EXPERT SYSTEMS – FASTENERS THREADED DESIGN

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Abstract. The purpose of these instructions is to serve as a guide for formatting papers to be published in the Proceedings of the XXII COBEM. The abstract should describe the objectives, the methodology and the main conclusions of the paper in about 200 words. It should contain neither formulae nor reference to bibliography. The abstract will be included in a printed volume to be distributed to the symposium participants, whilst the full paper will be published in the proceedings CD-ROM.)

Keywords: Expert Systems, Fasteners Threaded, Machine Design

1. INTRODUCTION

Expert systems are computer programs designed to emulate the decision-making ability of a professional expert in a certain area. An expert system has a unique structure, different from traditional computer programming. It is divided into three parts, the interface engine, the knowledge base and the dialog interface. The interface engine reasons about the knowledge base like a human. It does so in a way faster and more efficient than any human could ever do. And the dialog interface gives the program the ability to communicate with the user.

The goal of the implemented system for this project is to aid the mechanical engineering designer during the development of mechanical projects, utilizing the computer to execute the tiresome and repetitive tasks, therefore, more susceptible to mistakes, like calculations and taking data from tables and graphs. This system may drastically reduce the time spent in the formulation of the project as well as improving its efficiency, since it allows the engineer to test a diversity of different configurations and settings for the mechanical project.

The main purpose of expert system developed on this paper is to determine the proper dimensions of steel hexagonal bolts to a certain operation. In this system the user will find a diversity of conditions that may interfere in the performance of the bolts, such as temperatures, loading, type of screw and members setting.

By analyzing these multiple input parameters the system will run the calculations and display all the important variables to specify a bolt on multiple configurations. Then it's up to the user to use its experience to choose the adequate configuration for the given project. That's the beauty of the expert system, while it's a powerful tool to help the engineer achieve its goal as fast and efficiently as possible, it's also dependent on the expertise of the user.

2. FASTENING BOLTS

2.1 Applications

The application of bolts as fastening element is widely known for its characteristic of promoting a stable and yet detachable structure. Other applications of screws can also be found, like power transmission (spindles), closing holes, adjustments and regulation, these applications won't be presented on this paper though. Figure 1 presents some examples of the fastening applications of bolts.
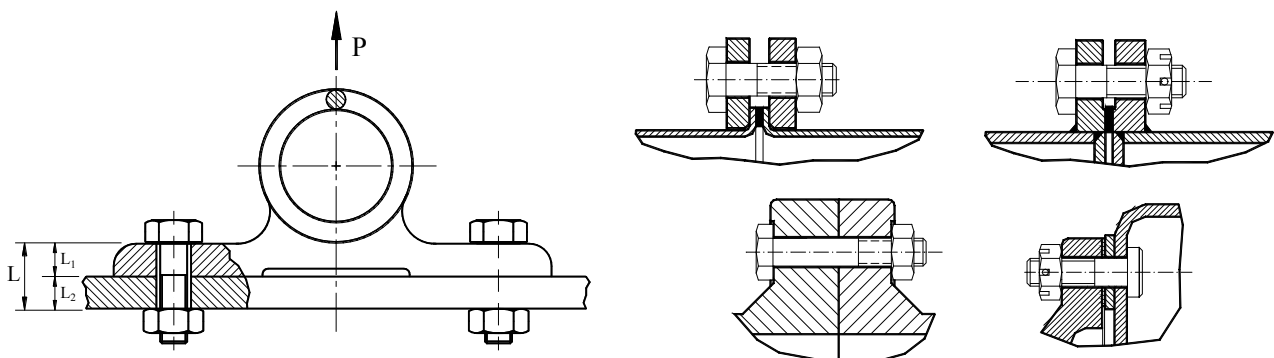

Figure 1 - Examples of fastening applications for bolts.

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In comparison with other types of fastening techniques, bolt fastening presents some disadvantages. One of them is not being able to ensure that the initial clench will be maintained, due to movement and vibrations, making it necessary to use security devices to prevent the bolt from getting loose.

2.2 Manufacturing bolts

Fastening bolts are most commonly manufactured by metal forming or machining, utilizing a diversity of materials, like steel, bronze, nickel, titanium alloys, aluminum, etc.

