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The Bolt Bearing Response and Tensile Deformation Capacity of Plates Made from a Titanium Alloy

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In this article, the bearing capacity and elongation characteristics of bolt holes in a titanium alloy (i.e., Ti-6Al-4V) deformed in uniaxial tension is presented and discussed. The specific role played by bolt hole confinement on bearing capacity is highlighted. The nature of final fracture is examined and the intrinsic features present on the fracture surface are rationalized in concurrence with macroscopic mechanical response. The behavior of the candidate alloy (Ti-6Al-4V) is compared with conventionally preferred and chosen candidate materials steel and aluminum alloys. An empirical relationship suitable for purpose of structural design is proposed.

Keywords bearing, deformation, failure, loading, plate, titanium alloy

1. Introduction

Selection of the appropriate material does play a key and vital role in the process of structural design. It is important for a structural engineer to give due consideration to material properties, spanning strength, toughness, corrosion resistance, and density, when designing a structure for load-critical or stress-critical applications. During the design process, a failure to consider the purpose of the structure, the nature of loading on the structure, service requirements and expectations, and the environment to which the structure is expected to perform while in service, can result in inferior performance of the structure with either a withdrawal from "active" service or culminate in catastrophic failure.

Traditionally, structural steel has been the candidate material for use in a spectrum of structural engineering applications that necessitate the need for a high specific strength (σ/ρ). This in turn results in an efficient structural member that has the ability to sustain the necessary load while concurrently minimizing its dimensions. An additional advantage in selecting and using structural steel is due to its relatively low cost when compared one-on-one with other viable choices spanning the domain of metallic materials that can offer near similar properties. Of all the alloys of titanium that have been developed and put forth, it is the Ti-6Al-4V alloy that is the most preferred and attractive choice for use in both performance-critical and non-performance-critical structural applications. The Ti-6Al-4V alloy is to be noted for its innate ability to provide high strength at roughly half the density when compared to structural steels. In addition to its unique qualities spanning the specific domain of mechanical properties, the Ti-6Al-4V alloy also offers an excellent resistance to corrosion or environmental degradation (Ref 1). However, despite its many advantages, this and other emerging alloys of titanium have only seen limited selection for use in those applications involving an exposure to extreme conditions during actual service, such as, in the aerospace industry. This is largely because of the high production cost associated with the family of titanium alloys since they are categorized as a specialty material and concomitant production in limited quantities.

Through the years, a gradual increase in the potential applications for the selection and use of the Ti-6Al-4V alloy as a structural material has provided the necessary impetus for increasing its production. This has been put in force in the titanium metal industry with a resultant reduction in cost of the specific alloy in various product forms.

A key aspect that is both related and relevant to a materials' intrinsic ability to perform under the influence of an external load or stress is its behavior or response in connections using mechanical fasteners. These connections find definite use in structures for the following reasons:

(i) Ease and reliability of installation.
(ii) An intrinsic ability to perform under dynamic loading.
(iii) Cost is either comparable or marginally more than traditional welding.Mechanical fasteners are required to perform in a manner that necessitates the need to transmit large load over a relatively small area. As a direct consequence, they tend to develop concentrated stresses both within the bolt and the connected material making them susceptible to mechanisms that facilitate and/or enable their failure. The key mechanisms contributing to failure of an individual bolt, as opposed to failure of a group of bolts, can be any one or a combination of the following:

    (i) Failure of the bolt through shear.
    (ii) Shear tear-out of the connected material.
    (iii) Bearing failure of the connected material at the bolt-material interface.

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These modes of failure have been extensively studied and are generally well understood when the candidate structural material in question is either steel or aluminum alloys. However, there still exists a paucity of research related to the mechanisms governing failure of titanium and its alloys.

It is the objective of this article to present the results of a recent study aimed at improving and enhancing our understanding of the behavior of the Ti-6Al-4V alloy when experiencing bearing failure at the bolt hole by direct comparison to failure mechanisms that occur in steel and in aluminum alloys. From the test results, the criteria essential to designate the limit states for bearing failure of a titanium alloy, i.e., Ti-6Al-4V are put forth with the objective of improving our understanding of its behavior as a candidate structural material for viable load-critical or stress-critical structural applications.

