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Factors affecting Failure mode and load of rubber polyester composite joint

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Abstract. The joining of rubber polyester composite is affected by design and geometry parameters. These parameters affect the failure load of the composite joint and the failure mode. Catastrophic failure modes should be avoided, and the optimum parameters are selected to achieve a progressive failure that could be observed. Geometry parameters such as the edge distance and the center distance between holes are tested under tensile loading to get the optimum values. Design parameters such as tightening torque of bolt and washer size are also tested under tensile loading, and their effect on the failure load is obtained and studied. The failure modes are investigated under the digital microscope in each case. It is found that the failure load increases by increasing the edge distance, the tightening torque, and decreasing the center distance between holes. The optimum washer size is varied according to the used tightening torque. The optimum obtained failure mode in tests is a mixed - mode of bearing and net tension modes.

1. Introduction

Compo site materials, especially the reinforced polymer composites, have wide use nowadays in many applications [1,2]. Fiber-reinforced composites are used in yachts, aviation, and automotive industries[3]. Glass fiber reinforced polyester is a commonly used composite, and fillers are added to reduce the cost of the final product[4, 5]. One of these fillers is waste tire rubber particles which improve the specific impact strength of the composite and reduce the cost of the final product[6]. The rubber particles volume fraction is selected to be 10% of the total volume of the composite as recommended by another researcher[7]. In the above-mentioned applications, the composites are joined with metals or any other materials.

Mainly, there are two types of joining materials which are adhesive and bolted joints. The bolted joints have many advantages compared to the adhesively bonded joints. Bolted joints can easily be assembled and disassembled for maintenance, easily replaced, and repaired[3]. Bolted joints have a disadvantage as the joint between the joined parts are the weakest part of the structure due to the fact of drilling the holes needed for joining.

On the other hand, many factors are affecting the strength of this joint and its failure load. The failure load is the maximum load the joint can withstand before failure. These factors could be categorized into four main groups, which are material, fastener, design, and geometry factors[8]. The material parameter includes the fiber type, form, and laminates sequence. The fastener parameter includes the fastener type and size. The design parameter includes the loading type and direction. Geometry parameter includes the distance of the hole from the end, the distance from the edge, the hole size, and part dimensions [8].

The width of the specimen (W) and hole size belong to geometry factors that can affect the strength of the joint. Width to hole diameter (W/D) is a ratio used to easily study these two factors and their effect on the strength of the joint. Okutan et al. proved that the increase of this ratio led to the increase of the bearing strength. Most studies and researches used W/D ranged from 2 to 5[8, 9]. The suitable value that is recommended to use is more than 3, as for smaller ratios, the joint becomes weak[8]. After a certain ratio of W/D, depending on the material, the mode of failure changed from tension to bearing mode, which is a desirable mode as it is a sign of failure before a catastrophic behavior is observed [8].

The distance of the hole center to the edge (E) is also studied as a ratio to hole diameter. Esmaeil et al. concluded that by increasing this ratio, the bearing strength increases [10]. Edge distance to hole diameter ratio (E/D) affects the strength of the joint and its failure mode [11]. There are different failure modes which are catastrophic modes such as net tension, shear out, and cleavage modes. The desirable mode is the bearing mode which is a progressive failure mode. The tested specimens are examined to consider failure mode. Up to a certain point, the increase in E/D ratio increases the strength of the material, then the value stabilizes, and the mode of failure changed to bearing mode. The studied ratio ranges from 1 to 5. At smaller values, the failure mode is shearing out mode, which is a catastrophic, not desirable mode. The suitable recommended ratio is beyond 2[8].

The effect of clearance between bolt and hole on the joint strength is also investigated where two different types of clearances are compared to each other. Esendemir et al. proved that the bigger clearance has a lower bearing strength of the bolted joint [12].

Bolt tightening torque (T) and washer size are two design factors that affect the bearing strength of the joint. It is observed that by increasing the tightening torque, the bearing strength increases, and by increasing the washer's outer diameter, the bearing strength increases up to a limit that may differ from one material to another and then decreases[13].

In applications, more than one hole is needed in a joint. The effect of the hole-to-hole distance (M) on the bearing strength of the joint becomes a point of interest. This geometrical parameter is studied as a ratio between hole-to-hole distance and hole diameter (M/D) [14, 15]. The bearing strength of the joint increases by increasing this ratio, and the studied range is from 2 to 5[14, 15].

