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EFFECT OF BEARING DIAMETER OF BOLT HEAD ON INTERFACIAL PRESSURE IN BOLTED JOINTS

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ABSTRACT
The proper selection of the bolted joints is very important factor. The contact pressure distributed is the key factor behind success of the interfacing. The consideration of the contact pressure during the design makes it possible to have successful integrity. The problems faced due to the theoretical analysis and the absence of the practical or experimental analysis leads to failure of the proper distribution of the pressure. Authors worked on the ultrasonic applications to understand the pressure distribution at the interface. The load considered is axial for the experiment. With increase in the load, the contact pressure increases. In bolted joints, the constant distribution point dose not depends on the load.

KEY WORDS: Contact pressure, ultrasonic reflection, ultrasonic technique, interfacial stiffness, bolted joints.

INTRODUCTION

The recently developed structures of the engineering mainly use the bolted joints. The carrying ability of the load has made the bolted joints very admired. The applications of the machine design also support the use of the bolted joints. These joints are found easy to assemble or reassemble. The process of manufacturing these joints is very efficient. [1] The failure of the fastener in the operation makes it avoidable to use. [2]Their operations are also safety critical. The failures in some cases are of serious consequence.[3-6]
Consequently, bolted joints have commanded the attention of many investigations and many of these have been focused on the integrity of bolted joints as a function of their stiffness and response to loading and, in some cases, ability to conduct thermal energy at the joints[7, 8].The contact pressure distribution is important when calculating the clamping performance of bolted joints, and also when assessing the fatigue life of the joints [9].
The factor affecting the pressure distribution at contact is the radius of contact, thickness and radius of bolt head. [10-13] Contact stress can be determined by the placement of the pressure sensing film between contacts. [14-15]

THEORETICAL BACKGROUND

The concept of the bounded interface is practically impossible as air gap affects the junctions. The ultrasound waves are reflected by the interface. The sound is reflected from the air-metal interface as shown in the figure.

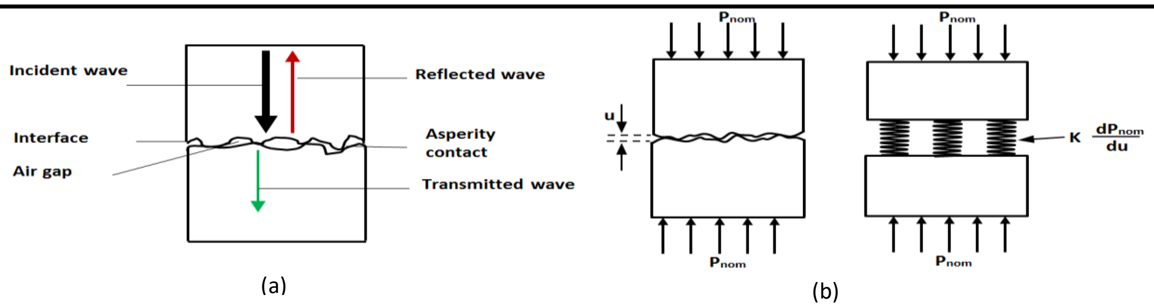

Figure 1: (a) Ultrasonic reflection at a rough interface and (b) Schematic representation of an interface using the spring model.

The coefficient of reflection is given by

$$R = \frac{z_1 - z_2}{z_1 + z_2} \qquad (1)$$

Where,

Z is acoustic impedance. The suffix indicates the sides of the boundary.