2. Use of Titanium Alloy and Mechanical Connections

Despite being the most widely chosen and used of the titanium alloys, the Ti-6Al-4V suffers from a lack of adequate research information in the knowledge-based relevant to the behavior of mechanical connections. A typical example of much interest being the bearing behavior of a single bolt upon the edge of a bolt hole. This type of behavior has been extensively studied and documented for steel by Kulak et al. (Ref 2), and the alloys of aluminum (Ref 3). By understanding the fundamental design criteria used in concurrence with the two most widely chosen and used metals, i.e., steel and aluminum, and by drawing comparisons with the Ti-6Al-4V alloy a similar design criterion can be developed.

In a typical shear splice connection, Kulak et al. (Ref 2) in their study found that loading on a typical bolt can be divided into four distinctly separate stages for the situation or case of a typical non slip-critical connection.

(i) In the first stage of loading, static friction provided by the tension force of the tightened bolt is sufficient to prevent slip in the connection. The variation of load with elongation is for the most part linear.
(ii) In the second stage, the load increases gradually to a point where it exceeds the resistance provided by static friction followed by slip of the connection. This places the bolt in direct bearing with the side of the hole.
(iii) Beyond this point the connection enters the third stage, which is characterized by a return to the linear loading pattern that was observed in the first stage. This is ascribed to be due to the contact stresses remaining well within the elastic range of the stress versus strain curve of the material.
(iv) When yield strength of the material is reached, at the initial point of contact, the final stage of loading is entered. The fourth stage concludes with either failure of the bolt hole or shear fracture of the bolt (Ref 3).

Once slip of the connection has occurred, the material at the side of the hole comes in contact with the bolt. This results in the development of a bearing stress that is initially localized at the point of contact (as shown in Fig. 1a). With a gradual increase in load, the material at the contact point will begin to yield causing the occurrence of an embedment of the bolt into the side of the hole. This in turn results in an increased area of bearing. The increased area results in a more uniform distribution of the stress across the material that is in contact with the bolt (Fig. 1b). Since the actual bearing stresses at the bolt-hole interface are often complex and difficult to measure, the bearing stress is assumed to be uniform across the contact area between the bolt and the edge of the hole (Ref 4). This is shown in Fig. 1(c). Making this assumption provides an expression for the bearing stress to be:

$$\sigma_{\mathrm{b}} = \frac{P}{\mathrm{d}t} \qquad \text{(Eq 1)}$$

where P is the load transferred through the bolt, d is diameter of the bolt, and t is thickness of the material.

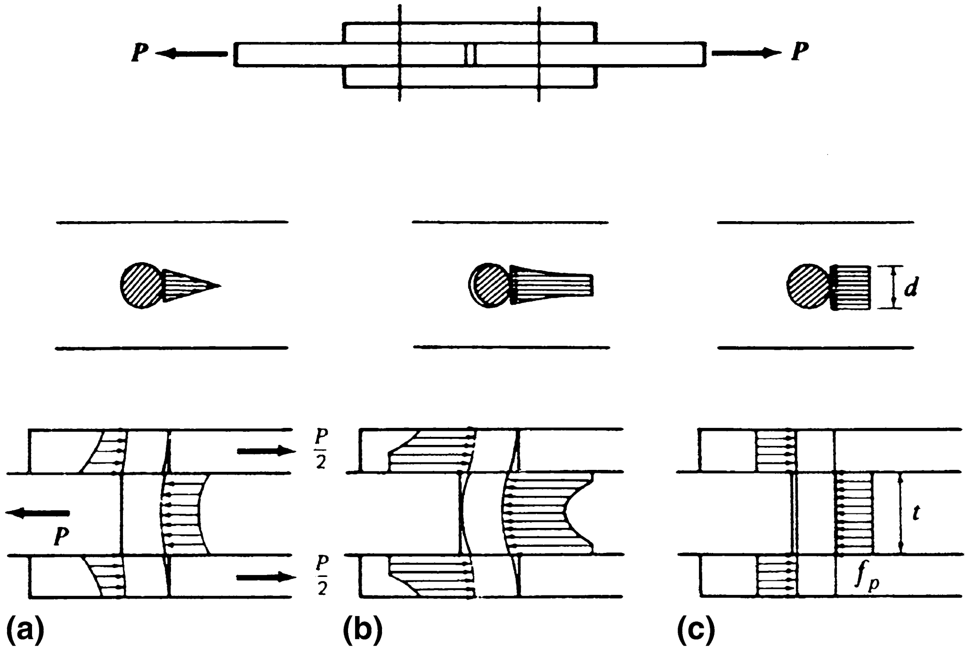

Fig. 1 Profile of bearing stresses across bolted plates: (a) elastic, (b) elastic-plastic, and (c) nominal (Ref 1)