But what really matters to determine the resistance of the bolts is the manufacturing process of the screw thread, that can be done by machining (milling, turning, rectification), but they are widely produced by thread rolling. After the threading, the bolt may go through a surface treatment, like cadmium plating, zinc plating, chrome plating, nickel plating, phosphating, etc.

On this paper, only steel hexagonal bolts, according to the previous rules, will be treated.

2.3 Bolted joint theory

To determine the correct dimensions of a bolted joint the following consideration must be made: the bolt must bear, without fracture and without allowing the members to get loose, the external load P, on the members, and the internal loading, F_i, from the reaction of the members to the fastening. This way two conditions must be satisfied. The first is the compression condition, i.e, no separation on the members, stated on the Eq. (1). The second is the no fracture condition, stated in Eq. (2). If the bolt is subject to a dynamic loading yet a third condition must be satisfied, stated in Eq. (3) that represents Goodman's criteria for fatigue failure. Figure 2 shows the system to be analyzed.

$$F_m < 0 \qquad (1)$$

$$F_b < A_t S_{ut} \qquad (2)$$

$$\frac{m}{S_{ut}} + \frac{a}{S_e} < \frac{1}{SF} \qquad (3)$$

where: F_m = load on the members
F_b = load on the bolt
A_t = bolt area under tension
S_y = yield stress limit
S_{ut} = ultimate tensile stress limit
S_e = fatigue stress limit
$_m$ = medium tension
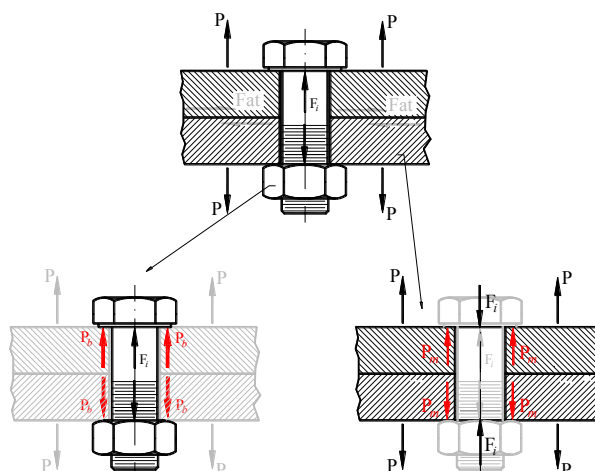$_a$ = amplitude tension
SF = safety factor

Figure 2 - Force analysis of a bolted joint.

The total load on the bolt is given by the combination of two portions: the initial fastening load, F_i and the external load on the members, absorbed by the bolt, P_b.

On the members, the total load is also given by the combination of two portions: the initial fastening load, F_i and the external load on the members, absorbed by the members, P_m. Equations (4) and (5) describe this behavior.

$$F_b = P_b + F_i \tag{4}$$

$$F_m = P_m - F_i \tag{5}$$

where: F_i = initial fastening load
$\quad\quad P_b$ = external load absorbed by the bolt
$\quad\quad P_m$ = external load absorbed by the members

To determine the portions of the load absorbed by the bolt and the members, P_b and P_m, it's necessary to consider that there is no gap between the elements.

$$\delta = \frac{P_b}{K_p} = \frac{P_m}{K_m} \tag{6}$$

$$P = P_b + P_m \tag{7}$$

where: δ = strain on the bolt and the members
$\quad\quad K_b$ = stiffness of the bolt
$\quad\quad K_m$ = stiffness of the members

Combining Eq. (6) and (7) yields:

$$P_b = \left(\frac{K_b}{K_b + K_m}\right)P \tag{8a}$$

$$P_m = \left(\frac{K_m}{K_b + K_m}\right)P \tag{8b}$$

The stiffness of the bolt can be determined by Eq. (9).

$$K_b = \frac{F}{\delta} = \frac{A_t E_b}{L} \tag{9}$$

where: E_b = elasticity modulus of the bolt
$\quad\quad L$ = bolt length

To determine the stiffness of the members it's necessary to analyze each element of the members as a compressible spring, which gives Eq. (10) and (11).

