STATISTICAL MODEL FOR PRESSURE DISTRIBUTION OF A BOLTED JOINT

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This paper analyzes theoretically the contact pressure distribution in bolted metal joints. Based on previous data obtained by the authors, three different configurations were used for the bolted joints. The first one is composed by two aluminum discs; the second by two stainless steel discs and the third by aluminum and stainless steel discs. The discs are bolted through a hole in their center. Two screws with different bolt head radius were considered. Five different axial loads are applied for each bolted joint. Some existing models are compared against the data. As a good agreement between data and literature models is not achieved, a correlation for the pressure distribution between contacting surfaces, based on the Weibull distribution, is proposed, with a good match with experimental data.

Nomenclature

a	=	bolt hole radius
Al-Al	=	joint with two plates of aluminum
Al-Ss	=	joint with ane plate of aluminum and one of stainless steel
b	=	bolt head radius
c	=	contact radius
D%	=	percentage difference
F_a	=	axial force
Fe	=	model of [12]Fernlund
M Pa	=	model of [6]Madhusudana parabolic
P_a	=	average axial pressure
R^2	=	determination coeficient
Ss-Ss	=	joint with two plates of stainless steel
$\overline{X}_{y_i}$	=	average measured values
$Xy(r_i)$	=	average of value resultant of Weibull
α	= angle	
β, η, ρ	= Weibull parameters	
Jlmn	= joint configuration, *l* applied load, *m* joint material and *n* bolt used.	

I. Introduction

THIS work deals with contact pressure distribution in bolted joints. One of the several applications of bolted joints is in the thermal control system of microelectronics devices aboard spacecrafts and satellites. The pressure distribution between contacting surfaces in bolted joints plays a very important role in modeling the

thermal contact conductance. If the contact pressure distribution between the surfaces is uniform along the interface of the bolted joint, the contact conductance can be calculated using theorical results or correlations actually available in the literature. Many authors such as [12]Fernlund, [8,9]Motosh, [2,3,4]Chandrashekhara et al. show that the pressure reaches the highest peak near the bolt and decreases to zero in a distance of a few radii away from the centerline. Depending on the applied load, the contact can be lost in regions away from the bolt, as shown in Fig.1. The main objective of this study is to develop a contact pressure correlation, based on a probability density function named Weibull. The data collected by [14]Gonçalves and analysed by [13]Pereira is used. [14]Gonçalves studied six different configurations of bolted joints, subjected to five different axial loads. A correlation is presented for each configuration studied.

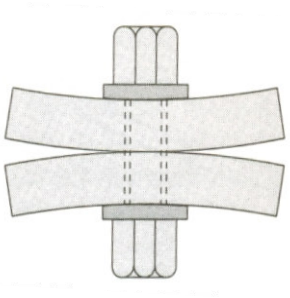

Figure 1. A typical bolted joint

II. Bolted Joint Configuration

[14]Gonçalves studied experimentally, at the Texas A&M Laboratory, the pressure distribution of contacting surfaces of two plates connect by a bolt, using a pressure sensitive film manufactured by the Fuji Corporation. The pressure sensitive film consists of two sheets in contact, one containing very small ink bubbles. When the films are forced against each other, some of these bubbles rupture, dying the other sheet. The pressure data was compared against the total pressure applied, measured by means of a load cell located between the lower plate and the bolt head, as shown in Fig. 2. He tested three kinds of joints. The first bolted joint was composed by two plates of Aluminum 6061, the second by two plates of Stainless Steel 304 and the third by one plate of Aluminum 6061 and the other of Stainless Steel 304. He used two kinds of screws, with cap of different diameters. He also applied five different axial forces to the bolted joint.

The bolted joints are formed by circular plates of r_0 = 46 mm of outer radius. The thickness of the aluminum and stainless steel were d_{Al}=19 and d_{Ss}=13 mm, respectively. Each plate is lapped, so that the surface roughness of each plate is less than 3.7 μm. The plates were bolted together by means of a heat-treated cap screw. Two different bolt head radii are applied: b_1=5 mm and b_2=9 mm. The plate hole radius is a= 0.3 mm.

