts there could be stripping of the part thread before the rupture of the bolt if the thread assembly is not correctly dimensioned. In literature a simple relationship can be found to determine the minimum necessary length of threading between a bolt and a nut, both with materials with very similar mechanical properties. It has been said that the installed length of threading should be 0.8 to 1.5 times the diameter of the bolt [1] to [8]. This ratio is to assure that, in case of failure of the assembly; this is due to rupture of the bolt and not by stripping of the part thread. This way, the remedial and less expensive action would be the replacement of the bolt. Nevertheless, in addition to the fact that this ratio is only for assemblies in nuts, it is also not sufficient when the material of the part and the bolt have different mechanical properties. Some other existing methods of calculation allow the prevention of the stripping of the threads like the one presented in [1], this method comes from numerous tests and that have been completed or sharpened by more contributions in [2] to [4]. These methods only allow

dealing with the assemblies of bolt and nut, and they do not propose anything for thread parts.

In this article we propose a simple equation that will allow the designer to make precise and fast calculations for the length of the thread installed to prevent the stripping, before the rupture of the bolt, for a given applied static load.

This equation was obtained from the study of the behavior of a threaded assembly between a bolt and a threaded part. To do this, an axisymmetric model of numerical simulation of finite elements with a criterion of rupture by damage was formalized. This allowed us to recognize the effect of the most significant parameters of the assembly. Finally, we determined the proposed equation by the application of an experiments design and numerical simulations with the formalized FEM model. That equation was validated using results of laboratory tests considering all three different possible ways of failure in a threaded assembly of a bolt and a tapped part from metallic materials of very different mechanical resistance.

II. FINITE ELEMENT MODEL AND CALCULATION PROCEDURE

The model of finite elements proposed here will allow us to simulate the phenomenon of deformation present in a thread assembly under traction load in a simple and reliable way while considering the different parameters that influence the assembly behavior. Also, the technique of simulation-comparison to determine fully loads, based on a rupture criterion must allow us to model the phenomenon of initial failure in the assembly.

A. Model characteristics

In the proposed model we dismiss the helical angle of the thread; that allows us to use an axisymmetric model. This feature gives us a diminution in calculation time. A similar model was used by us for the calculation of the stripping of the threading in an assembly of bolt and nut [9] to [11]. The threading in the assembly is of heavy step and is defined by ISO standard NF E03.001/ISO 68. The friction and the sliding as well as the possible separation of the faying surfaces are possible and are allowed during the simulation. Static load is applied to traction to the bolt without considering the initial tight torque. The used materials have elasto-plastic characteristics, which have been determined from tests of traction in the universal machine [9].

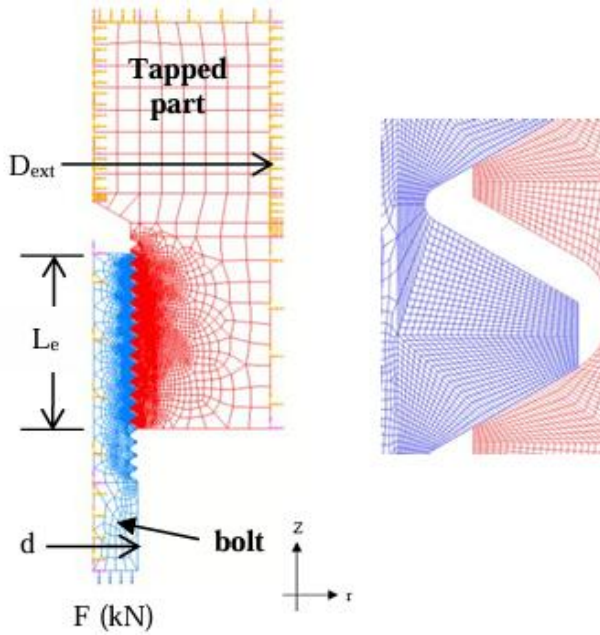


Fig. 1 Finite elements model. On the left side, the axisymmetric model. On the right, threads in contact.