$$\frac{1}{K_m} = \frac{1}{K_1} + \frac{1}{K_2} + \cdots + \frac{1}{K_i} \tag{10}$$

$$K_i = \frac{P_i}{\delta_i} \tag{11}$$

But the load on each element, P_i, is not constant along the members, so to find each stiffness, Shigley supposes that the area under pressure of the members should be calculated according to a frustocone with an angle of 45°.
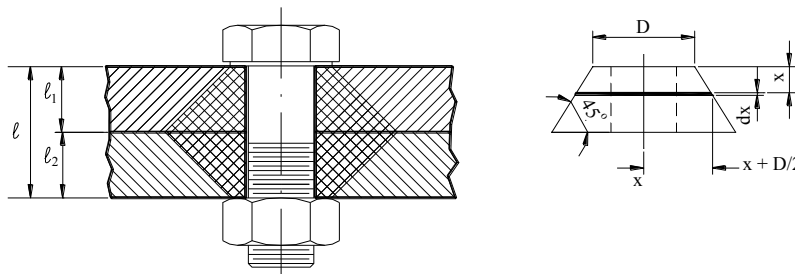

Figure 3 - Area under tension on the members.

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Referring now to Fig. (3), the contraction of an element of the frustocone with thickness dx subject to the compressive load P, is given by Eq. (12).

$$\delta = \frac{Pdx}{EA} \tag{12a}$$

The area of the element is

$$A = \pi \cdot (r_o{}^2 - r_i{}^2) = \pi \left[\left(x.\tan\alpha + \frac{D}{2} \right)^2 - \left(\frac{d}{2} \right)^2 \right] = \pi \left(x.\tan\alpha + \frac{D+d}{2} \right) \cdot \left(x.\tan\alpha + \frac{D+d}{2} \right) \tag{12b}$$

Substituting Eq. (12b) at Eq. (12a) and integrating, yields:

$$\delta = \frac{P}{\pi E} \int_0^l \frac{dx}{\left(x\tan\alpha + \frac{D+d}{2} \right)\left(x\tan\alpha + \frac{D+d}{2} \right)} \tag{12c}$$

Solving the integral we have the contraction for each element as

$$\delta = \frac{P}{\pi E d \tan\alpha} \ln\frac{(2l\tan\alpha + D - d)(D+d)}{(2l\tan\alpha + D + d)(D-d)} \tag{12d}$$

Ergo, using Eq. (11) and (12d) the stiffness of each element of the members is given by

$$K_i = \frac{\pi E_i d \tan\alpha}{\ln\frac{(2l\tan\alpha + D - d)(D+d)}{(2l\tan\alpha + D + d)(D-d)}} \tag{13a}$$

This theory was developed for a frustocone with an angle of 45º, this value overestimates the stiffness of the members, the typical value used for this angle belongs to the interval $25° < \alpha < 33°$. So for this paper the value of α will be taken as 30°. That finally gives Eq. (13b), that will be used to estimate the stiffness of each element of the members and with Eq. (10) will give the equivalent stiffness of the members, K_m.

$$K_i = \frac{0.5774\pi E_i d}{\ln\frac{(1.155l + D - d)(D+d)}{(1.155l + D + d)(D-d)}} \tag{13b}$$

Once both stiffness are know (K_b and K_m) the Eq. (4) and (5) can be rewritten

$$F_b = C_b P + F_i \tag{14}$$

$$F_m = C_m P - F_i$$

where: $C_b = \frac{K_b}{K_b + K_m}$ and $C_m = \frac{K_m}{K_b + K_m}$

Now that the loads on the members and on the bolt were found it's possible to evaluate the conditions stated by Eq. (1), (2) and (3) to determine whether or not the bolted joint will resist to the external load on it. But before the final equations can be stated, it's important to make the distinction between static loading and dynamic loading.

If the bolted joint is under static loading, Eq. (1) through (15) are enough to analyze it. But if the bolted joint is under dynamic loading it's necessary to calculate the fatigue stress limit, S_e, the medium tension, σ_m and the amplitude tension, σ_a. These tensions are given by the Eq. (16a), (16b) and (16c).

$$S_e = k_a k_c k_d k_e S_e' \tag{16a}$$

$$\sigma_a = \frac{C_b(P_1 - P_2)}{2A_t} \tag{16b}$$

$$\sigma_m = \frac{C_b(P_1 + P_2)}{2A_t} + \frac{F_i}{A_t} \tag{16c}$$

In Eq. (16a) the fatigue coefficients, k_a, k_c, k_d and k_e, are determined through a series of tables that depend on the operational conditions and some manufacturing characteristics of the bolt. And for axial loading, $S_e' = (0.566 - 9.68x10^{-5}S_{ut})S_{ut}$.