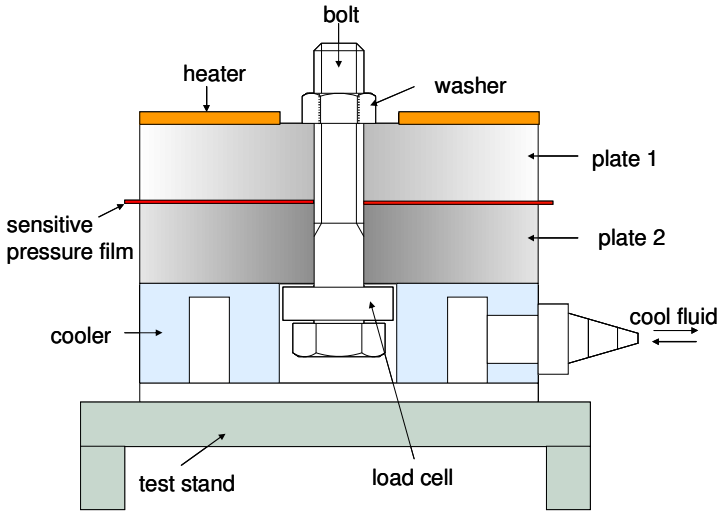

Figure 2. Schematic of the test facility.

The bolted joints formed by aluminum plates is denominated by Al-Al, those formed by two plates of stainless steel, by Ss-Ss and those formed by aluminum and stainless steel by Al-Ss. The following axial forces of *1624, 3247, 6672, 12233* e *18371 N* where applied to each configuration.

Table 1 shows a list of all the tests performed, denominated by *Jlmn,* where *J* means bolted joint, *l* axial force applied, *m* one of the three configurations of joints (*Al-Al*, *Ss-Ss* e *Al-Ss*) and *n* one of the two kinds of bolt (radius b_1 and b_2).

The results obtained by the pressure film can be converted to pressure distribution data by means of software developed by Fuji, the film manufacturer. The present paper authors believe that, while the load cell gives a good measurement of the applied load, the pressure film gives a god insight of the pressure distribution. As the total load obtained by the integration of the pressure distribution along the contact area in the radial direction is not equal to the load cell readings, the pressure distribution obtained by the film is corrected, so that the integration results is the same as the load cell measurements. Fig. 3 shows a typical pressure distribution of one of the joints studied, for the five applied axial forces. In the legend, the axial forces in the first column refer to the corrected *(c)* data results, while those of the right column,to the original data. In this plot, data is presented for b_1 (smallest cap screw radius) bolt. From this figure one observes that the axial load has a strong influence in the pressure distribution.

The average axial pressure is a very important data,used to non-dimensionalize the pressure distribuitions, which are compared with the literature models. The average axial pressure (P_a) is obtained by the axial force (F_a) divided by the bolt head area, which is circular of radius *b,* minus the hole bolt area, of radius *a*. Therefore the average pressure is determined from the expression:

$$P_a = \frac{F_a}{(b^2 - a^2)\pi} \quad (1)$$

The axial force F_a is measured by the load cell installed between the bolt head and the plate 2 as shown in Fig.2. This force should be the same of that obtained by the integration of the pressure distributed along the contact surface areas, according to the sensitive film data.

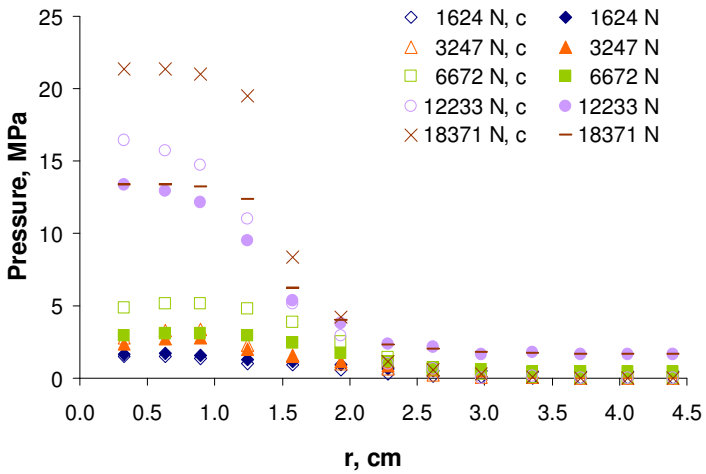

Figura 3. The original and corrected pressure distribution of *Al-Al, b_1*.

Table 1. Tests realized

	b_1			b_2		
Axial Force, N	*Al-Al*	*Ss-Ss*	*Al-Ss*	*Al-Al*	*Ss-Ss*	*Al-Ss*
1624	J111	J121	J131	J112	J122	J132
3247	J211	J221	J231	J212	J222	J232
6672	J311	J321	J331	J132	J322	J332
12233	J411	J421	J431	J412	J422	J432
18371	J511	J521	J531	J512	J522	J532

III. Literature Models

Numerical and analytical models developed to predict pressure distribution of bolted joints and experimental studies as well are found in the literature. Actually, the analytical models calculate the pressure distribution as a function of the contact radius, which is, in turn, functions of the contact plate thickness and of the bolt head radius.