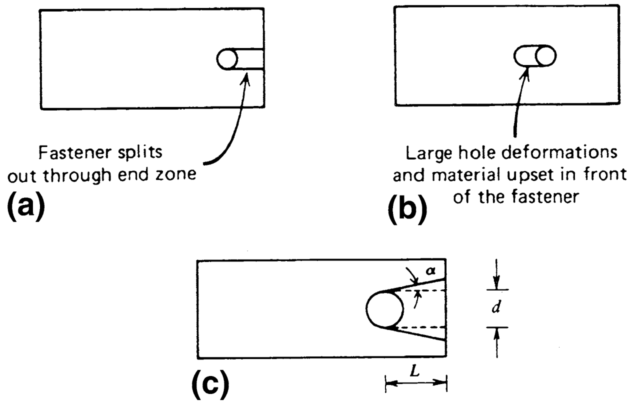

Fig. 2 Profile of characteristic failure modes: (a) fastener splits through the end zone, (b) large hole deformation with material upset ahead of the fastener, and (c) path of failure at a bolt hole (Ref 1)

The occurrence of failure in the bearing is dependent on the distance of the bolt hole from the edge of the material measured parallel to the direction of loading. If this distance is insufficient, a tear-out type of failure is favored to occur rather than a gradual failure of the bearing. This type of failure is modeled as shear rupture along two paths from edge of the bolt hole to edge of the material and is shown in Fig. 2(a) (Ref 2). Using this model, a lower bound value for the load to facilitate a "tear-out" failure is obtained using the expression:

$$P_u = 2t\left(L_e - \frac{d}{2}\right)\tau u \qquad \text{(Eq 2)}$$

In this expression, τ_u is ultimate shear strength of the material, and L_e is the length measured from the center of the bolt hole to the edge of the material. This expression describes the minimum path required for a shear tear-out. However, the paths are often angled outward as shown in Fig. 2(c). This result in the tear-out strength being noticeably larger than the value obtained using Eq 2.

Strength in bearing was also found to increase by the presence of a clamping force provided by the bolt. This can be attributed to a partial transmission of load by means of frictional resistance between the two plates (Ref 2). More recently, similar tests performed by Menzemer et al. (Ref 3) on an aluminum alloy conformed with their belief that a portion of this effect can be attributed to the clamping force thereby limiting the ability of the aluminum alloy to deform freely. Consequently, this tends to reduce the elongation of the hole in direct comparison with samples where no clamping force was provided (Ref 3). A conjoint and mutually interactive influence of these effects at the microscopic level contributed to the actual bearing stress being lower than the ultimate stress that was obtained by dividing the total load by the bearing area.

3. Design of Experimental Test Setup

The material chosen for this specific study was the Ti-6Al-4V alloy. The material was provided by ATI Wah Chang (Salem, OH, USA) as pre-cut samples (12 in number) measuring 300 × 100 × 3 mm and cut from flat sheet stock. The nominal chemical composition of the as-provided material is given in Table 1.

Table 1 Nominal chemical composition of Ti-6Al-4V (in wt.%)

Material	Ti	Al	N	V	C	Fe	H	O
Ti-6Al-4V	90.0	6.0	0.05	4.0	0.1	0.4	0.02	0.20

In order to prepare the samples for testing, two 21 mm bolt holes were drilled along the center of the sample and spaced at a distance of 4 bolt diameters (corresponding to 75 mm) from either end of the plate so as to either induce or promote progressive bearing failure. The holes were de-burred to remove and/or minimize the role and contribution of the surface irregularities and/or imperfections on the bearing surface. Prior to testing, the diameter of each bolt hole was precision measured using a digital micrometer on both the front- and the back-side of the samples, and the average value was calculated. A picture of a standard sample is shown in Fig. 3(a).

Two separate plate fixtures were used to test the plates.

(i) The first fixture was composed of a pair of simple 400 × 100 × 25 mm steel plates with a 21 mm hole drilled 38 mm from the edge of the plate. Two test samples were joined to the interior steel plates using either a 14 mm case-hardened steel pin or a 14 mm A490 bolt to form a symmetric butt joint on either side. This is shown in Fig. 3(b). In the tests using an A490 bolt to secure the plates to the test fixture, washers were used on both sides of the bolt to ensure solid contact with the material. The bolts were tightened by hand without the use of a wrench or other mechanical device. This facilitated in preventing a large initial clamping force from being induced due to bolt pre-tension.

