

[54] TENSION INDICATING FASTENER

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[22] Filed: Dec. 24, 1970

[21] Appl. No.: 101,298

[52] U.S. Cl.85/62, 73/88 F

[51] Int. Cl.G01d 21/00

[58] Field of Search .85/62, 45; 73/88 A, 88 R, 88 F; 356/34, 114

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[57] ABSTRACT

A bolt having a shank and integral head has a strip of photoelastic material mounted in the head for manifesting in the form of photoelastic fringes linearly related to bolt tension the bending stresses created in the head during loading of the bolt. To determine the tension in the bolt during or after loading, polarized light is directed toward the photoelastic strip and reflected light from the strip is analyzed to measure fringe order. The fringe order is related to the amount of bending stresses in the head of the bolt by a predetermined calibration curve, the bending stresses being linearly related to bolt tension.

5 Claims, 10 Drawing Figures

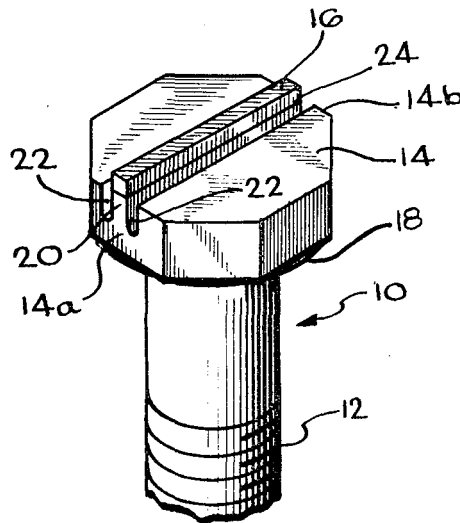


FIG.1

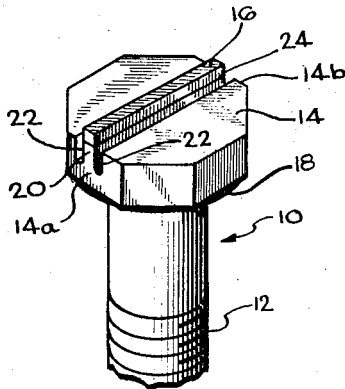


FIG.2

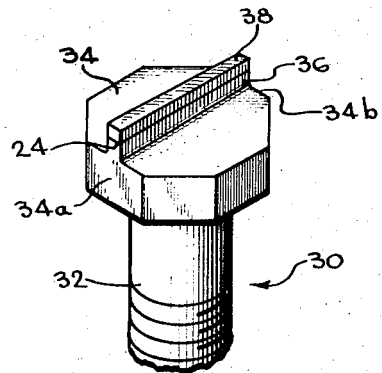


FIG.3

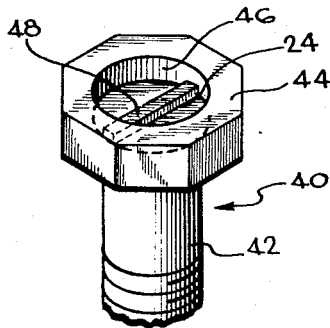


FIG.4

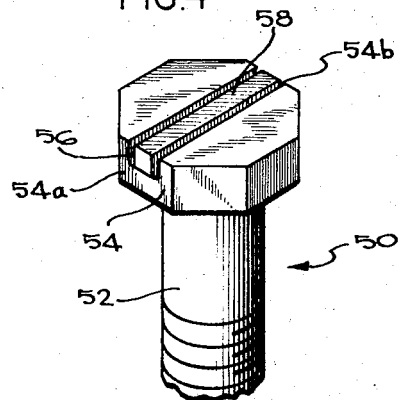
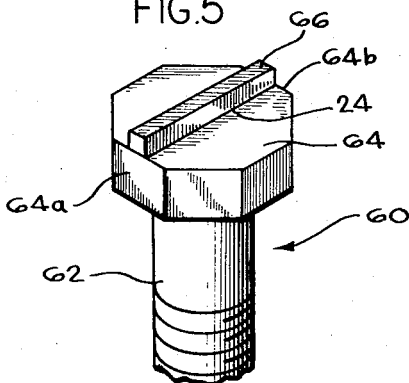