Rötsher (see [12]Fernlund) was one of the first researchers to calculate the contact radius of two plates in a bolted joint. He considered that the joint stress disperses within a frustum cone of semiangle of 45°. He also considered that the interfacial pressure is constant up to the distance of the contact radius (*c*). This hypothesis was the first approximation for the contact radius, but the pressure distribution was not described satisfactorily.

[12]Fernlund developed an analytical method from the elasticity theory to obtain a pressure distribution on the interface of two plates bolted in function of his radius. The researcher used a Hankel transform method and considered that two bolted plates in contact, with the same thickness and material, can be represented by a single plate. The contact pressure between the two plates was assumed equal to the stress in the average plane of the single plate. As the method was difficult to apply, an approximate method was proposed, where the contact pressure was represented by a polynomial of fourth order, which is a function of the non-dimensional radius *r/a*.

[5]Gould and Mikic investigated pressure and contact radius using finite element method. They analyzed single and double plate models to describe two contacting plates, in several different geometric configurations. The comparison between their results shows that the contact radius calculated applying double plate model is significantly lower than that of the single plate. They also studied joints with plates of equal and of different thicknesses, concluding that the contact radius between plates with different thicknesses is lower than that of plates of the same thicknesses.

[1]Bradley et al. used freezing analysis technique of three-dimensional photoelastic stresses to measure the distribution pressure. Nine different geometries were studied. It was observed that increasing the ratio between the radius of the bolt head and the bolt hole, increase the level of the bolted joint pressure. Also, the increase of the plate thicknesses has the same effect.

[2,3,4]Chandrashekhara e Muthanna developed an analytical solution in terms of Fourier-Bessel series, treating the problem as if the plate is thick, with infinite size, with a circular hole in its center and submitted to an axissimetric

normal load. Various ratios of *t/a* and *b/a* were considered, for material with different values of the Poisson coefficient. The results, shows that the pressure in the interface tends to zero levels for r/*a* > 5. They also observed that, for elastic deformation, the only property of material that can affect the pressure distribution was the Poisson coefficient.

[6]Ito et al. measured the interfacial pressure distribution on bolted flanges by means of ultrasonic waves. These authors showed that the plate surface roughness, material and the thickness of the plates influence the pressure distribution and the contact radius. Stainless semi-hard (S45C), brass (BsBM1) and aluminum (AlB1) plates were investigated with applied axial forces varying from 9,8 to 19,6 kN. The bolt of stainless steel presented the highest contact pressure levels, when compared to those of brass and aluminum (the lowest values). They concluded that, the smallest the plate thickness, the highest the pressure levels. They maintained the lower plate thickness and varied only the upper plate thickness.

[7]Madhusudana et al. proposed three different pressure distributions on bolted plate joints: linear, parabolic and polynomial, depending on the plate thicknesses, the bolt hole radius and the bolt head.

[8]Mittlebach et al. developed an experimental study for both the interfacial pressure distribution and the thermal conductance of bolted joints. The variables considered included: bolt torque (the axial force), plate thicknesses and interface average temperature. They studied joints formed by plates of aluminum (6061-T6), with roughness lower than 3.7 μm, outer radius of 45.7 mm, *b/a* =1.6 and with ratio thickness of: 19.1/19.1, 12.7/19.1 e 25.4/19.1 mm. The axial load varied from 6.69 to 13.425 kN. The pressure distribution data were obtained with a pressure sensitive film. These researchers investigated various literature pressure distribution models, which were compared with experimental data. They concluded that the [3]Chandrashekhara and [12]Fernlund models were the best to adjust the experimental data. Besides, they verified that the peak pressure value obtained by Chandrashekhara was higher than that obtained by the Fernlund model, but, on the other hand, the Chandrashekhara contact radius value is smaller than Fernlund´s. They also noticed that, according to the angle of the frustum cone, Fernlund model approached to the results obtained by Chandrashekhara.

The experimental data of [8]Mittlebach et al. revealed that, for rough surfaces, the highest value of pressure was not next to hole of the bolted joint, but away from the hole. Another interesting aspect observed was that the variation of the thickness plate did not influenced considerably the contact radius, but presents high influence in the pressure distribution close to the bolt.

IV. Comparison of Experimental Data and Literature Models

In this section, the pressure distributions, obtained by [12]Fernlund and [7]Madhusudana models, are non-dimensionalized by the average axial pressure, given by Eq. 1. To allow the comparison, the data was also non-dimensionalized in the same way. These models are based on the contact radius, which is calculated using the Rötscher model, which depends on the angle α, the thickness *d* and bolt head radius *b*, through the following equation, which shows that, the larger the angle, the larger the contact radius:

$$c = b + d(\tan\alpha), \qquad (2)$$

[12]Fernlund and [7]Madhusudana models could not be used to Al-Ss joints, because these models are valid only for junctions composed with plates of the same material and thickness. Even though, the data were compared with models, considering that equal plates composed the joints.