This study aims to study the design and geometry factors affecting the failure load of the novel composite joint. This work is a collective study of different factors that affect the joint. The optimum factor is obtained in one test and set as a constant for other tests to obtain a final joint of the composite of optimum loading conditions and grantee desirable failure mode.

The specimens are drilled and the effect of different factors on the failure load of composites are studied. The width of the specimen and the hole diameter are kept constant in all tests. The studied factors are as follows; the distance between the edge and the hole center (E), the tightening torque of the bolt, the washer size, and the distance between two parallel holes (M) on drilling more than one hole.

2. Experimental work

2.1 Materials

A glass fiber reinforced polyester with rubber particles (of volume fraction 10%) composite is prepared in laminates as specified in detail in a previous study[6].

2.2 Set up preparation

Specimens -of 120 mm length, 25 mm width, and 3.5 mm thickness- are prepared then drilled according to the needed dimensions specified in each test. A tensile test attachment is manufactured according to ASTM D 953 – 02 [16] to hold the specimen during the test, as shown in Figure 1a. A drilling jig is also manufactured to ensure accurate dimensions of holes in each specimen, as shown in Figure 1b.

The specimen dimensions nomenclature is shown in Figure 1c. The hole diameter is equal to 5 mm. The width to hole diameter ratio is kept constant in all performed tests and equals 5.