FIG.5



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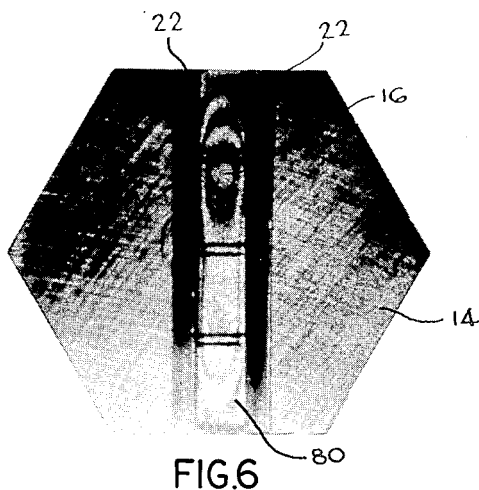


FIG. 6

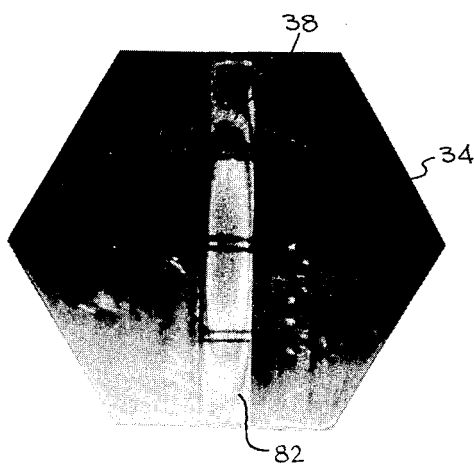


FIG. 7

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FIG. 8

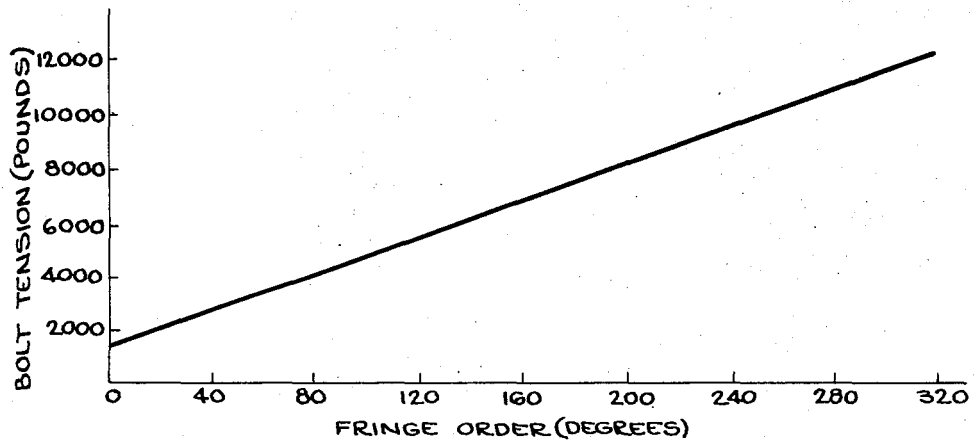


FIG. 9

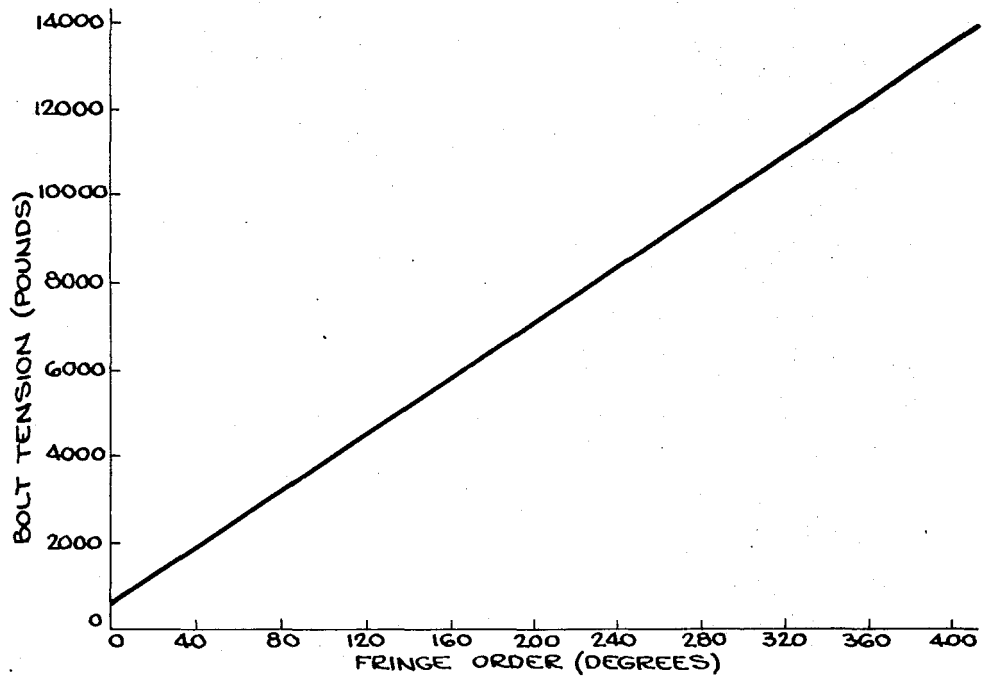
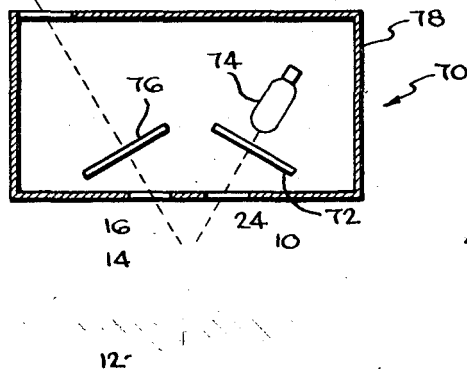


FIG. 10



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TENSION INDICATING FASTENER

This invention relates to a fastener having means for indicating the amount of tension therein upon the application of a driving force and to a method for determining the amount of tension in the fastener.

It is recognized in the fastener industry that there is a need for a practical device for measuring tension in bolts. Knowledge of bolt tension and the accurate determination thereof is of importance in the construction of aircraft, missiles, rockets, bridges, pressure vessels and some types of buildings. In these applications, the use of torque wrenches to determine bolt tension is generally unsatisfactory since this is an indirect method which determines bolt tension only within an accuracy range of plus or minus 20 percent. Other types of tension indicating bolts and devices are also available on the market. For example, embedded strain gage bolts are capable of indicating tension within an accuracy range of plus or minus 0.5 percent. However, each such bolt costs between about 50 and 150 dollars, requires compatible strain readout equipment and is difficult to manufacture on a production basis. Force washers have an accuracy range comparable to strain gage bolts but are subject to the same deficiencies. Pin-type bolts are less expensive than strain gage bolts but have an accuracy range only within about plus or minus 10 percent. When it is necessary to determine tension accurately within a range of between about 2 to 5 percent, only strain gage bolts and force washers are presently commercially available for utilization.

In accordance with the invention, when an externally threaded bolt is tightened by a wrench or the like within an internally threaded article such as a nut, the torque applied to tighten the bolt produces tension in the shank thereof. The tension in the shank as well as the frictional shear forces acting on the underside of the bolt head are transmitted to the head of the bolt. The tension in the shank produces bending stresses in the head which are linearly related to the tension in the bolt, if the bolt is formed of a linear material and the deflection of the head due to the bending stresses is small. By determining the magnitude of the bending stresses in the head, the tension in the bolt can be measured.

Accordingly, an object of the present invention is to provide a fastener for indicating the bending stresses and strain therein.

Another object of the invention is to provide a method of determining the amount of tension placed on the fastener during the loading thereof.

A further object of the invention is to provide a simple and inexpensive tension indicating bolt having an accuracy range of between about 2 and 5 percent.