B. Model description

As shown in figure 1, the engaged mesh made in the threading is refined and regulated since it is in this zone where the greater concentration of plastic deformation appears. The rest of the model network was made free to reduce calculation time. We used axisymmetric elements of fourth order with four nodes of reduced integration with isotropic characteristics and elastoplastic material with hardening by deformation.

C. Model refinement

We made a study of convergence of the mesh in the engaged thread; for the plastic unitary deformation, local Von Mises stress, and for the applied force for each diameter used in our analysis. We obtained convergence with a minimum of 31 elements in contact in the most affected zone [9] to [11]. The obtained results of load against displacement are very close to the ones obtained in the behavior during the test of traction of the assembly in a universal machine. Figure 2 shows this comparison.

D. Simulation procedure

To determine the load at the moment of the failure, we followed the same procedure as in [9]. First, we detected the element with greater plastic deformation. When the plastic deformation of the most damaged element, calculated by software is practically equal to calculated by the criterion of rupture by damage [12], we get the applied load. This value corresponds to the load at the beginning of the macroscopic rupture.

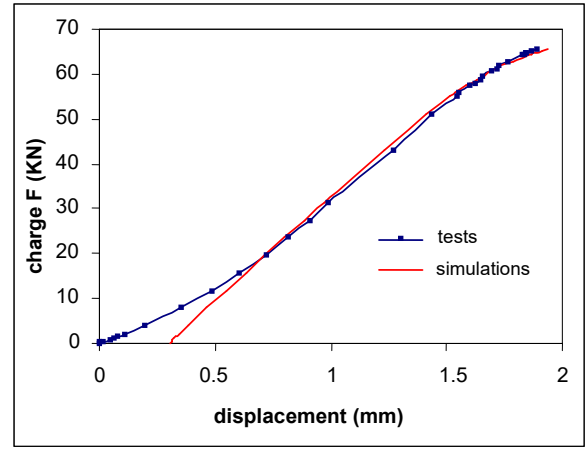


Fig. 2 Evolution of bolt displacement versus applied charge. Comparison of Tests and simulation results.

Table 1 shows results in one pass of simulation for an Aluminum part AU4G, with an applied load that causes the virtual rupture. The value of PEMAG represents the accumulated plastic deformation in the most damaged element. The value of P_R is the maximum plastic deformation up to rupture according to the criterion used and for characteristics of the material in study, as it is in the equation (1).

$$P_R = 0.25 \left[0.88 + 1.08 \left(\frac{\sigma_H}{\sigma_{VM}} \right)^2 \right]^{-0.893975} \quad (1)$$

The values of the hydrostatic stress (σ_H) and Von Mises (σ_{VM}), are also obtained and calculated from the results of simulation for the same element. We could notice in [9] that this procedure of calculation gave good results and was very close to those obtained in laboratory tests as it is in figure 3.

TABLE I
SIMULATION RESULTS IN DAMAGED ELEMENT (DAMAGE AT 400 MPa)

ELEMENT	PT	S11	S22	S33	MISES	PEMAG	SH	Py	PI-PEMAG
13434	1	-3.88E+04	-1.21E+05	-5.60E+04	4.97E+05	2.99E-02	-71847.6667	3.29E-02	2.99E-03
13435	1	-9.74E+04	-4.46E+05	-2.21E+05	4.82E+05	1.81E-02	-254842.667	2.58E-02	7.76E-03
13482	1	-2.99E+04	4.61E+04	1.09E+05	4.39E+05	3.85E-03	41628.6667	3.33E-02	2.95E-02
13483	1	-2.96E+04	1.66E+04	9.88E+04	4.36E+05	3.33E-03	28577.6667	3.35E-02	3.01E-02
13484	1	-6.38E+04	8.89E+04	5.41E+04	4.85E+05	2.01E-02	26401.6667	3.35E-02	1.34E-02
13485	1	-1.13E+05	-2.54E+05	-1.68E+05	5.04E+05	3.81E-02	-178183.333	2.96E-02	-8.51E-03
13530	1	-3.33E+04	4.90E+04	1.14E+05	4.34E+05	3.07E-03	43308.6667	3.33E-02	3.02E-02
13531	1	-7.85E+04	4.56E+04	6.99E+04	4.48E+05	5.50E-03	12347.6667	3.36E-02	2.81E-02
13532	1	-1.14E+05	8.68E+04	1.52E+04	4.93E+05	2.68E-02	-4089.33333	3.36E-02	6.84E-03
13558	1	1.45E+05	1.34E+05	2.43E+05	3.50E+05	0.00E+00	174276.667	2.65E-02	2.65E-02
13559	1	-1.65E+05	6.06E+04	6.17E+04	4.36E+05	3.33E-03	-14322.3333	3.36E-02	3.03E-02