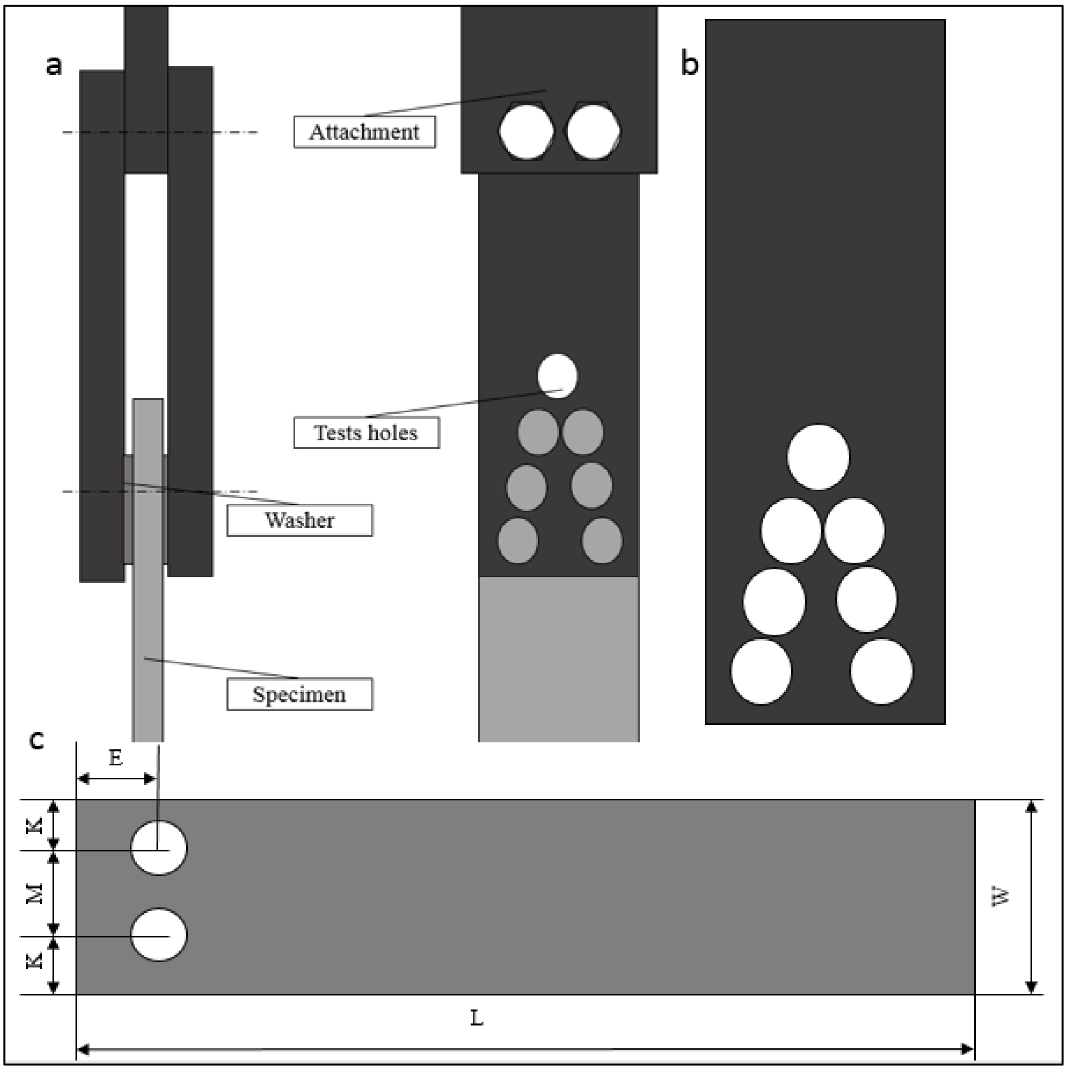

Figure 1. Test set up; a) Test attachment, b) Drilling jig, and c) Specimen dimensions nomenclature

2.3 Tests procedure

Tensile tests are performed on a LLOYD universal testing machine-30 tons, and a load-displacement curve is obtained in each case. The crosshead speed is 0.5 mm/min, in agreement with another research[17]. Four groups of tests are performed to study four different factors that affect the failure load of composites. Specimens are tested in each case, and a load-extension curve is obtained. The four factors are as follows;

2.3.1 *The ratio between the edge distance and the hole diameter (E/D).* This test is performed to get the suitable distance of the hole from the edge to avoid undesired failure modes. The studied ratios are 1, 3, and 5. A pin of outer diameter 5 mm is used. The failure modes are then investigated according to ASTM D 5961/D 5961M – 01 [18]. The optimum distance which gives the maximum failure load and the desired failure mode is chosen and set for the next test.

2.3.2 *The tightening torque (T).* Different tightening torques are tested to study their effect on the failure load of the composite. The studied torques are 0, 2, 4, and 6 N.m. A bolt of outer diameter 5 mm is used. A constant washer size of an outer diameter of 25 mm is used in this test. E/D is equal to 5. The optimum tightening torque, which gives maximum failure load depending on washer size, is selected and set for the next test.

2.3.3 *The washer size (S*). Four washer sizes of different outer diameters 10, 15, 20, and 25 mm respectively are used in this test to study the effect of washer size on the failure load of the composite. The tightening torque is 6 N.m, and the E/D is equal to 5. A bolt of outer diameter 5 mm is used.

2.3.4 *The ratio between the center distance of holes and the hole diameter (M/D).* The center distance between holes is restricted by the width, the diameter of holes, and the outer diameter of the used washer. The selected dimensions are E/D = 5, tightening torque = 2 N.m and the outer diameter of the washer is 15 mm. These values are chosen to fulfill design considerations.
This test is performed to check the optimum center distance between two holes to use a pin and bolt together to restrict the rotation of the specimen and avoid the effect of clearance in the bolt. The center distances of two parallel holes are varied depending on the width of the specimen, where 25 =2K+M. The tested M/D ratios are 2.2, 2.6, and 3.

2.4 Specimens examination
A digital microscope is then used to examine the tested specimens to evaluate the specimen condition and define its failure mode.

3. Results and discussion
The results and discussion of the four performed tests are as follows;

3.1 Effect of edge distance/hole diameter (E/D)
The average failure load of tested specimens is calculated in each case and the results are plotted as shown in Figure 2a. The results show that by increasing E/D, the failure load increases up to a limit then the load stabilizes. The decision is not clear. Therefore, the average displacement at failure in each case is calculated and plotted as shown in Figure 2b. This figure shows that the displacement at the highest tested E/D is the highest which means that the specimen has more displacement before failure, and this could be the effect of bearing mode. Therefore, E/D equals 5 is selected to be the optimum in this case.