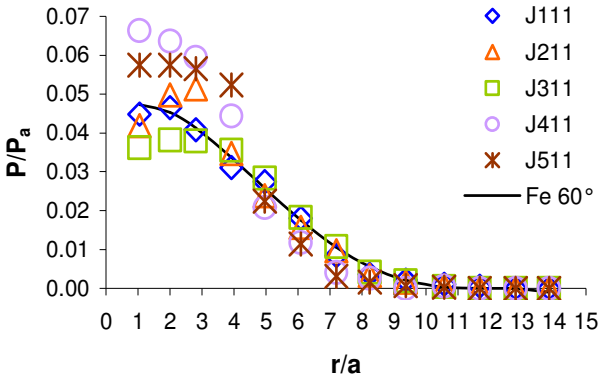

Figure 4. Fernlund model for *Al-Al*, b_1 and α=60°.

[3]Chandrashekhara e Muthanna proposed a model for the angle α, as a function of the ratio *d/a*. Angles α larger than 50°, where employed in their models for the joints analyzed in this work.

Figures 4 to 9 show only the model which presented the best comparison for each bolted joint tested. Even though, all data were compared with Fernlund model and with Madhusudana models, for linear, parabolic and polynomial pressure distributions, considering frustum cone angles of 50°, 55°, 60°, 65°. In these figure captions, the following nomenclature is adopted: Fe is for Ferlund model and M Pa for parabolic Madhusudana models. In each figure caption the angle used to calculate the model is also presented.

Figure 4, shows non-dimensional pressure data, obtained for the aluminum-aluminum joints, submitted to five different levels of axial load. This figure also contains the pressure distribution obtained by the Fernlund model, using an angle of α=60°. Data referring to aluminum-aluminum joints tightened by a bolt with head radius of b_2 is presented in Fig. 5 for Fernlund model with angle of 55°.

Joints composed by two stainless steel plates tightened by the b_1 bolt head, present better comparison with Fernlund model, for α=65°, as shown in Fig. 6. Even though the model do not characterize the decrease on the pressure near the central area, where the hole is located. For stainless steel joints with bolts with head b_2, for a parabolic Madhusudana model with α=65°, the plot in Fig. 7 can be obtained.

Figures 8 and 9, show a comparison of experimental data of Al-Ss junctions using both bolts. For the model application, two plates of Al-Al where considered for joint of Al-Ss (see Literature Models section). For bolt of radius head of b_1, the best comparison is obtained for Fernlund model, with α=65° (Fig. 8), while for the b2 bolte head junction, the best comparison is for the parabolic pressure distribution model of Madhusudana model, for α=65° (Fig.9).

Form these plots one can conclude that the *Al-Al* joints present the best comparison with the literature models, while only the *Ss-Ss* b_1 have a reasonable agreement with data and model, better than for the *Ss-Ss* b_2 joint. Also, the comparison between Al-Ss dada and models are not good. Therefore, a better model is needed. A correlation is proposed in the next section.

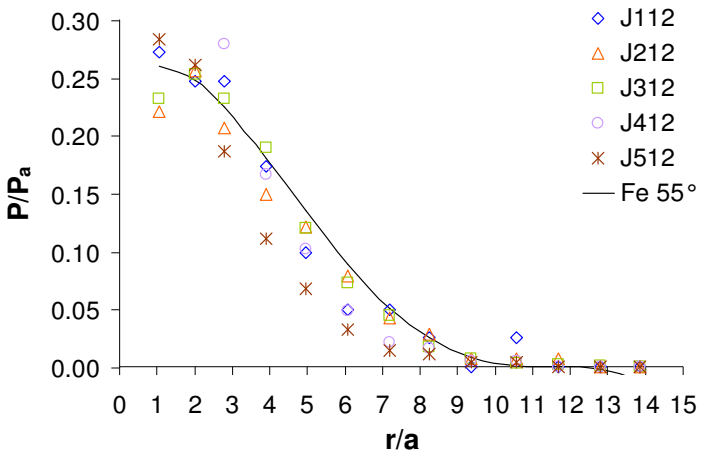

Figure 5. Fernlund model for Al-Al, b_2 and α=55°.