According to Tabor and Kendall [23] for the rough surface the interfacial stiffness K affects the reflection coefficient.

$$|R| = \sqrt{\frac{(\omega z_1 z_2)^2 + K^2(z_1 - z_2)^2}{(\omega z_1 z_2)^2 + K^2(z_1 + z_2)^2}} \qquad (2)$$

For homogenous contact with two similar materials, the relationship between them is reduced to and governed by the relationship:

$$|R| = \frac{1}{\sqrt{1 + (2K/\omega z)^2}} \qquad (3)$$

Where,ωrepresents the angular frequency of sound wave

$$K = -\frac{dP_{nom}}{du} \qquad (3)$$

Where, u is the separation of the mean lines of roughness of the two surfaces

EXPERIMENTAL PROCEDURE

TEST SPECIMENS

The bolted joints used in this study consist of steel plates made from EN24 steel.The base plate was 12 mm thick with threaded blind tapped hole for M16 bolt. The upper plate was 10 mm in thickness with clearance hole for M16 bolt drilled through it. The contact surfaces of the plates were ground to an average surface roughness of 0.5 µm (Ra).The plates were clamped together (as shown in Figure 2a) with steel bolts (grade 8.8) of metric 16 mm threaded shank. The bolts, as shown in the Figure 2b, were manufactured from M24 bolts with bearing surfaces of 24, 27, 30, 32, 34 and 36 mm in diameter using a CNC lathe in order to increase geometric tolerances and uniformity.

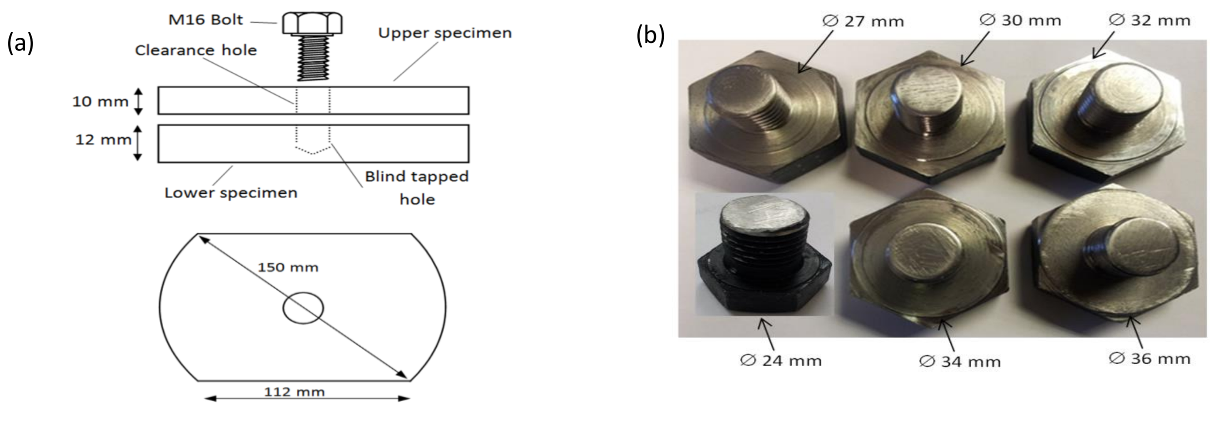

Figure 2: (a) Schematic diagram of bolted joint specimens showing side and plan views and (b) Bolt specimens showing different bearing surfaces.

SCANNING PROCEDURE

Except for the bolt with 24 mm diameter bearing surface (which has a scanned area of 40 mm by 40 mm), the scanning was performed on a square area of 60 mm by 60 mm in order to capture a larger area of the contact interface. With the upper plate in position, the bolted joint specimens were torqued up from 30 Nm to 70 Nm in steps of 10 Nm using the digital torque wrench with a calibrated accuracy of ±2%. It was then mounted on the locating fixture attached to the scanning tank so that the bolt hole was always at the centre of the scan. The transducer attached to the scanning tank was controlled to move over the scanned area of the bolted joint specimen in the x direction with 0.25 mm steps, and 0.125 mm steps in the y direction. Therefore, as shown in Figure 5b the amplitude of the reflected ultrasound pulse from the interface was also measured at every 0.25 by 0.125 mm over the rectangular scanned area of the bolted joint specimen. The whole scanning process is controlled by programme written in Lab VIEW.