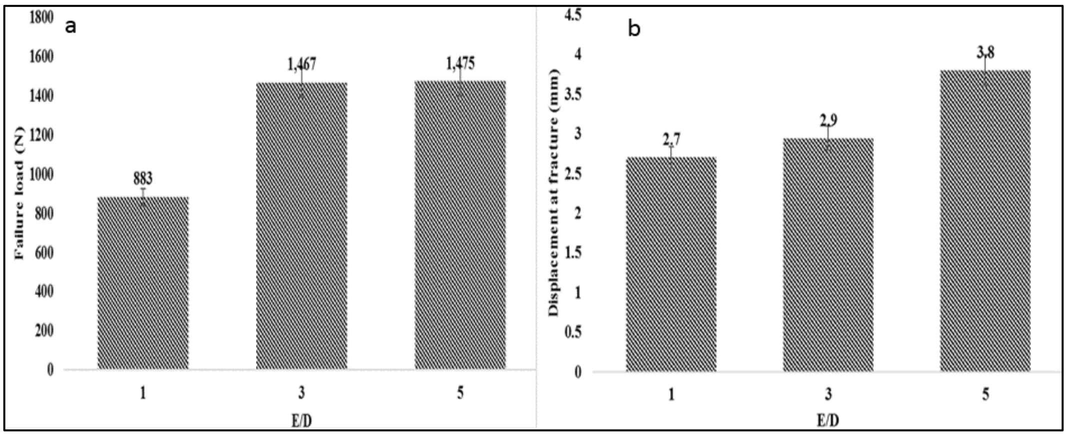

Figure 2. a) Failure load at different E/D and b) Displacement at failure at different E/D

The tested specimens are investigated under the microscope, and the mode of failure in each case is detected. Figure 3a shows that the failure mode at E/D = 1 is cleavage mode, Figure 3b shows that the failure mode at E/D = 3 is a mixed-mode of cleavage-net tension failure. Both failures are sudden failures that are undesirable modes. Figure 3c shows that the failure mode at E/D = 5 is a mixed-mode of bearing-net tension failure, which is a desirable mode as it does not result in a catastrophic failure. This figure confirms the results of failure loads and displacements at failure.

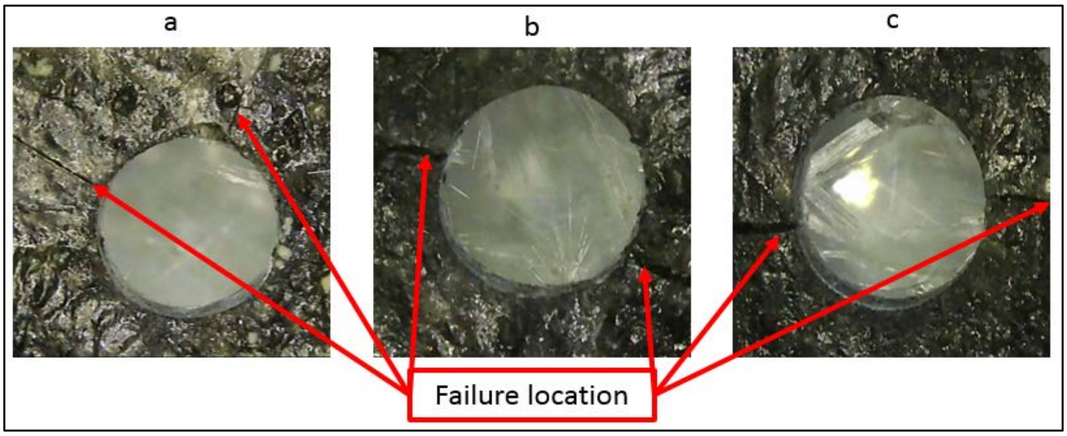

Figure 3. Fractography of specimens at different E/D ratios; a) E/D = 1, b) E/D = 3, and c) E/D = 5

The decision here is that the optimum value for E/D is equal to 5 which corresponds to E = 25 in the performed tests. The corresponding failure load at E/D = 5 is approximately 1474 N. This result is set as constant for the next tests.

3.2 Effect of the tightening torque (T)

The average failure load is calculated in each case and plotted as shown in Figure 4. The figure shows that by increasing the tightening torque, the failure load increases. This is due to increasing the axial force. The axial force increases the contact pressure, which increases the frictional force between the jointed members. The frictional force prevents slipping of the members, which prevents the bearing of the bolt on the edges of the hole. Therefore, the failure load of the joint is increased. This is agreed with other researchers[19].

The figure also shows that the failure load at T = 0 is approximately 1450 N which is slightly lower than the optimum value (1474 N) that is obtained from the previous test. This may be due to the clearance found in the case of using a bolt. The tight fit obtained in the case of using a pin increases the failure load compared to the case of a bolt with clearance. The contact area between the pin and joint increases so, the stress on the joint decreases, and the joint load-carrying capacity increases in agreement with another researcher[20].