In Eq. (16b) and (16c) P_1 and P_2 are the maximum and minimum external loads on the bolted joint respectively. The final conditional equations to state if the bolted joint is safe for the operation characteristics are the following.

- For static loading:

$$C_m P - F_i < 0 \qquad (17a)$$

$$\frac{S_{ut} A_t}{C_b P + F_i} = SF > 1 \qquad (17b)$$

- For dynamic loading:

$$C_m P - F_i < 0 \qquad (18a)$$

$$\frac{S_e S_{ut}}{\sigma_m S_e + \sigma_a S_{ut}} = SF > 1 \qquad (18b)$$

Using all the equations presented on this section, it is possible to determine the exact safety factor and load on the members for a given configuration of bolt dimensions, members dimensions and work characteristics. These are very important variables for the project of a bolted joint.

3. EXPERT SYSTEM DESCRIPTION

The expert system developed was called BoltSpec. The programming language chosen was Python, and the program is compatible with the latest versions of the Windows operating system. Most of the features of the program are completely functional as long as it's running on a Windows operating system, but some of them require Microsoft Word and AutoCAD installed on the computer, as they have been prepared to generate files only manageable by these softwares.

3.1 Initial data input

Figure 4 shows the first window of the program, on that window the user can pass all the information needed to describe a certain operation involving a bolted joint as well as call all the other features of the program, like the design of a bolt and tension analysis for a bolted plate with multiple bolts.

Figure 4 - Data input screen.

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On the example show at figure 4 the chosen bolt was the M20x1.5 working with dynamic loading that goes from 1.5 kN to 78 kN at a temperature or 450 °C with a fastening load of 60 kN. With this set of parameters the safety factor is 1.169, the loading on the members was -7471 N (compression) and the estimated number of cycles before fracture was 21483.

Note that some other important parameters to evaluate the bolted joint like manufacturing condition and the configuration of the members, were not changed on this initial screen. To perform these changes and execute the program more accurately, the user must use the menu entitled "Editar". On this menu the user will find all the remaining parameters that might interfere on the performance of the bolted joint.Sometimes it's interesting to show the behavior of the important parameters as the fastening load varies, with that in mind, the user can use the button "PLOTAR" to find the graphs that describe this behavior.

Three other buttons are present on this screen:
[1] "CALCULAR" - is used to evaluate the parameters inputted;
[2] "AVALIAR" - evaluates the parameters and shows the user, if possible, the safe interval for the fastening load;
[3] "EMITIR RELATÓRIO" - generates a report on docx format, with all the information the user may need to analyze a bolted joint based on the inputted information (to use this function the user needs to install Microsoft Word on the computer);

3.2 Important windows

Another important parameter to perform the evaluation on the bolted joint is the configuration of the members. On the members window the user can choose up to 5 member elements to represent the members on the bolted joint. The member elements may have different lengths and materials.
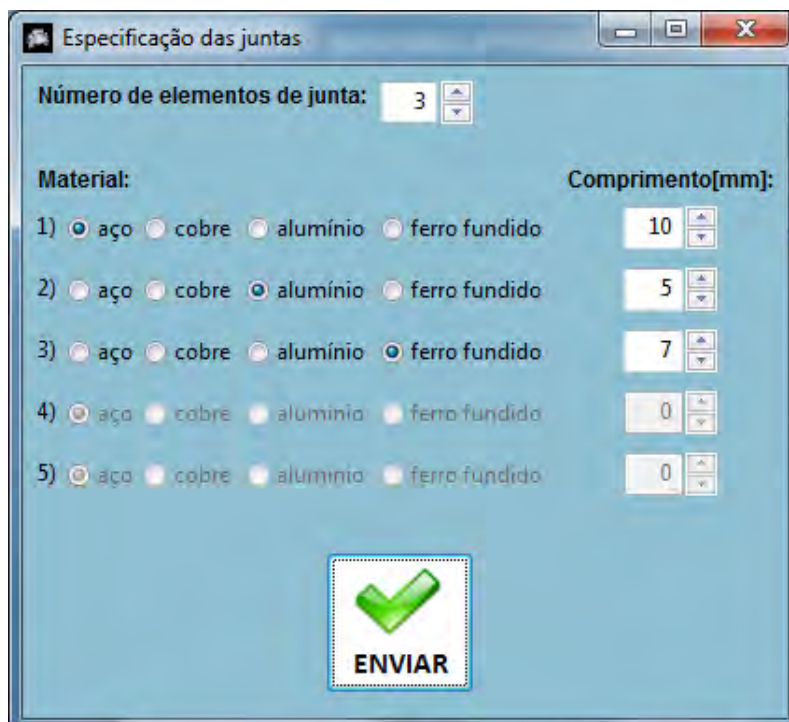