The reference scan was also performed with the upper plate absent in order to create a metal-air interface so that the entire ultrasonic signal was reflected (Figure 5a). The map of reflection coefficient from the bolted interface, which represents the fraction of ultrasound incidence at the interface that is reflected from it, is obtained by dividing the reflected voltage of the loaded joint with that of the reference.

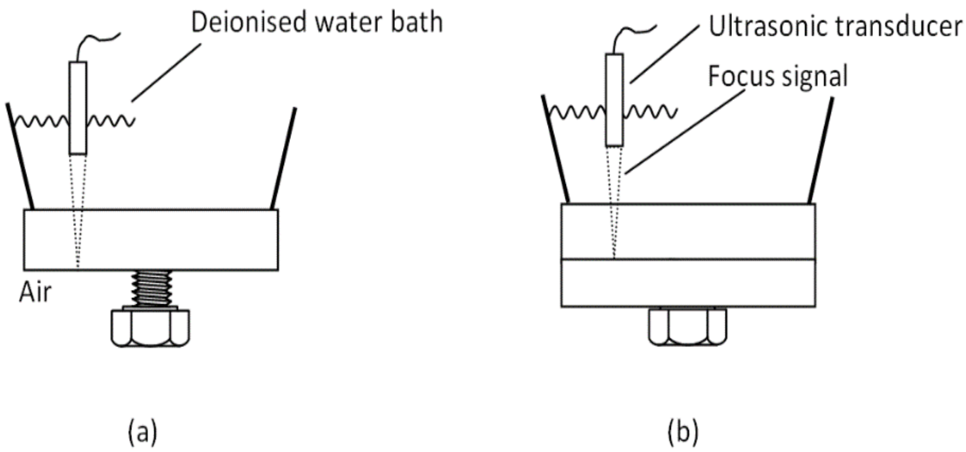

Figure 5: Ultrasonic scanning of specimen. (a) Reference scan (b) Loaded joint scan.

CALIBRATION

The calibration experiment follows the methodused by Marshall *et al.*[19] To find the linear relationship between the stiffness and contact pressure.The calibration specimens were made from the same material and subjected to the same surface treatment as that of the experimental plates. The specimens were loaded as shown in Figure 6a, and single-point reflections of the contact interface were recorded for a series of loads. The reference measurement was also recorded with the lower specimen was absent. The reference measurement was used to divide the reflected signals to get the reflection coefficient at each of the different loads applied.

Interfacial stiffness at each load was then calculated from the reflection coefficients. Since the contact area of the specimens was known, the contact pressure at each load could be calculated and plotted against the corresponding interfacial stiffness, as shown in Figure 6b. The relationship between the contact pressure P and the interfacial stiffness K is given as:

$$P = mK \quad (6)$$

The same specimens used in Stephen *et al.*[21]were used, and from the calibration experiment, the value of the m (which is the inverse of the gradient of the least square fit line that relates contact pressure to the interfacial stiffness) was found to be 61.2.

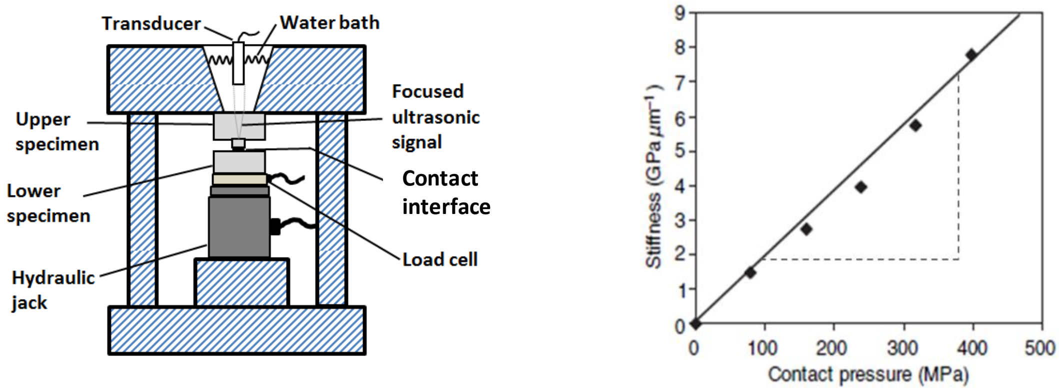

Figure 6: (a) Calibration experimental set-up and (b) Calibration graph relating interfacial stiffness to contact pressure [19].