These and other objects of the invention will become apparent upon consideration of the following detailed description and accompanying drawing, in which:

FIG. 1 is a perspective view of a tension indicating bolt in accordance with one embodiment of the present structure;

FIG. 2 is a perspective view of a modified embodiment of the tension indicating bolt;

FIG. 3 is a perspective view of another embodiment of the tension indicating bolt;

FIG. 4 is a perspective view of still another embodiment of the tension indicating bolt;

FIG. 5 is a perspective view of yet another embodiment of the tension indicating bolt;

FIG. 6 is an enlarged photograph of the head of a tension indicating bolt similar to that shown in FIG. 1 in its loaded state, showing a photoelastic fringe pattern thereon;

FIG. 7 is an enlarged photograph of the head of a bolt similar to that shown in FIG. 2 in its loaded state, showing a photoelastic fringe pattern thereon;

FIG. 8 is a calibration curve of bolt tension against fringe order for a bolt in its loaded state in accordance with the embodiment shown in FIG. 1 and having a photoelastic fringe pattern shown in FIG. 6;

FIG. 9 is a calibration curve of bolt tension against fringe order for a bolt in its loaded state corresponding to the bolt embodiment shown in FIG. 2 and having the photoelastic fringe pattern shown in FIG. 7; and

FIG. 10 is a schematic view of a reflection polariscope useful in the method of the present invention.

Generally, and with reference to FIG. 1 of the drawing, a fastener such as a bolt 10 has an externally threaded shank 12 adapted to be inserted into an article to be fastened and a head 14 integrally formed at the end of the shank 12 and adapted to limit the extent of insertion of the shank into the article. Photoelastic means in the form of a strip 16 of photoelastic material is mounted upon the bolt head 14. When the bolt is tightened, bending stresses and strain are introduced in the bolt head and transmitted to the strip, the strip becoming birefringent in direct proportion to the intensity of the stresses or strain. The birefringent strip 16 thereby manifests in the form of photoelastic fringes the bending stresses created in the head 14. It should be noted that the term "fringes" is a general description of bands, rings, lines or other configurations. This photoelastic fringe pattern can be viewed and linearly related to the bolt tension so that the bolt tension can be readily determined. It is not necessary that the photoelastic constant of the strip 16 be known or that any particular mathematical relationship be developed between the magnitude of the bolt tension and the fringe pattern in order to determine the bolt tension.

In designing the bolt such that bending stresses in the bolt head are manifested in the photoelastic strip, the strain-optic law in normal incidence should be considered. This law is contained in the following formula:

$$N = 2h(\epsilon_1 - \epsilon_2)/f_e$$

where N is the fringe order observed, h is the distance the light travels through the strained photoelastic strip 16, the quantity $(\epsilon_1 - \epsilon_2)$ is the difference in the principal strains in the strip and f_e is the material fringe value in terms of strain.

In application of the strain-optic law to the design of the bolt, the difference in the principal strains in the strip is controlled by the difference in the principal strains in the bolt head $(\epsilon_1 - \epsilon_2)$, which is determined by the shape or geometry of the bolt head and the shape of the strip attached to the bolt head. The difference in the principal strains in the strip is best maximized by employing a rectangular strip to avoid cancellation of the photoelastic effects. The thickness of the strip is also important since response of the strip, i.e. in terms of fringe order, is linearly proportional to

the strip thickness. This thickness should be made as large as possible without impairing the efficiency of the fastener system. Sensitivity of the strip to bending stress increments in the bolt head is affected by the strain fringe value (f_e) of the strip and for maximum sensitivity this value should be minimized. This can be accomplished by selection of a proper photoelastic material.

Several fastener configurations determined in accordance with the strain-optic law have been found suitable in terms of optimum sensitivity and response. Typically, the fastener is an hexagonal head steel bolt such as a No. $\frac{3}{4}$ -16 NF-5 bolt. This nomenclature indicates a bolt $\frac{3}{4}$ in. in diameter having 16 National fine threads per inch, the bolt being 5 inches long and having a nominal head thickness of about 0.475 in. prior to preparation. Such a bolt has a yield strength of about 32,100 lbs. Of course, any other suitable bolt could also be employed.