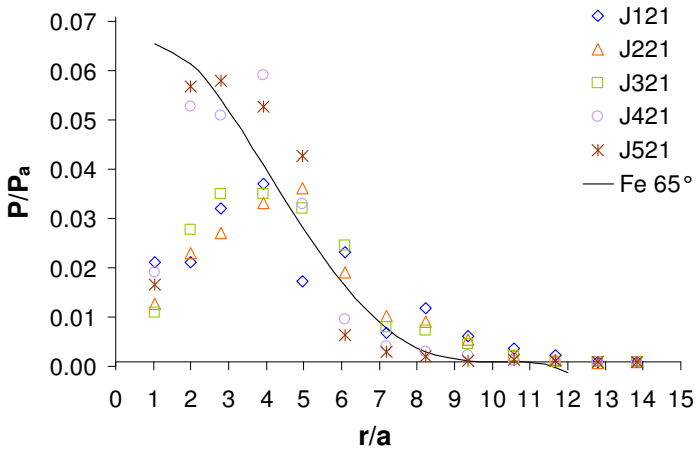

Figure 6. Fernlund model for *Ss-Ss*, b_1 and α=65°.

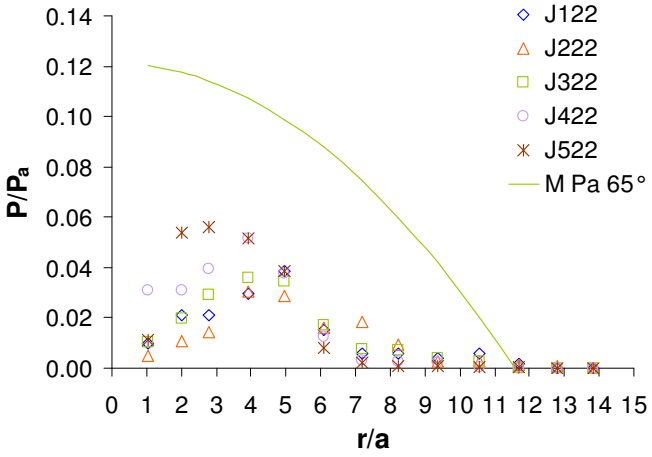

Figure 7. Madhusudana parabolical for Ss-Ss, b_2 and α=65°.

Figures 8 and 9, show a comparison of experimental data of Al-Ss junctions using both bolts. For the model application, two plates of Al-Al where considered for joint of Al-Ss (see Literature Models section). For bolt of radius head of b_1, the best comparison is obtained for Fernlund model, with α=65° (Fig. 8), while for the b2 bolte head junction, the best comparison is for the parabolic pressure distribution model of Madhusudana model, for α=65° (Fig.9).

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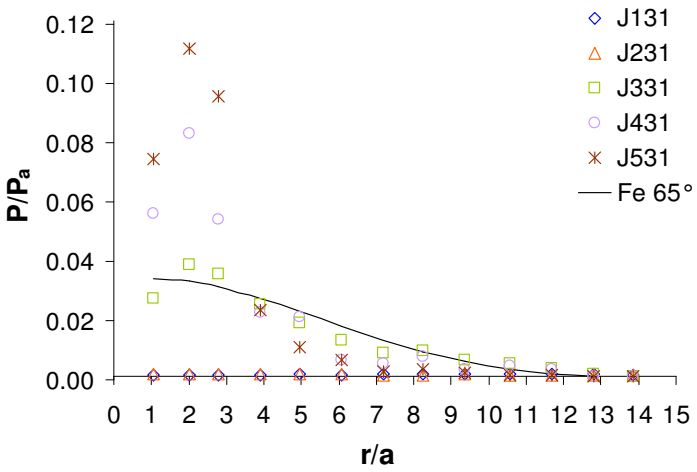

Figure 8. Fernlund model for *Al-Ss*, b_1 and α=65°.

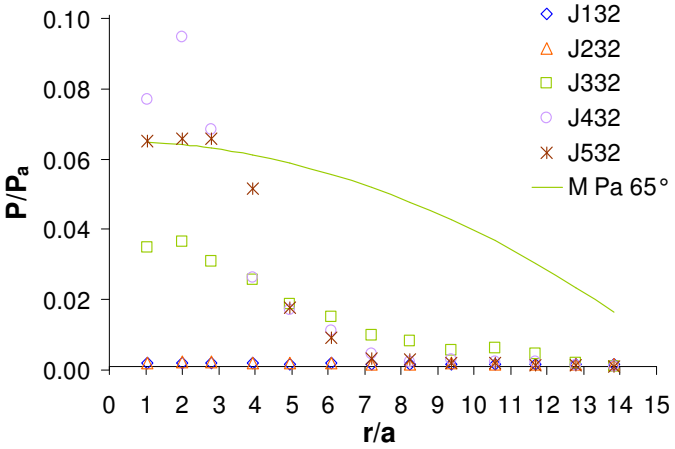

Figure 9. Madhusudana parabolic model for *Al-Ss*, b_2 and α=65°.