RESULTS

Pressure maps of the bolted interface from the bolted joint with 32 mm diameter of the bearing surface of the bolt head and for bolt torques of 30, 40, 50, 60 and 70 Nm are shown inFigure 7(a). Figure 7(b) shows the pressure map for the six different diameters of the bearing surface of the bolt head for bolt torque of 50 Nm.

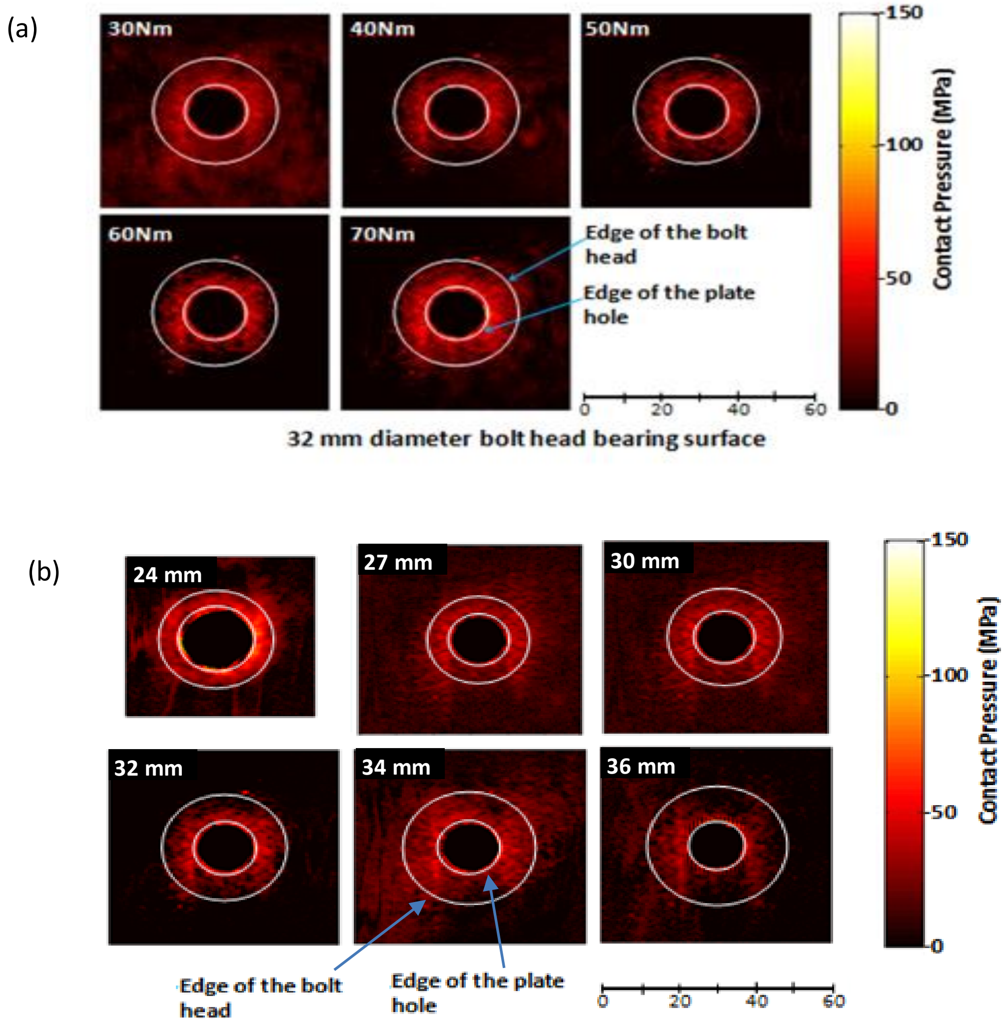

Figure 7: Contact pressure map of bolted joint (a) at different torques and (b) at differentdiameters of bearing surface of bolt head.