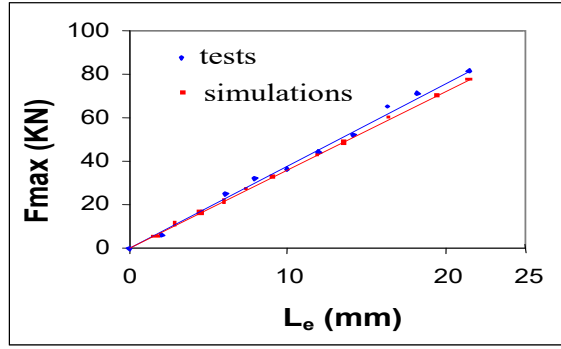


Fig. 3 Comparison of tests and simulation results. Threaded assembly M10 12.9/AU4G.

III. STUDY PARAMETERS

Using the proposed model, we made a finer qualitative study for a better understanding of the effect of each present parameter in the behavior. The retained parameters are the length of the engaged thread, the resistance of the material of the bolt or the resistance of the tapped part, the ratio of these resistances, the size of the tapped part and the diameter of the cross-section of the bolt. This allowed us to put in evidence the effect and behavior of these parameters.

A. Effect of the threads engagement length (L_e)

We varied the length of the engaged thread (L_e) in our finite elements model. The other parameters to be considered were maintained constant during the simulations. We obtained the load up to the stripping of the thread and rupture of the bolt for each L_e value. We could observe that the behavior of the load with respect to the length grew almost linearly in the case of the stripping of the thread of the bolt or the tapped part, until reaching the virtual cross-section rupture of the bolt. This same load was compared with the calculated one from the resistant section [1]. See figure 4.

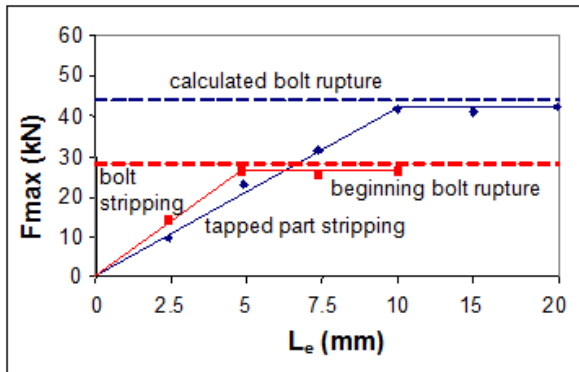


Fig. 4 Development of the Fmax load according to L_e .

B. Effect of the strength of bolt (R_{mb}) and tapped (R_{mp}).

We simultaneously studied the behavior of the stripping of the thread of the bolt according to different materials for the bolt and the same material of the tapped part. Later, we made

a similar study for the stripping of the tapped part for different materials for the part and same material of the bolt simultaneously. The other parameters were also maintained constant simultaneously. We determined that the stripping load, either for the case of the bolt or the case of the tapped part, has a linear behavior with respect to the ultimate strength of its material. See figure 4.

Also, we studied this behavior changing other parameters and, in all cases, we found the same linear behavior, but with different slopes. See figure 5.