Figure 5 - Member configuration window.

Figure 5 shows a configuration of member elements with 3 elements with the following characteristics:
(1) Steel member with 10mm of length;
(2) Aluminum member with 5mm of length;
(3) Steel member with 7mm of length;

As stated previously, there are cases when it's important to observe graphs to make the best possible decision. On this window some very important graphs are available for the user. Figures 6a and 6b show the graphs that were plotted with the same parameters inputted for the previous example.
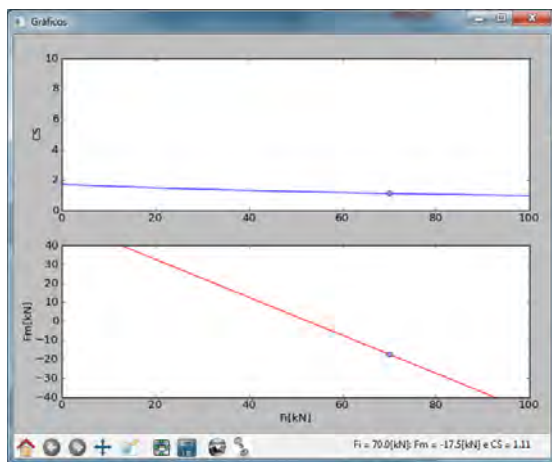
Figure 6a - Graphics for safety factor and loading on joint's members vs. load applied.
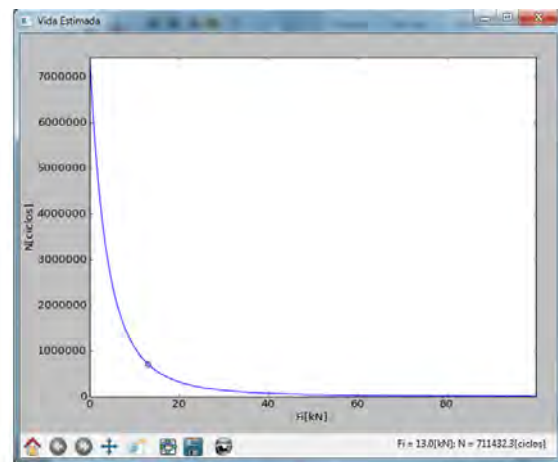

Figure 6b - Graphic for estimated number of cycles until fracture vs. load applied..

The plot presented in Fig. (6a) shows two graphs, one for the safety factor and other for the loading on the members. In Fig. (6b) the graphs show informs and estimate of the number of cycles until fracture.

The analysis of the three graphics is the best way to make a decision about the chosen bolt. Looking at the graphs from Fig. (6a) it's clear that even with really big fastening loads the safety factor is higher than 1, but as the fastening load grows, the number of cycles sustained by the bolt falls quickly. In this case, the graphs indicate that the critical conditions stated in Eq. (1), (2) and (3) are satisfied. But depending on the application and on the desired safety factor, it's up to the user to decide whether or not another bolt should be taken as solution to this operation.