The birefringent strip is preferably rectangular in shape so that the principal strains therein are maximized when a hexagonal head bolt of the type described above is utilized. However, other suitable strip configurations could also be utilized, such as a strip having a triangular cross-section or a strip circular in shape although a circular strip may result in cancellation of the photoelastic effects. Desirably, the thickness of the birefringent, photoelastic strip when employing such a bolt is about 0.08 in. so as to maximize response in terms of fringe order. Several materials have been found suitable for the strip in that they have a minimum strain fringe value and maximum sensitivity. Epoxy resins have been found particularly sensitive to bending stresses. Such epoxy material can be either cast into place or cemented onto the bolt head. Furthermore, the epoxy material is inexpensive, rugged and relatively easy to form. However, additives such as solvents and plasticizers should be avoided since they tend to desensitize the epoxy. One suitable material for forming the birefringent strip is a clear high modulus plastic designated PS-2 and sold by Photolastic, Inc. of Malvern, Pennsylvania. This plastic material is inherently birefringent and becomes birefringent in direct proportion to the applied intensity of strain. This birefringent property can be observed and measured in the form of a fringe pattern. It should be apparent that any other suitable birefringent, photoelastic material can also be employed for the present purpose, e.g. glass, gelatin, or a polymeric material such as polycarbonate.

In FIGS. 1 through 5 of the drawing, the various embodiments which have been found suitable for the tension indicating bolt are illustrated. It should be noted, however, that other configurations might also be suitable for the present purpose and the present invention is not intended to be limited to the embodiments shown but is intended to encompass all other configurations which are equivalent.

In FIG. 1, the head 14 of the bolt 10 is provided with an undercut seating collar 18 which concentrates the applied load to improve linearity and increase response, particularly upon repeated tightening of the bolt. A ridge 20 is formed in the head and extends entirely across the width thereof between parallel opposing flats 14a and 14b. This ridge 20 is adapted to transmit bending stresses created in the head 14 during load-

ing of the bolt as the shank 12 is inserted into the article to be fastened. In forming the ridge 20, a pair of parallel slots 22 are cut or otherwise formed in the upper surface of the bolt head 14 and extend entirely across the width thereof between the parallel opposing flats 14a and 14b. The slots 22 serve to isolate the strip 16 from contact with the head 14 so that transverse stresses can be disregarded. These slots 22 are desirably about one-half the thickness of the bolt head. The area of the bolt head between the slots 22 comprises the ridge 20, which has a width about twice the width of a slot.

The strip 16, which is desirably rectangular in shape, when the bolt head 14 is hexagonal in shape, is secured to the bolt head 14 along the upper surface of the ridge 20. The strip 16 of photoelastic material is adapted to manifest the bending stresses in the bolt head in the form of photoelastic fringes linearly related to the bending stresses in the head and hence to the bolt tension.

The strip 16 is secured to the ridge 20 by a layer of reflecting adhesive 24. This layer of reflecting adhesive 24 allows the fringe pattern to be observed in the birefringent strip 16 as well as secures the strip to the ridge. The reflecting adhesive 24 is of any suitable type for securing the strip 16 to the upper surface of the bolt head 14. One presently preferred adhesive is a mixture of 100 parts resin, type PC-1, and 10 parts hardener, type PCH-1, available from Photolastic, Inc. The strip 16 can be cemented or bonded to the bolt head either at its ends or along its bottom face. In either case, a visual fringe pattern can be obtained which can be related to the bolt tension. When the strip is bonded at its ends to the bolt head, it will be compressed when the bolt head bends and the periphery of the head rotates inwardly due to bolt tension. The fringe pattern in this case will be of uniform intensity alternating in color tone in a systematic manner as the tension on the bolt increases. When the strip is bonded along its bottom face to the bolt head, it will respond along its length to the bending stresses and as a consequence the fringe order will increase from zero at the end to a maximum fringe order at the center of the strip. The maximum fringe order at the center as well as the gradient in the fringes increase systematically with the bolt tension.

In FIG. 2, there is shown a second embodiment of a tension indicating bolt 30. The bolt 30 similarly has a threaded shank 32 and an integral head portion 34. On the upper surface of the head 34 a ridge 36 is integrally formed. The ridge 36 extends entirely across the width of the bolt head 34 between parallel opposing faces 34a and 34b and the strip 38 of photoelastic material is mounted by a layer of reflecting adhesive 24 to the upper surface of the ridge 36. The ridge is of substantially the same dimensions as the ridge 20 of the embodiment of FIG. 1. Preferably, the ridge 36 is formed by cutting away a portion of the bolt head 34 so that the ridge is integral therewith, although the ridge 36 could be formed separately and then fastened to the head 34.