From each of the maps, the shape of pressure distribution at the interface can be seen as the bright circular zone around the dark centre hole of the bolt. This shows that the majority of the load is supported at this region and decreases away from the bolt. In addition, for each bolt head (as shown for the 32 mm diameter bolt head bearing surface) the intensity of the contact pressure grows in a circular ring as the torque increases, without any corresponding increase in the overall size of the pressure distribution.

As shown in Figure 7, the pressure distribution is not symmetrically uniform around the centre hole at the interface. Furthermore, the maximum contact pressure is away from the edge of the bolt hole, and is in agreement with observations from an earlier study by Marshall *et al*. [19] and Stephen et al.

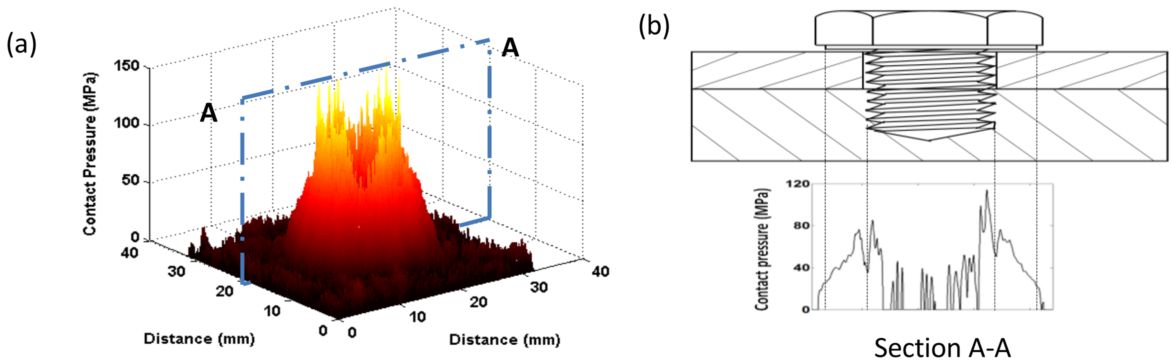

Figure 7: (a) Contact pressure at the bolted interface and (b) Contact pressure through the vertical section of the plates

AVERAGE PRESSURE LINE

Figure 8 shows the average contact pressure distributions for different applied load and bolt head bearing surface diameter taken at a distance equal and greater than 8 mm (i.e. from the edge of the clearance hole) from the centre of the hole. As shown in Figure 8(a), the peak of average contact pressure increases as the applied load increases. As the torque increases from 30 to 70 Nm, the contact pressure peak increases from 32 MPa to 62 MPa for bolt head with 24 mm bearing surface. This was also observed in the results of other bolt heads. However, for different diameter of the bearing surface of the bolt head, the peak of average contact pressure distribution decreases as the increases from 24 mm to 36 mm. The peak of average contact pressure distribution decreases from 48 MPa to 28 MPa as the diameter of bearing surface of the bolt head increases from 24 mm to 36 mm for the 50 Nm torque.