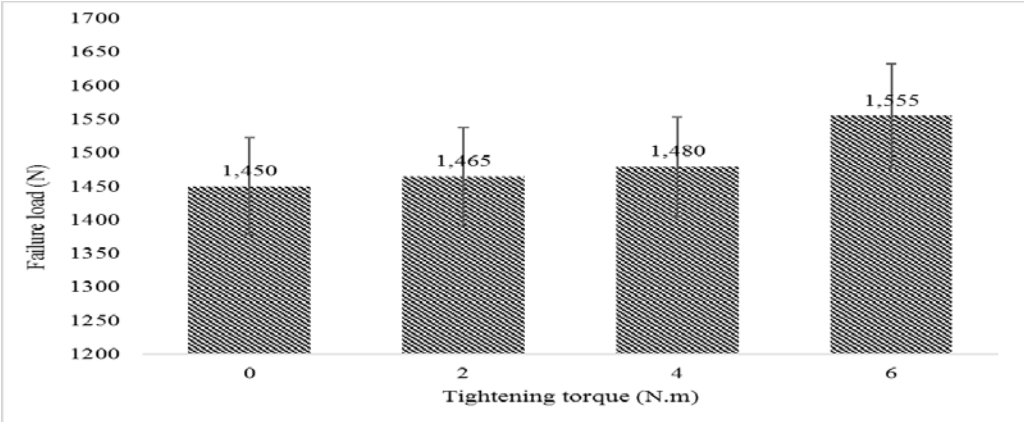

Figure 4. Failure load at different tightening torques

The tested specimens are investigated under a digital microscope. The figure shows that the failure mode is unchanged by varying the tightening torque. The observed failure mode is a mixed-mode of bearing-net tension, as shown in Figure 5.

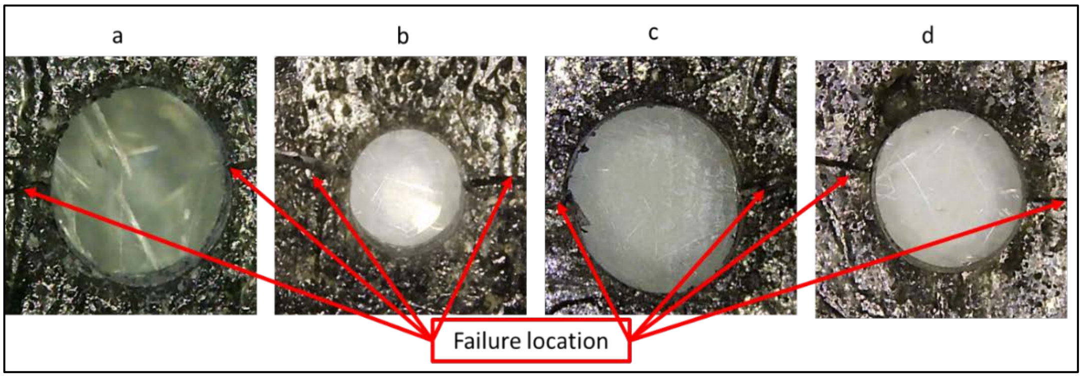

Figure 5. Fractography of specimens at different tightening torques; a) T = 0, b) T = 2, c) T = 4, and d) T = 6 N.m

The optimum tightening torque from this test is 6 N.m as it increases the failure load of the joint. The corresponding failure load is approximately 1555 N.

3.3 Effect of the washer size (S)
The effect of washer size on the failure load is studied, and the results are plotted as shown in Figure 6. The available washer sizes are categorized into two groups; big washers of outer diameters 20 mm and 25 mm and small washers of outer diameters 10 mm and 15 mm.

It is noticed that for each group of washers, the decrease of washer’s size, leads to an increase in failure load. This is due to the larger pressure obtained for a smaller contact area having the same axial load resulting from the use of the same tightening torque. The tightening torque exerted an axial force, and the pressure is distributed on the washer's contact area, as illustrated in Figure 7

Small-sized washers have lower failure loads than big-sized washers while they have lower contact area and higher pressure. The high pressure that exceeds the material's strength leads to microcracks under the washer after applying the tightening torque.