(ii) The second fixture that was used to test samples of the titanium alloy individually was composed of three 240 × 100 × 25 mm steel plates welded together in a symmetric butt joint and having a 100 mm overlap. A 21 mm hole was drilled through each of the lap plates and positioned 63 mm from the edge of the plate. The Ti-6Al-4V alloy sample was connected between two of these fixtures using a case hardened steel pin thus forming a second symmetric butt joint at either end of the specimen (as seen in Fig. 3c).

The mechanical tests were performed on a universal test machine [Model: Instron 1000HDX]. The samples were loaded at a constant rate over a range of stress values up until actual failure of the test specimen. The rate of loading for each titanium alloy test specimen was determined by taking the target value and dividing it by 5 min. This gave a loading rate in KN/minute, which was programmed into the control software of the test machine. This loading rate was maintained through the entire test. Prior to commencing the test the connections were checked to ensure that no load was being transmitted through the connection. Having established this, the load on the test machine was then balanced to zero to prevent weight of the test fixture from being incorporated into the test data related to load.

Data for load and extension of the test fixture were automatically sampled by the control software of the test machine and the output generated was a graph that monitored progress of the test on the titanium alloy sample. In the event of failure of the bolt hole the test was automatically stopped. Both care and caution were taken to collect pieces of the titanium

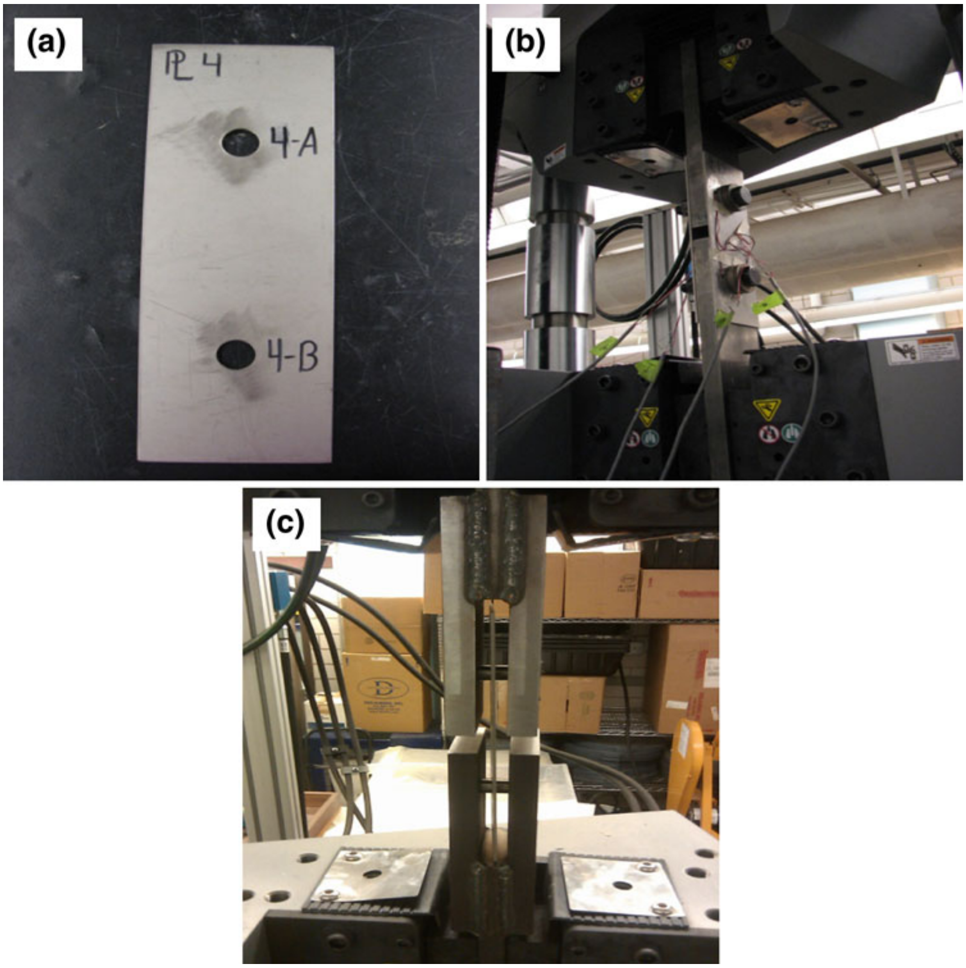

Fig. 3 (a) The standard test sample used in this study, (b) A A490 bolt used to form a symmetric butt joint, and (c) the titanium alloy sample with test fixtures mounted on the universal test machine

alloy that had separated on failure for purpose of examination of the fracture surface in a scanning electron microscope.