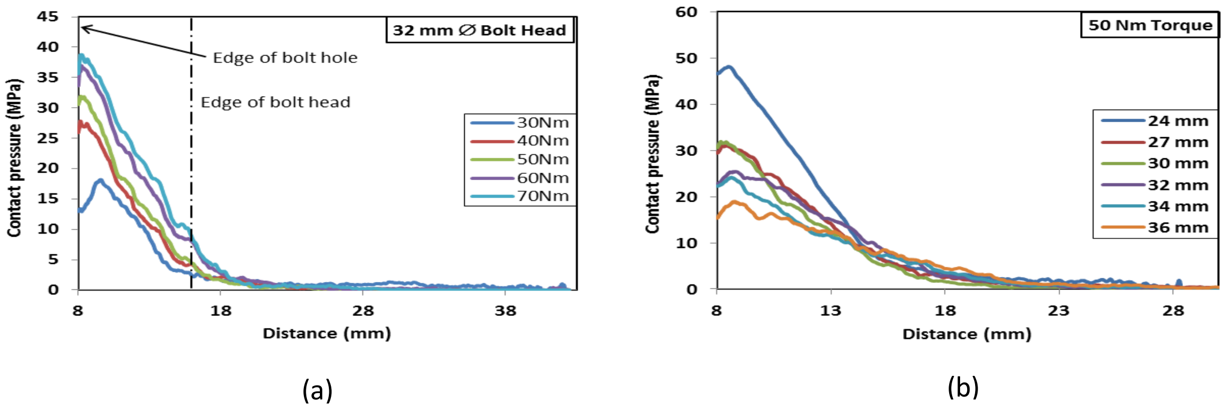

Figure 8: Average contact pressure line scans of (a) 32 mm diameter bearing surface ofbolt head and (b) all diameters of bearing surface of bolt head.

As shown in the Figure 8(b), the average contact pressure profile for each of the bearing surfaces of the bolt head shows different degrees of smoothness. This observation is due to the different degrees of profile irregularities of the bearing surface of the bolt heads. Figure 9 shows the profile graphs of 24 mm, 32 mm and 36 mm diameter surface bearing, taken at equal 1 mm distance from the shank of the bolts. The values of 0.9 µm and 5.2 µm were respectively recorded as Ra (average roughness) and Ry (maximum peak-tovalley height) values for the standard forged M16 bolt having 24 mm diameter bearing surface, while 4.5 µm and 5.7 µmwere recorded as values Ra, and 30.3 µm and 51.7 µm as Ry values for bolts with 32 mm and 36 mm diameter surface bearing respectively. These values of profile roughness along with the graphs show that the roughness of the bearing surface of bolt head have a corresponding effect on the contact pressure at the bolted interface.

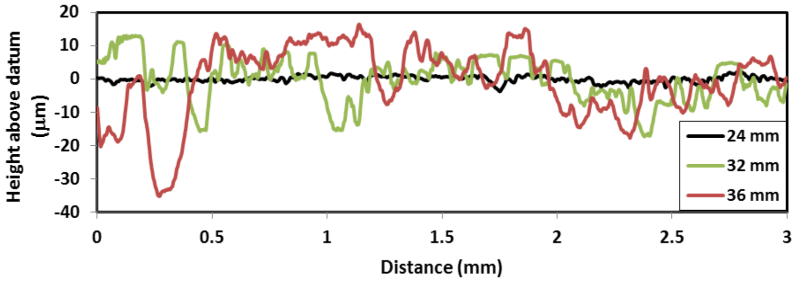

Figure 9: Surface profile of the bearing surface of the bolt heads with 24 mm, 32 mm and 36 mm diameter.

DISCUSSION

Table1 and 2respectivelyshow the total joint load for the measured distributionat various applied torques and diameter of bolt heads. Their percentage differences to calculated theoretical joint load are presented. The total joint load for the measured pressure distribution for each of the torques for ultrasonic measurement were obtained by integrating the area under curves using a Trapezoidalmethodwhile the theoretical load was calculated using the proposed empirical relation ($T = 0.2Fd$; where T is the bolt torque, F is the tightening load and d is the bolt diameter) by Shigley and Mischike [29].