V. Statistical Model

A more precise correlation is proposed for the pressure distribution between two plates on a bolted joint. This correlation is based on a density probability function, denominated Weibull function.

The Weybull distribution is a probability density function used due to its versatility, in many fields, such as in life data analysis, in life tests engineering ([11]Meyer), survival analysis among mother areas..It is usually related to the probability of failure of the parameter under observation, such as human life (death), break of a mechanical structure, etc.

The general expression of Weibull distribution has three parameters and is defined mathematically as:

$$f(T) = \frac{\beta}{\eta}\left(\frac{T-\gamma}{\eta}\right)^{\beta-1} e^{-\left(\frac{T-\gamma}{\eta}\right)^{\beta}}, \qquad (3)$$

where T is the time, for example, of the material rupture, β is a parameter which established the curve shape, defining the slope of the Weibull distribution, η is a scale parameter, γ is a position parameter, $f(T) \geq 0$, $r \geq 0$, $\gamma, \beta > 0$, $\eta > 0$, $-\infty < \gamma < \infty$. When the position parameter is equal to zero, the resulting Weibull function distribution is called the two parameters Weibull distribution. This distribution can be reduced to just one parameter, when the shape parameter β is fixed, or if the scale parameter so the scale parameter η is set.

Weibull distribution can be applied to predict the contact pressure distribution, because it can be related to the failure of the contact, when the pressure goes to zero levels. It also can be related to the probability of the color points of one film to explode (end of life) dyeing the other film, showing the contact region. The dyeing represents probability to occur contact between plates of the bolted joint along the radius. In this work, the Weibull distribution of two parameters is used. This has shown to be enough to model the contact pressure distribution.

To be applied to the data, the Weibull distribution function was corrected by a parameter ρ, which assure that the curve integration along the contact area results in the total force obtained by the load cell readings. The following

equation, based on Weibull distribution of two parameters in function of plate radius is used in the comparison with data:

$$f(r) = \rho \frac{\beta}{\eta}\left(\frac{r}{\eta}\right)^{\beta-1} e^{-\left(\frac{r}{\eta}\right)^{\beta}} . \quad (4)$$

To fit this correlation with pressure distribution data, the EES (Engineering Equation Solver) software was used. The program looks for the best values of β, η e ρ.

As already mentioned, the parameters of the Weibull function have direct influence the resulting curve. The parameter β has the information about the curve shape: small values of β flattens the resulting curve, keeping the area under the curve the same. The η parameter causes a narrowing or stretching of the curve; the increase of η, displaces the curve to the left, increasing the peak values and increasing the area under the curve.

As already mentioned, the parameter ρ, is associated to the curve amplitude. This parameter presents higher values for the curve adjustment, when the applied axial force increases. This expected, once that the area under the pressure curve is related to applied force. The values of β, obtained for junctions with plates of equal materials stay almost constant for different values of applied load. On the other hand, this parameter changes very much with the junction materials. The values of β for junctions of Ss-Ss are higher than for Al-Al junctions. For the Al-Ss combination, this parameter is variable. The behavior of parameter η is very repetitive for all configurations analyzed, only with small variations.

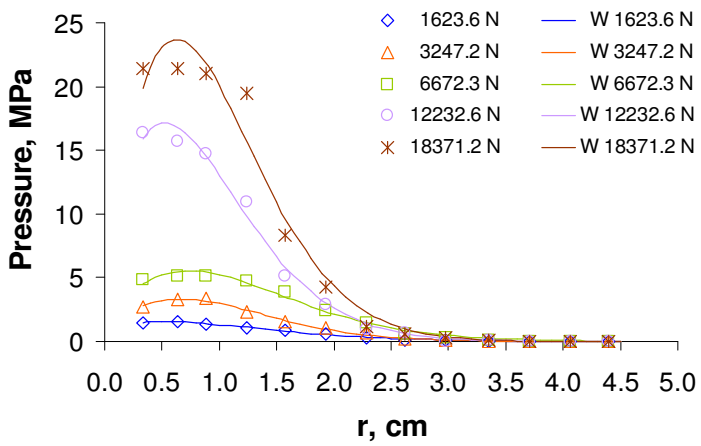

Figure 10. Adjustment of Weibull curves for *Al-Al*, b_1.

Figures 10 to 15, show the Weibull distribution curves (continuous lines) fitted to experimental data (symbols) for each bolted joint studied.

Figures 10 and 11 show the comparison between the Weibull curves and the experimental data to junctions made of Al-Al for both bolts. In these plots one can observa that, for low pressure levels, the comparison between the data and model is very good. With the axial pressure increase, the correlation overestimates the experimental data in the regions near of the bolt hole.