Subsequent to mechanical testing culminating in failure, the dimension of the bolt holes in the sample were precision measured, using a micrometer, on both the front- and the backside and the average value calculated. The original bolt hole diameter was then subtracted from the value following mechanical testing to obtain a measure of elongation of the bolt hole. This value was compared with the load transferred through the connection. The loads were obtained by

(i) Dividing the total load by a factor of two for tests that utilized the initial test fixture, which tested two plates simultaneously, and
(ii) Simply using the maximum load in the case of the second fixture.

4. Results and Discussion

4.1 Mechanical Test Results

By establishing the variation of elongation of the bolt hole with the load transmitted through each connection, a few patterns become apparent in establishing the behavior of this Ti-6Al-4V alloy. First, it is observed that variation of load with elongation experienced by the bolt hole is linear up to a load of about 56.98 kN. This value corresponds to a nominal stress that is equal to the yield stress of the Ti-6Al-4V alloy plate. This is shown by the straight line in Fig. 4. Beyond this point two separate or distinct regions of plastic elongation can be easily differentiated based on the type of connection used.

(i) For a simple bearing connection consisting of a pin with no confinement, progressively larger elongations for a unit increase, or increment, in the load begins to occur at loads of approximately 77.80 kN per bolt hole. This value corresponds to a bearing stress that is 1.33 times the ultimate strength of the material. This effect is attributed to the occurrence of plastic deformation of the Ti-6Al-4V alloy at the initial contact point being confined by the material immediately behind it. This results in an observable increase in bearing strength of the bolt hole beyond the value corresponding to a uniform distribution of the ultimate stress across the contact area as shown in Fig. 1(c). Beyond this point the behavior becomes plastic before culminating in failure. The failure is reminiscent of the occurrence of "local" buckling of the Ti-6Al-4V alloy plate immediately behind the bolt (Fig. 5a). However, in some cases traditional bearing failures were observed to occur with minimum distortion to the titanium alloy plate beyond the bolt hole.

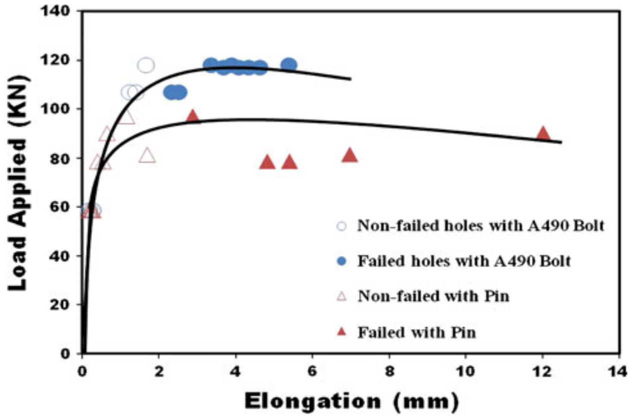

Fig. 4 Variation of load transmitted through the bolt hole versus its elongation

(ii) A similar pattern was noticeable for connections consisting of an A490 bolt and washer. The noticeable difference observed in the use of these connections is a higher bearing strength. A rapid increase in elongation, relative to load, was observed to occur almost immediately and the variation of load versus elongation began to deviate from a straight line for the bearing samples. Further, a gradual increase in elongation, relative to the load, was observed for the bolted Ti-6Al-4V alloy samples. Though no longer linear, the failures were observed to occur upon reaching a bearing stress that is 1.83 times the ultimate strength of the material (as shown in Fig. 4). Despite the bolts being only hand tight, the additional confinement of the Ti-6Al-4V alloy by the washers does appear to exert a noticeable difference. Further, the material in direct contact with the bolt was confined from behind, while the ease to expand in a direction transverse to the line of compressive load was restrained by the washers. This created a "local" stress state in the Ti-6Al-4V alloy immediately behind the bolt and is quite similar to triaxial compression, thereby increasing the alloy's ability to withstand loading prior to failure. It is further assumed that an expansion of the Ti-6Al-4V alloy in a direction transverse to the axis of loading led to a gradual increase in contact pressure between the two plates. Evidence of this is supported by the fact that a significant effort using a wrench was found to be essential to enable removal of the bolts from the fixture following testing, despite the bolts having been initially hand tight. The increase in pressure allowed for a portion of the total load to be easily transmitted through frictional resistance between plates of the alloy.When failure of this connection did eventually occur, it was a typical bearing failure with a crescent of material separating from the plate by shear failure behind the bolt. Due to thinness of the lap plates relative to the interior plate, there was evidence of the occurrence of a slight bowing-out of the lap plates upon failure (as seen in Fig. 5b) (Ref 5).