The configurations of the bolts 10 and 30 shown in FIGS. 1 and 2 are the presently preferred embodiments. In both of these configurations, the respective strip 16 or 38 of photoelastic material is mounted on a ridge 20 or 36, respectively, and is spaced from the remainder of the bolt head. In both embodiments, the

longitudinal sides of the respective ridges 20 and 36 are spaced from contact with the bolt head except at the lower portion of the ridge joining the bolt head. As the strip of photoelastic material is spaced from the head and as the ridge to which the strip is mounted has its sides generally spaced from the bolt head, the influence of head stresses in the direction transverse to the rectangular strip is diminished. The result is increased sensitivity to bending stress increments coupled with a fringe pattern which is relatively easy to read.

FIGS. 3 through 5 illustrate alternative embodiments of tension indicating bolts. In FIG. 3, a tension indicating bolt 40 has a shank 42 and an integral head 44 provided with a channel or depression 46 therein. This depression 46 extends to a depth about one-half the thickness of the bolt head 44. As shown, the depression 46 is substantially cylindrical in shape. The depression 46 tends to reduce the bending resistance of the head. The strip 48 of photoelastic material extends entirely across the width of the depression but as it is rectangular in shape, it extends only across a portion of the area thereof. As the strip 48 extends only within the depression 46, it is somewhat shorter than the corresponding strips 16 and 38 of the embodiments shown in FIGS. 1 and 2, respectively, but is of substantially the same height and width. Again, the longitudinal sides of the strip 48 are generally spaced from the bolt head 44 so as to improve fringe order sensitivity. The strip 48 is mounted to the bottom of the depression 46 by a layer of reflecting adhesive 24.

Similarly, in FIG. 4, a tension indicating bolt 50 has a shank 52 and an integral head 54 in which a channel 56 is formed. The depth of the channel 56 is about one-half the thickness of the bolt head 54. In this embodiment, however, the channel 56 extends entirely across the width of the bolt head 54 between opposing parallel flats 54a and 54b thereof and consequently a strip 58 of photoelastic material which is disposed within the channel also extends entirely across the width of the bolt head 54. The strip 58 is of substantially the same dimensions as the strips 16 and 38 shown in FIGS. 1 and 2, respectively. The strip 58 is mounted to the base of the channel 56 by a layer of reflecting adhesive 24 such that the longitudinal sides of the strip 58 are spaced from the walls of the channel 56 and hence are generally spaced from the bolt head 54 so as to improve fringe order sensitivity.

In FIG. 5, a tension indicating bolt 60 similarly has a shank 62 and an integral head 64. However, in this embodiment, a photoelastic strip 66 is mounted directly upon the upper surface of the bolt head 64. Thus, no ridge or channel is formed in the bolt head 64. The strip 66 of photoelastic material is mounted to the bolt head 64 by a layer of reflecting adhesive 24 and extends entirely across the width of the bolt head 14 between opposing parallel sides 64a and 64b thereof. Preferably, the strip 66 is of the same dimensions as the strips shown in FIGS. 1, 2 and 4 and is mounted such that the longitudinal sides thereof are generally spaced from contact with the bolt head to improve order sensitivity.

Although several embodiments of the tension indicating bolt have been described, it should be apparent that other embodiments could also be constructed. The bolt configuration should be selected with the following factors in mind: ease of manufac-

ture, enhancement of response to load, and generation of a photoelastic pattern which is distinct and easy to read.

In use of the tension indicating bolt in accordance with one of the above-described embodiments, the bolt having the strip of photoelastic material fastened to the head thereof is threaded into an article to be fastened by applying a torque to the bolt to thread the shank into the article. The tension in the threaded bolt is transmitted to the head of the bolt producing bending stresses in the head. These bending stresses are manifested in the form of fringes on the photoelastic strip material which are linearly related to the bolt tension.