3.4 Bolt design and multiple bolt analysis

One of the extra features that can be found in the menu entitled "Funções" is the design window. On this window the user can find the technical drawing of the bolt chosen on the data input screen.
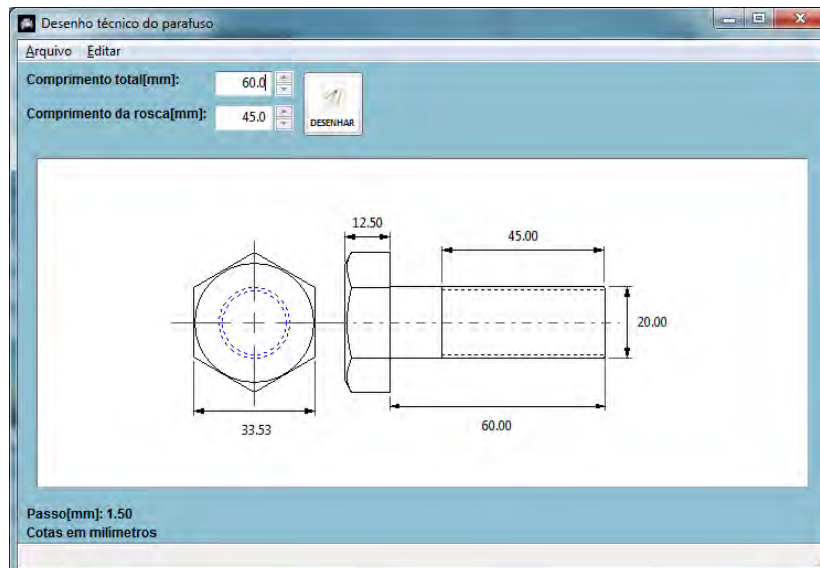

Figure 7 - Design window.

On this window it's possible to choose the type of head on type of head on the bolt as well of the way to represent the screw thread. This drawing can be saved as a jpeg file with no need to have any CAD (computer aided design) software installed on the computer. But if a precise and manageable drawing is needed and the user has AutoCAD it's possible to generate an AutoCAD version of tihe technical drawing. Note that the AutoCAD version of the technical drawing admits both 2D and 3D representations of the bolt. Figure 8 presents the three dimensional view of the bolt.

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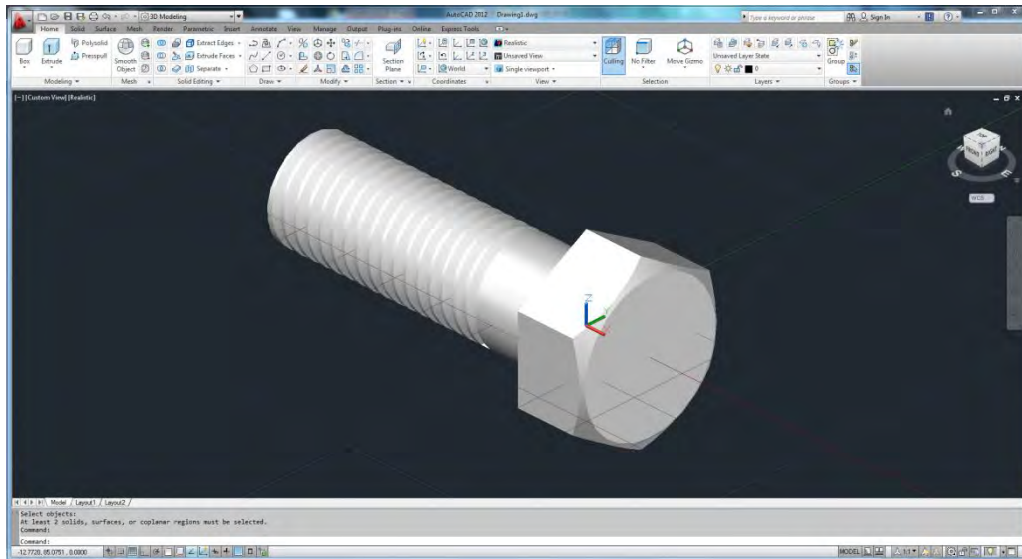Fasteners Threaded Design

Figure 8 - 3D AutoCAD model of the bolt.

The other function on the menu "Funções" gives the user the ability to simulate the installation of a circular plate with a certain number of bolts to perform the union. To perform this calculation the user needs to inform the diameter of the circular plate as well as the external loading on it. With this input, the program will use the parameters given on the initial screen relative to the other characteristics of the operation, such as members configuration and temperature.

Using this data the program returns a table containing all the possible arrangements of different sizes and categories of bolts that will result in a successful union, as shown in Fig. (9).