4.2 The Nature of Failure and Resultant Fracture Behavior

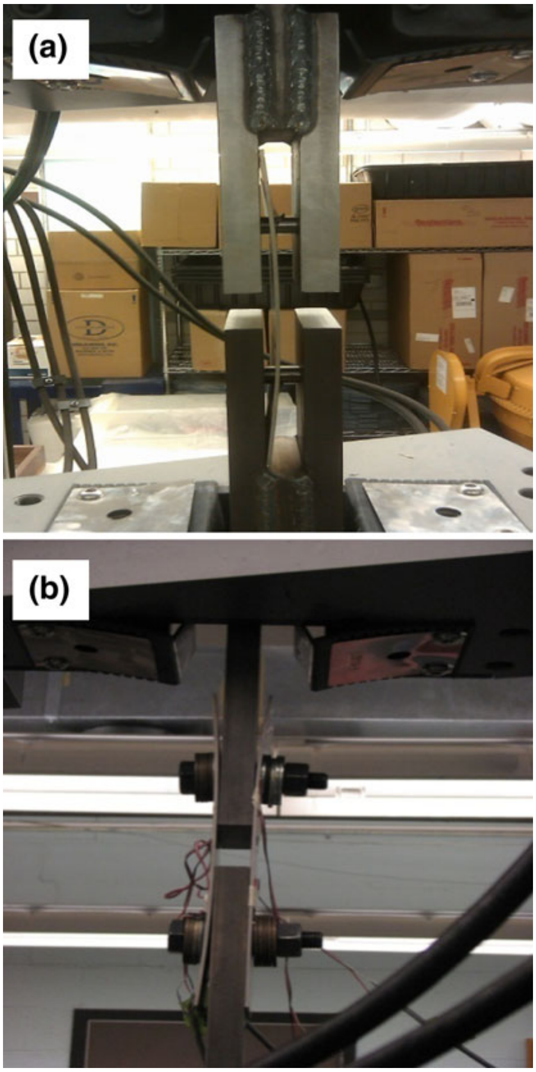

Fig. 5 Pictures showing deformation of the titanium alloy plate upon loading on the universal test machine: (a) "dishing" behavior of a single plate of the titanium alloy and (b) "dishing" of the titanium alloy plates in a double-lap configuration

Careful and comprehensive examination of the fracture surfaces in a scanning electron microscope helps reveal the intrinsic differences in failure modes of test samples of the alloy deformed in an unconfined bearing condition and test samples of the alloy deformed with bolted connections (Fig. 6, 7). When examining the fracture pattern of the Ti-6Al-4V samples that were deformed using the pin connection, it is apparent that failure occurred through a synergism of both shear and tension mechanisms at the microscopic level. Fine microscopic cracks were visible at the higher allowable magnifications of the SEM and are attributed to the occurrence of bending caused by a buckling of the titanium alloy plate behind the bolt hole. Similar features were observed for the laboratory scale test specimens of the alloy that were deformed in tension (Ref 6).

When examining the fracture surfaces of the samples deformed using A490 bolts and washers, a different pattern is recognized and is shown in Fig. 7. High magnification observation of the fracture surface revealed elongated dimples, indicative of the occurrence of shear displacements at the microscopic level. This conforms well to our analysis of a traditional bearing-type failure with evidence of shear along the fracture surface. In order to be able to make a generalization of this behavior to connections using bolts of varying size it is