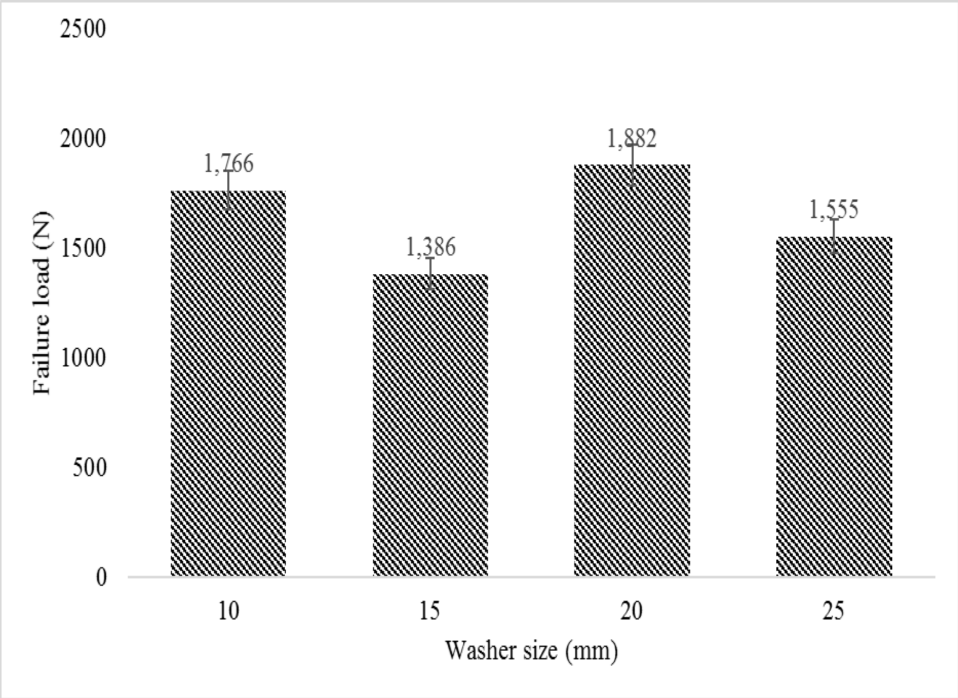

Figure 6. Failure load at different washer sizes

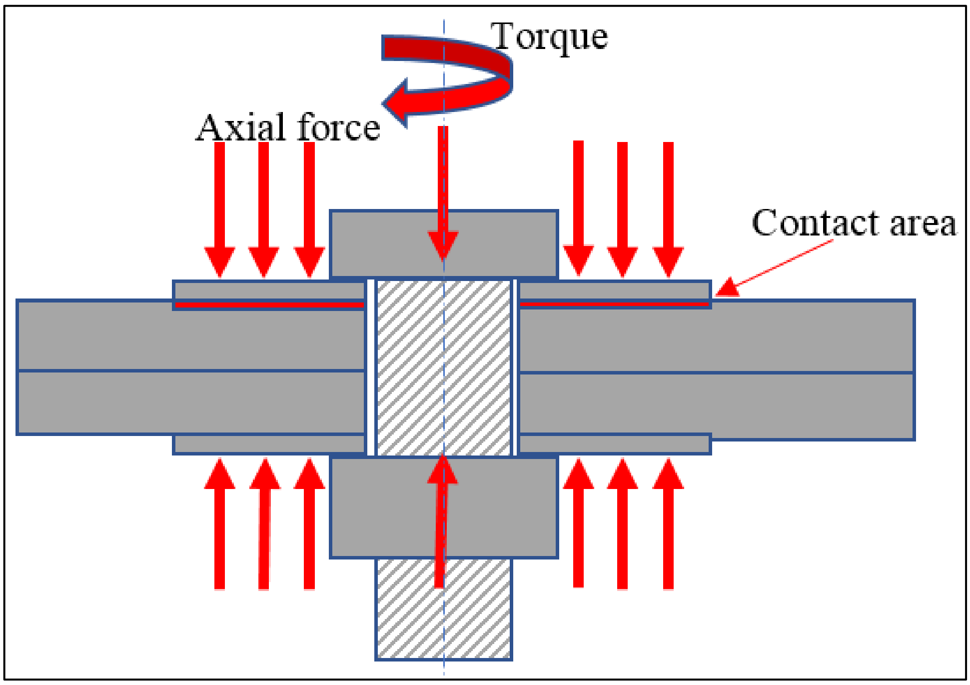

Figure 7. Illustration for the axial force exerted on the joint

The tested specimens are investigated under the microscope, as shown in Figure 8. Figure 8a and Figure 8b are corresponding to big washer sizes of Do = 20 and 25 mm respectively, the mode of failure is a mixed-mode of net tension and bearing. Figure 8c and Figure 8d are corresponding to small washer sizes of Do = 10 and 15 mm, respectively. Many cracks appeared under the contact area of the washer, and these cracks propagate during tensile loading and resulting in lower bearing strength of the joint. These figures comply with the results discussed in Figure 6.