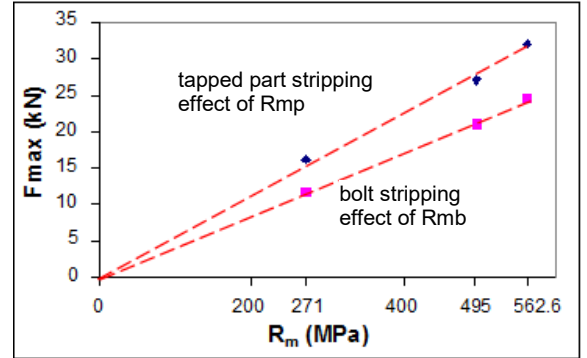
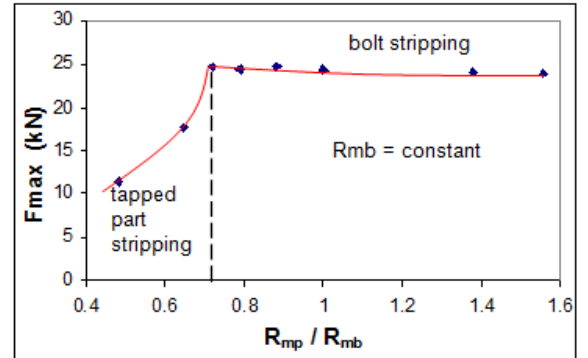
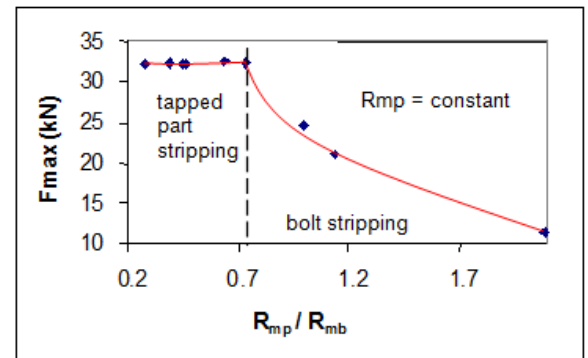


Fig. 5 Development of the Fmax load according to R_m , for effects of R_{mb} and R_{mp} .



(a)



(b)

Fig. 6 Development of the Fmax load according to R_{mp}/R_{mb} ratio (RR_m). (a) R_{mb} constant, (b) R_{mp} constant.

C. Effect of the relation between R_{mb} and R_{mp}

To analyze this effect, we maintained lengths of thread that assured us that the stripping happens before the cross-section rupture of the bolt. We varied the characteristics of the material of the tapped part for each material of the studied bolt and vice versa. Given the results from the tests and simulation, we decided to involve the ratio of the resistance of the materials of the part to the resistance of the bolt (R_{mp}/R_{mb}), and we called this ratio of strengths (RR_m) as in [1] and [3].

We varied this parameter for each value of (R_{mb}) and for several values of the other parameters, also, for each value of (R_{mp}) and for several values of the other parameters. See figure 6.

It is possible to notice that under $RR_m = 0.73$, the stripping of the thread of the part happens without apparent deterioration of the thread of the bolt [9]. Also, above this value, the stripping of the bolt thread happens, as is verified by the results of the laboratory tests in [11]. This behavior is not linear in both cases.

D. Effect of the tapped part size

This parameter determines the radial rigidity of the tapped part and therefore the influence of the radial mechanical expansion of the part due to the pressure of contact exercised by the threading of the bolt. We considered this parameter as the external diameter of the part, since we considered it axisymmetric. In fact, a reduction of the external diameter has therefore an increase of the radial expansion of the tapped part reducing its resistance to the stripping of the thread. The evolution of this parameter is related to the diameter of the bolt; therefore, we present the effect of the external diameter as a ratio of this one to the diameter of the bolt ($RD_d = D_{ext}/d$) as a significant parameter which is not linear under a value of 2.0