The correlations and experimental data of Ss-Ss bolted joints are shown in Fig. 12 and Fig. 13, for bolt of head radius b_1 and b_2. Mathematical models and the experimental data present a good comparison for low axial loads and for regions away from the plate center (bolt hole).

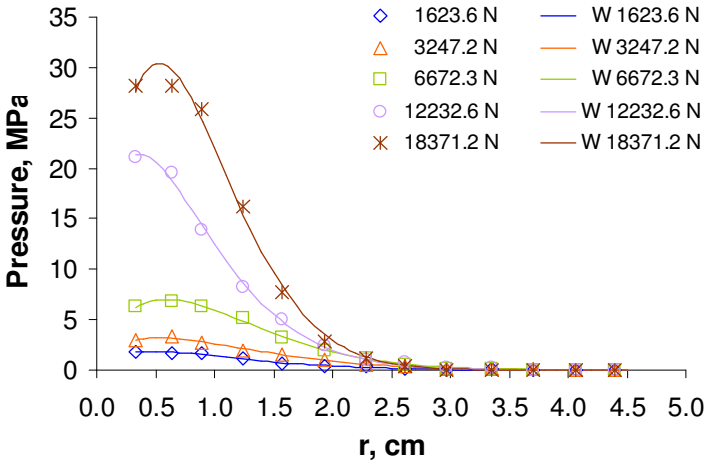

Figure 11. Adjustment of Weibull curves for *Al-Al*, b_2.

Figures 14 and 15 shows data related to *Al-Ss* junctions, for both b_1 and b_2 bolts In these figures it is observed that the Weibull curves fit well with data, near and far from the center plate.

The percentage difference between data and Weibull correlations to all bolted joints configuration studied are presented in Table 2. They are calculated by the following expression (5):

$$D\% = (1 - R^2)100\,, \qquad (5)$$

where R^2 is calculated by (6):

$$R^2 = \frac{\sum_{1}^{13} y_i - \overline{X}\, y_i}{\sum_{1}^{13} y(r_i) - \overline{X}\, y(r_i)}\,, \qquad (6)$$

where Xy_i is the average of the measured values, while $\overline{Xy}(r_i)$ is the average of the results obtained from the Weibull correlation.

Table 2 shows that the best comparison was obtained by joints composed by aluminum plates. According to the statistical analyses, the difference between data and correlation for bolted joints *Al-Al* reaches maximum values of 3.8% (see Figs. 10 and 11).

The best comparison can reach differences of 0.06%. The best comparison among the data and modes for *Ss-Ss* joints is 0.21%, to an axial force of 3247N. The worst agreement for these joints is 10.54%, for axial forces of 1624N. (see Fig. 12).

Finally, the Al-Ss joints presents a comparison of 0.10% for an axial force of 6672N, for the bolt of head b_2 (see Fig. 15) and 50.59% for axial force of 1624N, for the joint with the bolt head of b_1 (see Fig. 14).

In this work, it was not possible to estimate the values of β, η and ρ, as a function of bolted joints parameters. This would require a deep study of the behavior of the Weibull statistical function, which is beyond the objective of the present work and it is left for future work. In case of these Weibull parameters can be determined as a function of bolted joint parameters, it is believed that it will be possible to determine a single correlation for the pressure distribution of contacting surfaces of bolted joints.

VI. Conclusion

The literature models of [12]Fernlund and [7]Madhusudana et al. were applied to

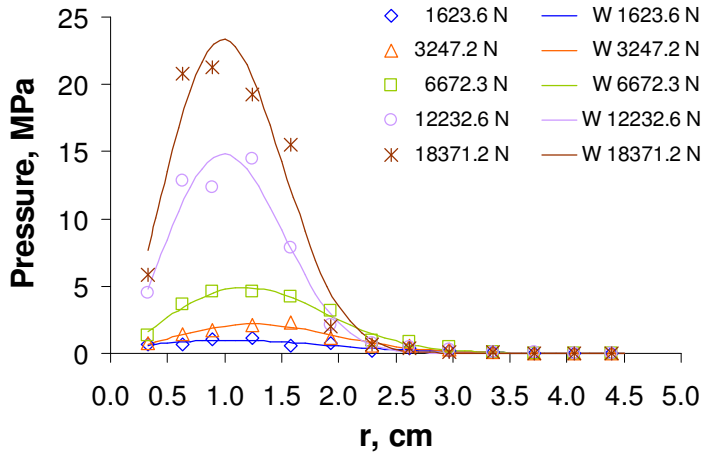

Figure 12. Adjustment of Weibull curves for Ss-*Ss*, b_1.