From the table, it can be observed that the joint load varies with the applied torque and also varies across all the junctions for the particular torque of 50 kN. The values of the joint load for the measured average contact pressure distributions for 40, 50 and 60 Nm torques are fairly close, and at low torque of 30 Nm the values are higher and the percentage differences are equally higher when compared to that from other applied torques. Overall, the percentage difference between the sum of joint load of measured contact pressure distributions and the sum of the theoretical loads are very low. Values of 1.2, 0.2, 0.0, 0.3, 1.1 and 0.5 percent of normalised difference are calculated for 24, 27, 30, 32, 34 and 36 mm diameters of bearing surface of the bolt head respectively when compared to the total calculated theoretical load.

Figure 10shows normalised average contact pressure distributions for all the torques for 24 mm diameter bolt head and mean normalised average contact pressure distributions for all the bolt heads. The contact pressure distributions are expressed in terms of normalised dimensionless p/q and r/a. This is obtained by dividing the average contact pressure distributions (p) by the mean stress (q) under the bolt head and also, distance under the contact pressure distributions(r) is divided by the bolt radius (a). For each of the contact pressure distribution, the profiles become approximately constant at a point irrespective of the applied load (Figure 10(a)).

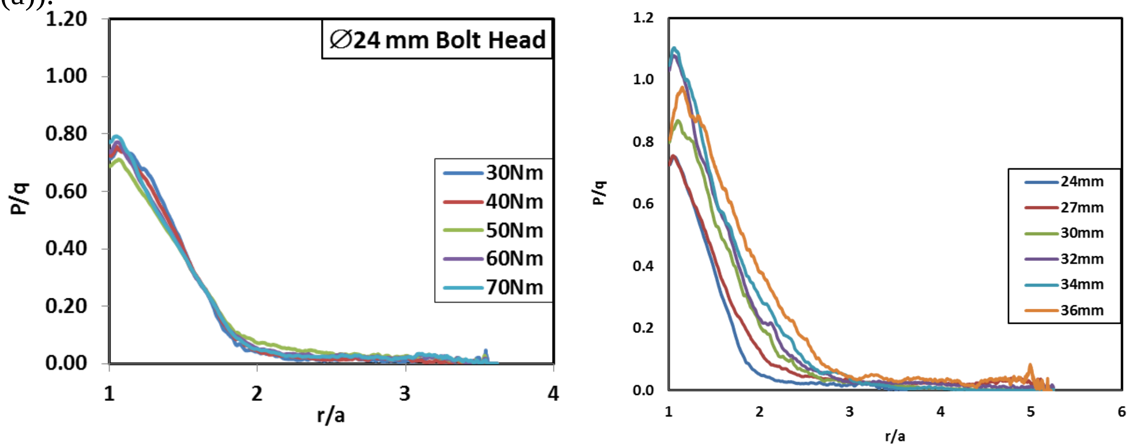

Figure 10: (a) Normalised average contact pressure and (b) Mean normalised average contact pressure of bearing diameter of the bolt heads.

Similar to what was observed by Marshall et al. [19] and Ziada and Abd El Latif [29], the stress concentration effect from the edge of the bolt head influences the position of the maximum contact pressure at the interface. The edge of the bolt head is a point of discontinuity and a stress raiser, and this increased the observed measured stress on the interface away from the bolt hole. Furthermore, the surface profile of the bearing surface of the bolt head affects the contact pressure distribution at the interface. This is because the peaks of the large asperities of the profile ridges on the surface of the bolt head also acts as a stress concentration and thus increased the stress at the corresponding points on the bolted interface.

CONCLUSIONS

The bolted joints pressure can be calculated by the ultrasonic technique.The signal is reflected to identify the pressure of joints. Authors have presented the method of measurement of the pressure on the joints under loading condition. It is also observed that the selection of the parameters for the bolted joints plays an important role as far as the distribution of pressure is concerned.Increase in the load results in the proportional increase in the pressure and increase in the bolt head results in the decrease pressure distributed.

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