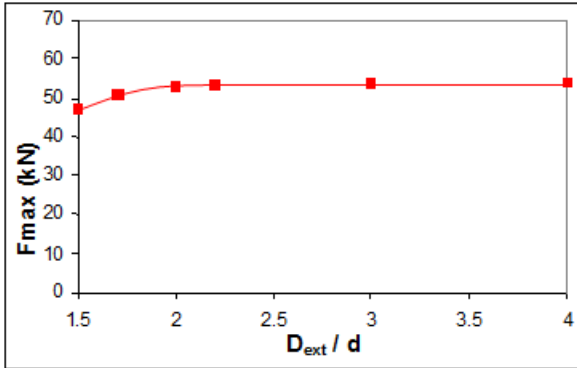


Fig. 7 Development of the F_{max} load according to D_{ext}/d ratio (RD_d).

Additionally, we examined the impact of the RR_m parameter on the effect of the RD_d parameter. For the studied superior limit of RR_m , the behavior of the load with respect to RD_d behaves asymptotically, i.e., it tends to be constant for $RD_d > 2.0$. Then we concluded that above this value, the increase of the external diameter does not present an

additional effect in the radial rigidity of the threading. See figure 7.

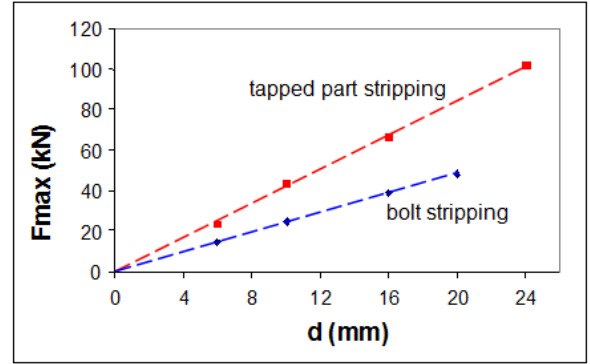


Fig. 8 Development of the F_{max} load according to d diameter for tapped part stripping and bolt stripping with $RD_d = 3$.

E. Effect of the bolt diameter (d)

The nominal diameter of the bolt is the fifth parameter that we studied. We obtained a linear evolution in the behaviour of the stripping load and the diameter of the bolt, figure 8. We varied this parameter using values between 6 and 20 and up to 24 mm, having fixed the value of RD_d . Also, we varied the RR_m parameter and we obtained the same behaviour.

IV. EXPERIMENT DESIGN

The study of the parameters allowed us to conclude that the load that causes the stripping of the bolt thread or the one of the tapped part, as well as for the rupture of the cross-sectional area of the bolt, can be represented as a function of the most significant parameters, $F = f(L_e, R_{mp}, R_{mb}, RR_m, RD_d, d)$. To determine this function and to propose an equation for the calculation of load F , we have developed a model of experiments design.

Since some parameters have a linear influence, we made this analysis for a specific case later to be generalized. Then, for the diameter of given bolt, a given engagement length and a specific type of material of the tapped part or the bolt, we studied the influence of two parameters of study, RR_m and RD_d .

We conformed a model of factorial experiments design at three levels since we suppose that they have a quadratic behaviour, see table 2. From the results of the experiments design we constructed, for the study of the bolt, a model of second degree for the stripping load for a XC38 bolt, with a diameter of 10 mm and an engagement length of 4.5 mm. For the study of the tapped part, we constructed a model of second degree for the stripping load for a AU4G part, with a diameter of bolt of 10 mm and an engagement length of 6 mm. And considering the linear effects of parameters d , R_m and L_e , we obtained for both cases equations of the following form.

$$F \text{ (kN)} = C d R_m L_e \quad (2)$$

TABLE II
LEVELS OF EXPERIMENT DESIGN PARAMETERS

Level	RRm Rmb = Constant	RRm Rmp = Constant	RDd
1	0.88	0.19	1.5
2	1.38	0.25	1.7
3	1.55	0.73	2.0

Where C is a dependent variable of RRm and RDd for the cases of stripping of the thread of the bolt or the tapped part, see table 3. This table allows the calculation of the parameters of the load that causes the beginning of the stripping of the threading, according to the case of analysis of C and Rm. Within the established limits of the value of the proposed parameters, this load is substantially the same that the one that causes the complete stripping of the thread.