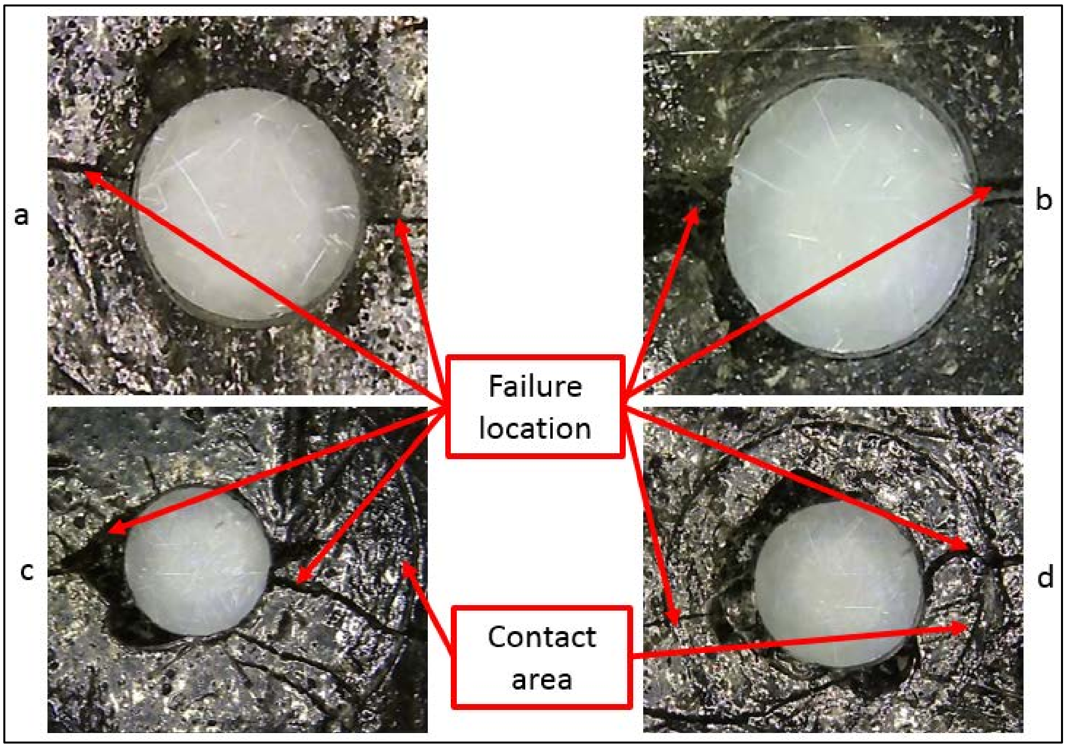

Figure 8. Fractography of specimens at different washer's outer diameter; a) Do = 25, b) Do = 20, c) Do = 15, and d) Do = 10 mm

The optimum result from this test is, using a washer of outer diameter 20 mm with a tightening torque of 6 N.m. It is also concluded that the optimum washer size depends on the used tightening torque.

3.4 Effect of center distance of holes to the hole diameter (M/D)

The effect of different M/D ratios on the failure load of the specimen is tested and the results are plotted as shown in Figure 9. The figure shows that by increasing the center distance, the failure load decreases, and this is because the lateral distance from the edges (K) decreases. When the distance K decreases, the probability of the crack propagation increases, and the separation of the joint is observed at lower loads.