Turning now to FIG. 10 of the drawing, there can be seen suitable apparatus generally designated by the reference numeral 70 for analyzing these photoelastic fringes. Such apparatus, conventionally known as a reflection polariscope, measures changes in the index of refraction by reflecting polarized light from the surface of a stressed part to which a photoelastic strip and reflecting adhesive have been applied. The reflection polariscope 70 generally comprises a polarizer 72, a light source 74 and an analyzer 76, all contained within a compact housing 78. Light from the source 74 passes through the polarizer 72 and the strip 16 and is reflected from the layer of reflecting adhesive 24 which mounts the photoelastic strip 16 to the head of the bolt 14. This reflected light, which is birefringent after passing through the photoelastic strip, is directed through the analyzer 76, which is rotated by the viewer relative to the polarizer 72 to determine the degree of fringe order. One suitable type of reflection polariscope is obtainable from Photoelastic, Inc., as that type is simple and compact, although any other suitable reflection polariscope can also be utilized. It should also be apparent that a plane polariscope could also be employed to produce a fringe pattern. Once the degree of fringe order is determined by a direct reading of the amount of rotation of the analyzer 76, a calibration curve (FIGS. 8 and 9) is employed to relate the degree of fringe order to the amount of tension on the head of the bolt.

Several examples will now be given of the manner of use and results obtained in employing a tension indicating fastener in accordance with the present invention.

EXAMPLE 1

A hexagonal head steel bolt designated $\frac{3}{4}$ -16 NF-5 was selected for conversion into a tension indicating bolt 10 in accordance with FIG. 1 of the drawing. To increase the response to load and to provide uniform seating of the head, the head 14 was reduced in thickness from a nominal 0.475 in. to 0.27 in. and provided with an undercut seating collar 0.02 in. wide. As shown in FIG. 1, two parallel slots 22 about $\frac{5}{32}$ in. apart were formed in the head, each slot being about $\frac{1}{16}$ in. wide, $\frac{3}{32}$ in. deep and extending across the entire width of the bolt head 14 between the opposing parallel flats 14a and 14b thereof. The published allowable load for this type bolt based on approximately 70 percent yield strength of the threads is about 32,100 lbs.

On the ridge 20 formed between the parallel slots 22, there was secured the rectangular strip 16 of birefrin-

gent photoelastic material. The strip 16 was about 5/32 in. wide and was secured entirely along its lower face to the upper surface of the ridge. The photoelastic material was of the type designated PS-2 and had a nominal thickness of about 0.08 inch. The layer of reflecting adhesive 24 for securing the strip to the ridge was a mixture of 100 parts resin of the type designated PC-1 and 10 parts hardener of the type designated PCH-1.

The bolt 10 was threaded into a block of steel used as a bolt loading fixture. The block had a 0.76 inch diameter hole drilled and reamed therein for the admission of the bolt. A torque wrench was employed to tension the bolt in increments of 20 ft. - lbs. from zero to 180 ft. - lbs. To measure the strain in the bolt in order to provide calibration and a check on accuracy, a force washer was disposed over the bolt shank 12. Upon threading the bolt in the fixture, the force washer rested between the undercut seating collar formed in the bolt head 14 and the fixture. The force washer was a Model SK-TR-47 made by Lockheed Electronics. Employment of the force washer necessitated the use of electric readout equipment, which in the present example was a Model 120 strain indicator made by the Budd Company. For each load level, the strain as measured by the force washer was recorded. The corresponding tension in the bolt was obtained from a calibration curve provided for the force washer.

Contemporaneously, a reflection polariscope 70 of the type shown in FIG. 10 was employed to cause the appearance of and to analyze the fringe pattern on the photoelastic strip. Polarized light was directed through the birefringent strip 16 and reflected by the layer of adhesive 24 back through the strip, the reflected light being analyzed by the analyzer 76 in the polariscope. The degree of fringe order corresponding to each load level was determined directly from the polariscope using the Tardy method of compensation. For each load level, the fringe order was recorded in degrees of counterclockwise rotation of the analyzer, with 180° of rotation corresponding to each whole fringe order.

The photoelastic fringe pattern at maximum load had the appearance illustrated in the photograph of FIG. 6. There it can be determined that the bolt head 14 having the strip 16 thereon displayed a photoelastic fringe pattern having a plurality of photoelastic fringes 80. The fringes 80 formed a relatively symmetrical pattern at the maximum load. The fringe order was relatively easy to read by the Tardy method since the zeroth order fringe could be readily located.