TABLE III
PARAMETERS TO CALCULATE F (kN)

	Tapped part $R_m = R_{mp}$	Bolt $R_m = R_{mb}$
C	$\left(\frac{-2.6719 + A_1 + A_2 + A_3}{1980} \right)$	$\left(\frac{-82.71533 + A_1 + A_2 + A_3}{25317} \right)$
A ₁	$0.19 < RRm < 0.73$ $0.14341 RRm + 0.4658 RRm^2$ $RRm > 0.73$ 0.352914	$0.88 < RRm < 1.55$ $27.5635 RRm - 10.1981 RRm^2$ $RRm > 1.55$ 18.2225
A ₂	For $1.5 < RDd < 2.0$ $5.1371 RDd - 1.2944 RDd^2$ For $RDd \geq 2.0$ 5.0966	For $1.5 < RDd < 2.0$ $91.991 RDd - 24.89765 RDd^2$ For $RDd \geq 2.0$ 84.3894
A ₃	For $0.19 < RRm < 0.73$ and $1.5 < RDd < 2.0$ $-0.255 RRm RDd$	For $0.88 < RRm < 1.55$ and $1.5 < RDd < 2.0$ $2.06328 RRm RDd$

V. RESULTS COMPARATION

We have validated the equation (2) using simulations and tests for different cases not used in the procedure from the experiments design.

Table 4 compares the considered value of F with the obtained value of finite elements F_{SIMS} for stripping of thread of the part. Table 5 compares the value of F with the ones obtained in tests of laboratory F_{TESTS}. The table 6 compares the considered value of F with the obtained value of finite elements F_{SIMS} for stripping of thread of the bolt. For all cases a good correlation of the results can be observed. In fact,

paired t-tests were made, with a 95% of confidence level and no statistical difference was noticed in the obtained results getting t-value of 2.03.

TABLE IV
SOME RESULTS. TAPPED PART STRIPPING, COMPARISON WITH SIMULATION RESULTS

Case	L _e (mm)	d (mm)	RDd	F (kN)	F _{SIMS} (kN)
St 8.8/Cu	4.5	10	1.5	12.86	13.20
IN100/AU4G	4.5	10	2.0	26.43	26.51
St 8.8/XC38	8.0	16	1.5	81.00	78.80
St 12.9/Cu	8.0	16	1.5	37.42	39.10
St 10.9/AU4G	3.0	6	2.0	10.13	9.68
35NC16/XC38	4.5	10	1.7	28.312	29.3
St 12.9/Cu	3.0	6	1.7	5.28	5.43

TABLE V
SOME RESULTS. TAPPED PART STRIPPING, COMPARISON WITH TESTS RESULTS

Case	L _e (mm)	d (mm)	RDd	F (kN)	F _{TESTS} (kN)
CHc12.6/XC18	6.3	14	2.0	48.175	49
CHc12.6/XC18	11.7	14	2.0	89.472	92
CHc12.6/XC18	16.8	14	2.0	128.47	130
St 12.9/ AU4G	10	10	2.0	58.3	59.9
St 10.9/Cu	10	8	2.0	25.5	26.1
St 10.9/XC38	10	10	2.0	66.351	67.6

TABLE VI
SOME RESULTS. BOLT STRIPPING, COMPARISON WITH SIMULATION RESULTS

Case	L _e (mm)	d (mm)	RDd	F (kN)	F _{SIMS} (kN)
Cu /St 8.8	5.0	20	1.5	23.1	22.2
AU4G /IN100	4.5	10	2.0	22.5	20.58
XC38 /St 8.8	4.0	16	1.5	33.2	29.66
Cu /St 12.9	4.0	16	1.5	15.2	14.07
AU4G /St 10.9	4.0	6	2.0	12.65	10.83
XC38 /35NC16	4.5	10	1.7	28.31	29.3
Cu /St 12.9	4.0	6	1.7	5.28	5.57