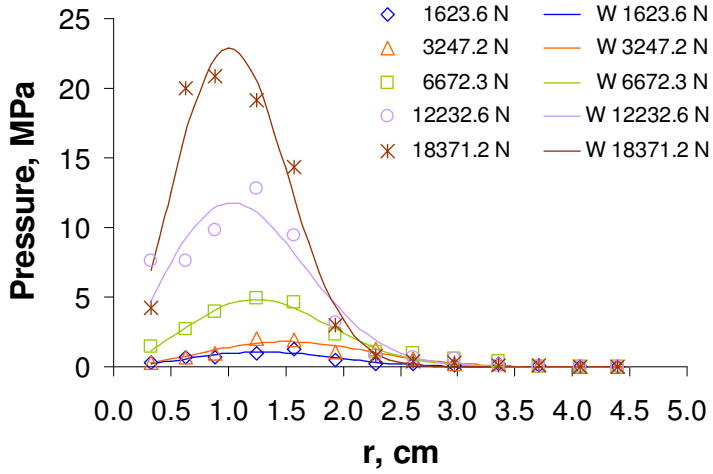

Figure 13. Adjustment of Weibull curves for *Ss-Ss*, b_2.

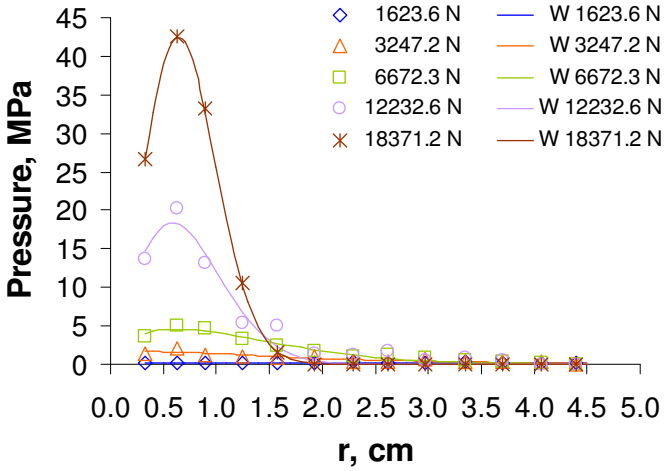

Figure 14. Adjustment of Weibull curves for *Al-Ss*, b_1.

predict the pressure distribution between contacting surfaces of bolted joints studied by [14]Gonçalves. This comparison shows that they do not present a good agreement, especially for bolted including Stainless Steel plates. However, the correlation proposed in this work, based on Weibull statistical distribution, showed a very good comparison with experimental data. The Weibull correlation parameters (ρ, β, η),which results in curves that presents the better comparisons with the experimental data, were determined through ESS software. The parameter ρ showed to be more sensitive to the load applied to the junctions analysed, while the others did not present any trend clearly defined.

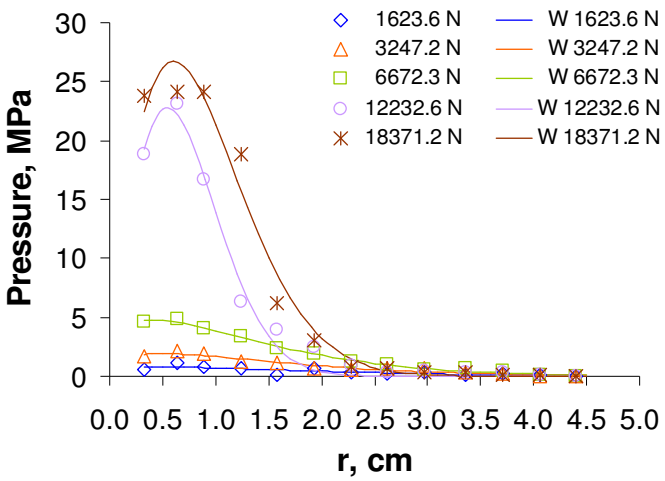

Figure 15. Adjustment of Weibull curves for *Al-Ss*, b_2.

Table 2. Percentage difference of the experimental dada and the Weibull model.

	1624 N		3247 N		6672 N		12233 N		18371 N	
	b_1	b_2	b_1	b_2	b_1	b_2	b_1	b_2	b_1	b_2
Al-Al	3,80	0,06	0,20	0,48	5,50	1,17	1,90	1,00	4,6	1,22
Ss-Ss	10,54	0,42	0,21	3,33	0,95	5,74	1,53	6,61	5,07	4,06
Al-Ss	50,59	27,12	13,50	5,35	4,47	0,10	7,63	4,70	3,03	2,24

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