As shown in FIG. 8, a calibration curve was prepared plotting the bolt tension (in pounds) against the fringe order (in degrees). The values of bolt tension were obtained from the calibration curve provided for the force washer at the respective strains indicated by the force washer. At the corresponding load levels, the fringe order (in degrees) was determined using the reflection polariscope 70 by rotating the analyzer 76 relative to the polarizer 72. The calibration curve was theoretically expected to be in the form of a straight line and a least squares straight line data fit was used to prepare the curve so that the theoretical curve was approximated. It has been found that the accuracy of the calibration curve was between about 2 and 5 percent as compared to the results obtained from the force washer standard. Thus, if the fringe order (in degrees) should

be about 236 as indicated by the polariscope 70, the bolt tension would be about 9,060 lbs. This is within an accuracy of less than about 2 percent.

EXAMPLE 2

A similar bolt was prepared for testing having the configuration shown in FIG. 2. A bolt of the same size and type as that used in the first example was converted to a tension indicating bolt 30 by removing a portion of the bolt head 34 such that the head was 0.27 in. thick while leaving a ridge 36 about 1/8 in. high and 5/32 in. wide extending across the entire width of the head between the opposing parallel flats 34a and 34b thereof. The photoelastic strip 38, which was similar in construction and size to the type described in Example 1, was secured to the upper surface of the ridge 36 by a similar layer of reflecting adhesive 24. The bolt 30 was threaded into the bolt loading fixture and the tension therein measured by both the force washer and the method of the present invention, in accordance with the procedures described in Example 1.

Upon employing a reflection polariscope 70, such as the polariscope shown in FIG. 10, a fringe pattern as shown in the photograph of FIG. 7 was obtained and analyzed. This fringe pattern at maximum load formed a relatively symmetrical pattern having a plurality of photoelastic fringes 82. The fringe order was relatively easy to read by the Tardy method as the zeroth order fringe could be readily located.

A calibration curve, as shown in FIG. 9, was prepared plotting the bolt tension (in pounds) obtained from the calibration curve for the force washer for particular load levels against the fringe order (in degrees) as read on the polariscope. It was found that the calibration curve could be used in the field to within an accuracy of between about 2 and 5 percent, as compared to the force washer used as a standard. For example, should the fringe order in degrees be about 213, the bolt tension would be about 7,430 pounds. This is within an accuracy of less than about 2 percent.

Thus, the present invention provides a tension indicating bolt allowing rapid determination of the bending stresses created in the head of the bolt during the loading thereof as the shank of the bolt is tensioned, the bending stresses being linearly related to the bolt tension. A method of determining bolt tension employing a birefringent material secured to the bolt head has been described which is accurate within a range of between about 2 and 5 percent. However, the method can also be employed when it is desired to determine bolt tension accuracy to a degree greater than 5 percent. Such a tension indicating bolt is relatively simple and inexpensive.

Although one form of the invention has been shown and described, it should be apparent that various modifications could be made therein without departing from the scope of the invention.

Various of the features of the invention are set forth in the following claims.

What is claimed is:

1. A bolt comprising an externally threaded shank, a head integrally mounted to the end of said shank, a ridge formed on said head, said ridge being adapted to transmit bending stresses created in said head during tensioning of said bolt while minimizing the influence

of stresses transverse to said bending stresses on said ridge, a strip of photoelastic material having a side mounted upon said ridge, said strip being adapted to manifest said bending stresses in the form of photoelastic fringes linearly related to the bolt tension, other sides of said strip being free of said head to reduce the effect of said transverse stresses on said strip, and a layer of reflecting adhesive for mounting said strip to said ridge, said layer of reflecting adhesive being adapted to permit the observation of said fringes on said strip by reflection.

2. A bolt according to claim 1, wherein said strip is formed of a birefringent material.

3. A bolt according to claim 2, wherein said material is an epoxy.

4. A bolt according to claim 1, wherein said head has a slot formed therein substantially parallel to and adjacent said ridge to isolate said strip mounted upon said ridge from said head.

5. A fastener for providing indication of the tension therein, comprising a shank, a head integrally mounted to the end of said shank, a portion of said head being substantially isolated from transverse stresses, and a photoelastic member having a side thereof mounted to said head portion and extending substantially across the entire width thereof, for manifesting in the form of photoelastic fringes bending stresses created in the head during tensioning of said fastener, said bending stresses being linearly related to fastener tension, said head portion being formed between a pair of parallel slots extending substantially across the entire width thereof, the portion of said head therebetween comprising a ridge, said slots serving to minimize the influence of stresses transverse to said bending stresses on said ridge, said photoelastic member being mounted upon said ridge.

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