VI. CALCULATING A MINIMAL THREADS ENGAGEMENT LENGTH

As it was possible to notice previously, for the presented types of failure in a threaded assembly, a minimum engagement length of thread exists to prevent the stripping of the threading of the bolt or that of the tapped part, and for which above of this length the rupture of the cross-sectional of the bolt appears, in case of failure. This type of rupture was modelled using our model of finite element in different cases from assemblies considering material and dimensions. As were demonstrated in [10], in most of the cases, we determined the beginning of the rupture of the bolt by modelling with comparable results to the equivalent ones

calculated according to the resistant section of the bolt (A_s) and the ultimate strength of the material ($F_{\text{bolt rupture}} = R_{mb} A_s$) [1]. Table 7 shows some results of the calculation of maximum load compared with the results from the simulation.

TABLE VII
SOME RESULTS. BOLT RUPTURE, COMPARISON WITH SIMULATION RESULTS

Case	F_{AS} (kN)	F_{SIMS} (kN)
Cu/Cu, $d = 10\text{mm}$, $L_e = 19.5\text{mm}$	15.718	15.22
XC38/Cu, $d = 10\text{mm}$, $L_e = 12\text{mm}$	32.63	30.67
AU4G/St 12.9, $d = 6\text{mm}$, $L_e = 6\text{mm}$	9.95	10.2
XC38/AU4G, $d = 16\text{mm}$, $L_e = 14\text{mm}$	88.33	87.6
AU4G/St 8.8, $d = 10\text{mm}$, $L_e = 7.5\text{mm}$	28.71	29.1

Given a maximum load up to the rupture of the bolt calculated from its resistant section, equations can be proposed for the calculation of the minimum engagement length, as they appear next in table 8.

TABLE VIII
MINIMAL ENGAGEMENT LENGTH TO AVOID THREADS STRIPPING

For similar materials	For light alloy parts
$L_e \geq \left(\frac{A_s}{C d} \right)$ or $L_e \geq 0.8 d$	$L_e \geq \left(\frac{A_s}{C d R R_m} \right)$

Table 9 shows some results of the calculation of the minimum engagement length, obtained from the equations of table 8 and compared with the lengths measured in tapped parts under traction load.

TABLE IX
SOME RESULTS. BOLT RUPTURE, COMPARISON WITH TESTS RESULTS

Case	L_e (mm)	L_e TESTS (mm)	Fail
St 12.9/AU4G, $d = 10\text{mm}$	14.44	14	Bolt rupture
St 12.9/AU4G, $d = 10\text{mm}$	14.44	13.5	Part stripping
St 10.9/AU4G, $d = 8\text{mm}$	9.42	9.5	Bolt rupture
St 10.9/AU4G, $d = 8\text{mm}$	9.42	9	Part stripping
St 12.9/Cu, $d = 10\text{mm}$	26.38	18.2	Part stripping
St 12.9/Cu, $d = 10\text{mm}$	26.38	21.5	Bolt rupture
St 12.9/Cu, $d = 10\text{mm}$	26.38	23.2	Bolt rupture
St 8.8/Cu, $d = 8\text{mm}$	11.39	8	Bolt rupture
St 10.9/XC38, $d = 10\text{mm}$	10.67	8.5	Bolt rupture
St 10.9/XC38, $d = 10\text{mm}$	10.67	6	Part stripping

VII. CONCLUSION

An equation for the calculation of the load applied in a threaded assembly is proposed, considering threaded light alloy parts and steel bolts. The equation can be used to dimension assemblies of tapped parts in aluminum. Also, the type of failure in the assembly can be predicted; by stripping of the threading of the part or the bolt or the rupture of the bolt. This model is valid only in the range of variations of the parameters studied and only in tensile load application, no tightening torque is considered. As can be noticed in the results, the calculations made with the proposed equation, are not statistically different from the ones calculated by model of simulation F_{SIMS} . This represents an important contribution, especially for the cases in which the acquisition of specialized software is not possible.

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