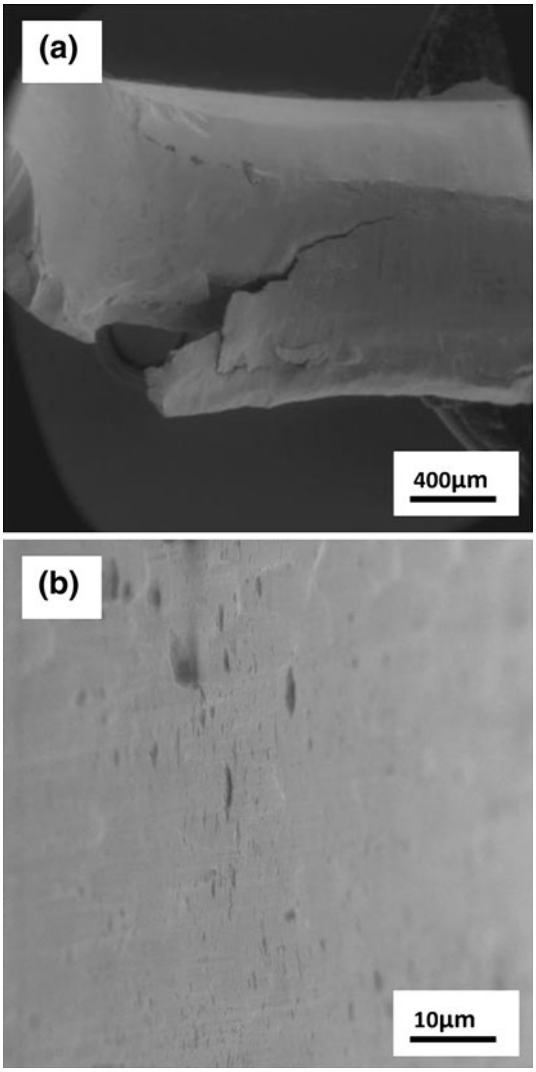

Fig. 6 Scanning electron micrographs of the failed titanium alloy (Ti-6Al-4V) sample deformed using A490 bolts and washers, showing: (a) overall morphology of failure, and (b) high magnification observation of (a) showing elongated voids of varying size reminiscent of locally ductile failure

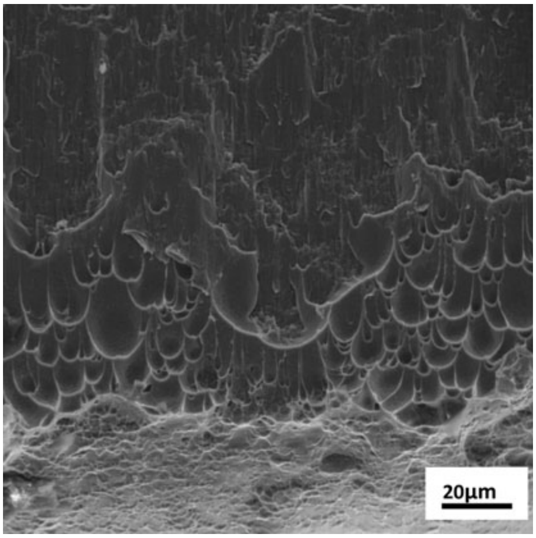

Fig. 7 Scanning electron micrograph of the fracture surface of the deformed and failed titanium alloy test sample showing a healthy population of elongated dimples interdispersed with fine microscopic voids, features reminiscent of locally ductile failure mechanism

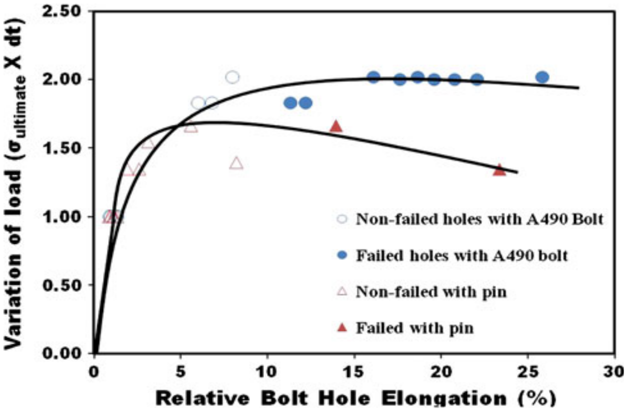

Fig. 8 Variation of load ($\sigma_{\mathrm{ultimate}} \times \mathrm{d}t$) with elongation of the bolt for the different conditions examined in this study

beneficial to express the load and elongation of the bolt hole in relative terms. This is accomplished by

(a) Expressing the load in terms of $\sigma_u dt$, which corresponds to the multiplication factor of the ultimate strength of the material multiplied by the bearing surface; and
(b) Elongation as d_f/d_0, or percent elongation, where d_f is diameter of the bolt hole after deformation and d_0 is the initial diameter of the original bolt hole.When variation of load with elongation is plotted as shown in Fig. 8 it reveals the same trend as shown in Fig. 4.