Figure 9 - Tension analysis for multiple bolts on a circular plate.

Note that on the bottom of the window the user has the option to choose a particular installation. On this example, with eleven M20x1.5 of class 8.8 fastened to a 43 kN load the safety factor was 1.01 and the loading on the members was - 0.50 kN, these results are consistent with what is shown on the table

from the upper part of the window. Even though the results show that this installation would satisfy the conditions (1) (2) and (3), it's reasonable to think that adding some extra bolts would advisable to be extra safe, but again, this is the user's decision.

If needed, there's also the possibility to create a 3D model of this installation on AutoCAD. To do so, the button "MODELO 3D" must be pressed and the user needs to inform AutoCAD's path on the dialog window.
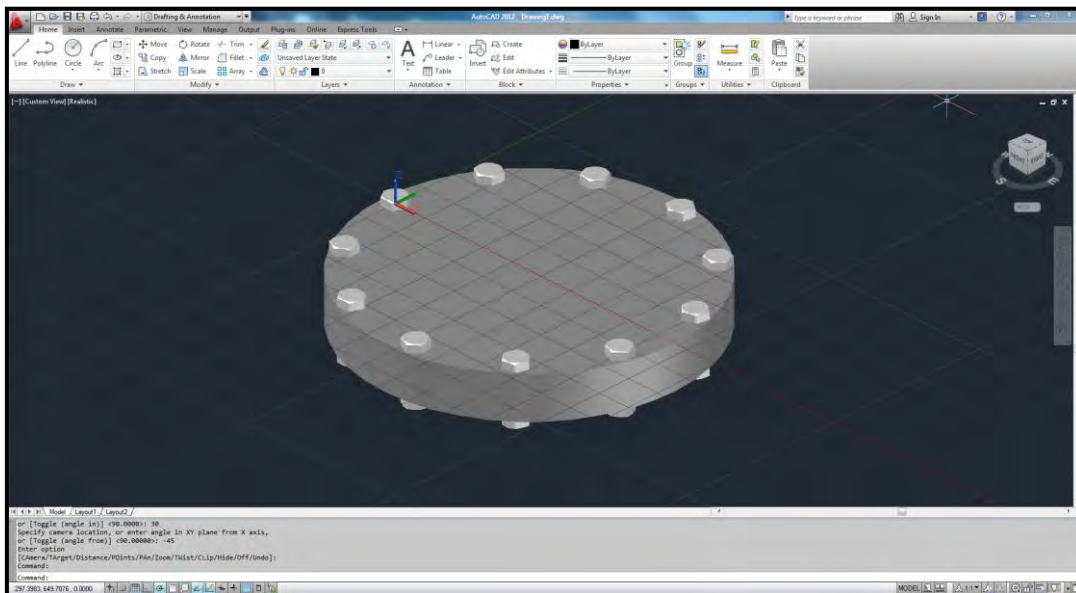

Figure 10 - 3D AutoCAD model for a circular plate fastened by eleven bolts

4. PROGRAM OVERVIEW AND COLCLUSIONS

We believe that developed work reached the initial objectives helping the engineers to find a optimized solution to the most diverse considered bolt models and configurations.

The developed algorithm offers to the mechanical engineer a powerful tool that it determines, with rapidity, efficiency and exactness of calculations, the most important characteristics of a suitable bolt to a certain application. On BoltSpec the user can simulate dozens of bolts configurations choosing the most adequate one.

All the dimensioning and calculations are based in associations like AGMA, DIN, ISO and ABNT, but we most followed the procedures shown in Richard G. Budynas & J. Keith Nisbett, 2011.

The operational system requirements is Windows 7, minimal system requirements to run AutoCad version 2012 or higher if needed; Python version 2.7; required disk space: 70 MB. Other programs that must be installed: Microsoft Word. No other programs or features are needed to run the program.

The presented program will help students and engineers, facilitating the calculations previously made manually. The algorithm was elaborated and developed with special concern in becoming it simple, efficient, auto clarifying and of easy understanding, everything in a friendly and pleasant environment. It is interesting to note that the project is controlling by the user. All decisions are taken by him; the program function as a guide and only display the results.

5. ACKNOWLEDGEMENTS

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