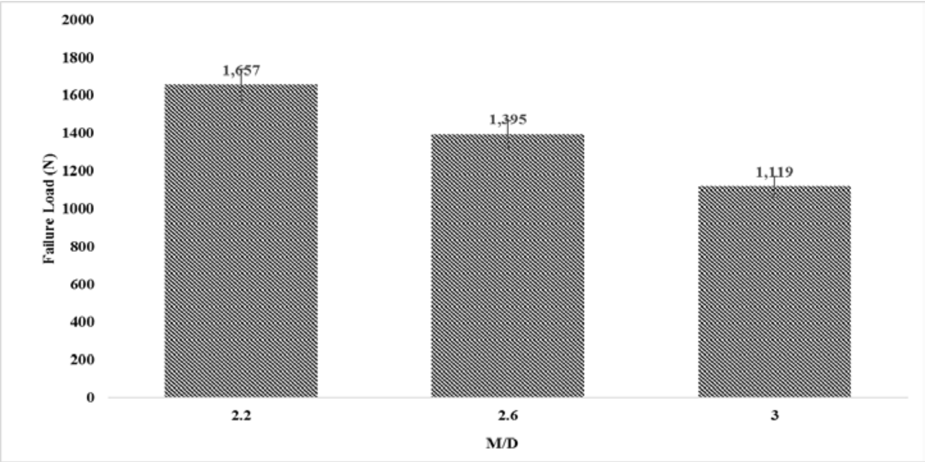

Figure 9. Failure load at different M/D

The tested specimens are investigated under the microscope as shown in Figure 10. The figure shows that changing M/D does not affect the failure mode. Mixed - mode of net tension and bearing is observed in all studied cases.

It is also observed that by using a washer of outer diameter equals to 15 mm with tightening torque equals to 2 N.m., there are not any cracks under the contact area of the washer. This proves that the washer size depends mainly on the axial force results from the tightening torque.

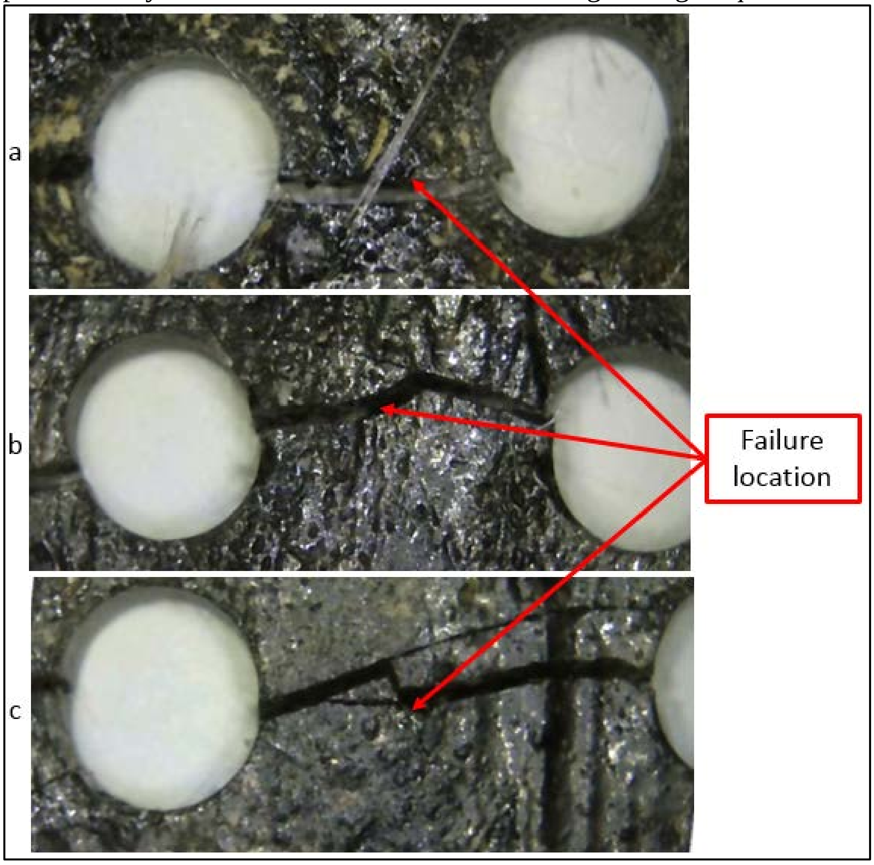

Figure 10. Fractography of specimens at different M/D ratios; a) M/D = 2.2, b) M/D = 2.6, and c) M/D = 3

The optimum result obtained in this test is that the minimum possible center distance -depending on the width and the outer diameter of the washer- gives higher failure loads compared to the bigger center distances.

4. Conclusion

Increasing the edge distance results in increasing the failure load and obtaining a mixed-mode of bearing and net-tension. Increasing the tightening torque increases the failure load as the axial load on the joint members' increases. The failure load increases by decreasing the washer size due to increasing the pressure on the joint. The small-sized washers have a bad effect on the joint as increasing the pressure too much can exceed the compressive force resulting in microcracks under the washer. The failure load increases with decreasing the center distance and increasing the lateral distance from the edges.

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