A careful examination of this variation clearly reveals that failure of the connection can be correlated with relative elongation of the bolt hole. It should be noted that beyond a relative elongation of 8 pct. there exists no data points for holes that have not experienced some kind of failure for either the pin bearing or the bolted connections. Prior to this point progressively larger relative elongations occurred with an increase in load.

When designing for actual load experienced by the structural component while in actual service it is both important and essential that elongation of the bolt hole be controlled to minimize the deformations that can occur under actual loading conditions. Therefore, it would not be prudent to design a connection based on a tolerable limit of deformation of 8 pct. since this is well within the region of plastic deformation. It is possible that events generating loads, which exceed the values during actual service, can occur. Such loads would tend to force a connection designed with the expectation of an 8 pct. Elongation, under actual in-service loads, could result in a progressive bearing-type failure.

Thus, it is recommended that when designing bolt bearing connections for the Ti-6Al-4V alloy, particularly for situations where elongation under the actual service load is of concern, relative elongation of the bolt hole should be limited to 4 pct. This value corresponds to a load that is 1.60 times the ultimate stress multiplied by the contact surface (obtained by multiplying the bolt diameter with the plate thickness). When compared to the value of 2.4 given in the AISC Steel Design Manual (Ref 6), it is apparent that a value of 1.6 is 33 pct. smaller than the value recommended (2.4) for designing a similar connection in steel. The most appealing rational for a reduction in this value can be related to reduced ductility of the Ti-6Al-4V alloy when compared to the candidate steels chosen and used in structural applications. The reduced ductility results in fracture of the material occurring at a lower plastic strain.

If bolt hole elongation under actual loads experienced during service is not of concern, one is tempted to increase the permissible elongation to increase the nominal design strength of a connection. Relative elongations of 8 pct. and bolt bearing coefficients of 2.02 were obtained in this study, and are at the extreme end of plastic deformation experienced by the bolted joint. Due to the relatively low elongation of this Ti-6Al-4V alloy when compared one-on-one with structural steel, failure of the bolt bearing tends to occur at short notice or quickly. In order to reduce and/or minimize the risk of sudden failure a relative elongation of 6 pct. is suggested for those connections where elongation under the direct influence of actual in-service loads is not of concern. This corresponds to a load that is 1.7 times the ultimate stress multiplied by the contact surface. Thus, increasing the tolerable deformation of the bolt hole for this case yields a slightly higher bolt bearing coefficient. For purpose of general design, this is only of marginal benefit. Therefore, for the purpose of simplicity, a bolt bearing coefficient of 1.60 is recommended for use for all bolted connections, regardless of elongation of the bolt hole under the extrinsic influence of service load.

5. Conclusions

Based on an experimental study to evaluate the bolt bearing behavior of the Ti-6Al-4V alloy the following are the key findings.

1. Use of a bolt and washer as a connecting element, even with only hand tightening, resulted in a significant increase in the ability of a connection to transmit load. This is ascribed to be due to the washer providing resistance to expansion of the material transverse in the direction transverse with respect to loading. The resistance allows for more frictional force between the two plates being connected, which aids in transmitting a portion of the load. Lack of confinement around the bolt hole results in buckling of the Ti-6Al-4V plate or a dish-type failure behind the bolt hole as was observed in several specimens. This is of concern when thickness of the plate material is relatively small compared to the bolt diameter.
2. The Ti-6Al-4V alloy revealed significantly lower ability to tolerate deformation at the bolt hole prior to the occurrence of progressive bearing failure when compared to structural steels.
3. Limiting the bearing stress on the Ti-6Al-4V plate material to 1.60 times the ultimate tensile stress of the material corresponds to an acceptable level of relative bolt hole elongation. This level is on the order of 4 pct., or roughly half the maximum relative elongation observed prior to the occurrence of progressive bearing failure.
4. Fracture behavior of the titanium alloy samples deformed using the pin connection revealed failure to occur through a synergism of both shear and tension mechanisms at the microscopic level. Fine microscopic cracks were visible at a higher magnification and attributed to bending caused by the buckling of the plate behind the bolt hole. High magnification observation of the fracture surface revealed elongated dimples, indicative of the occurrence of local shear displacements.

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