Advanced Composite Materials
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/tacm20

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Published online: 16 Jul 2013.

To cite this article: Yoshiki Fukada (2013) Bearing strength of carbon fibre/epoxy laminate with direct measurement of hole deformation, Advanced Composite Materials, 22:5, 311-325, DOI: 10.1080/09243046.2013.814752

To link to this article: http://dx.doi.org/10.1080/09243046.2013.814752

Advanced Composite Materials, 2013
Vol. 22, No. 5, 311–325, http://dx.doi.org/10.1080/09243046.2013.814752

Bearing strength of carbon fibre/epoxy laminate with direct measurement of hole deformation

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(*Received 22 November 2012; accepted 11 June 2013*)

The bearing strength of carbon fibre/epoxy laminates composite has been investigated with a new failure criteria instead of conventional 4%*d* load. A precise measurement of hole deformation allows to determine the failure load as a clear kink point on the load-displacement curve. The validity of the new failure criteria was evaluated by cyclic load tests. With the new failure criteria, the effect of bolt-hole clearance and the clamping force were re-evaluated. Effect of the gap between the specimen and bush was also investigated. The experiments show more than 0.1 mm clearance for 6.35-mm hole affect for the failure load but not maximum load. The tightening up torque affects both the failure and maximum load up to 15%. The gap between specimen and bush strongly affect the maximum load but not failure load. These results give a design criteria for thickness tolerance for the cases of using collar on the hole. Significant deviation between conventional 4%*d* load and new failure load were found in several conditions.

Keyword: bearing strength

1. Introduction

Improvement of fuel efficiency of automobile and aircraft has become increasingly important because of global warming. Adoption of carbon/epoxy structure for weight reduction is one of the most effective measures to reduce fuel consumption. But, assurance of strength/durability of composite materials is still very difficult because of their complicated nature. In bolted joint structures – one of the most basic structural element – our knowledge of structural design is still primitive.

Collings [1,2] pointed out the importance of the effect of bolt-hole clearance or the other design factor in his pioneer work for graphite/epoxy bolted joint. One may expect that a large bolt-hole clearance leads to lower strength; the FEA studies,[3–5]) also proved it. There are some experimental studies too. DiNicola and Fantle [5] investigated about the bolt-hole clearance effect on bearing strength in a toughened graphite/epoxy material. They found that bolt-hole clearance does not affect the maximum load but 4%*d* deformation load. Kelly G and Hallstr S [6] also concluded that bolt-hole clearance has large influence on 4%*d* deformation load but little effect on maximum load. Here, they employ 4%*d* deformation load as 'the load that the joint start damage'. The validity of the 4%*d* deformation load is one of the important issue of this study. It will be discussed later.

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Effect of lateral constraints is also an important factor. Stockdale and Matthews [7] and Khashaba et al. [8] studied the glass fibre/epoxy material. They reported that the bearing strength increases by the increase of clamping pressure. Xiao et al. [9,10], Smith et al. [11], Park [12] and Hsien-Tang et al. [13,14] focused on the relationship between damage progress and bolt clamping force to the strength. They concluded as follows. Surface constraint, by bolt clamp-up, restrains the outward deformation of the bearing area. So, the bearing area can sustain more bearing load.

The strength criteria itself is a difficult issue. Since the bearing area in the bolted joint is expected to be damaged before maximum load, as examined by Xiao and Ishikawa [10] and some other literature, the identification of bearing damage and defining of strength are very difficult. $4\%d$ deformation load defined in ASTM STD D953-87 [15] and JIS K7080 [16] is extensively used in various studies. $4\%d$ deformation load is defined as the load when the pin displacement reaches an equal value of 4% of hole diameter. The pin displacement is measured relative to the side edge of the test specimen. In JIS K7090, it is described that $4\%d$ deformation corresponds to material limit strain. But, the measured hole deformation does not correspond to the local strain of bearing area. According to the analytical solution of elastic deformation around pin-loaded plate studied by Bickley [17], the strain varies logarithmically to the distance from the pin. This means that the measured hole displacement is cannot be separated into local hole deformation and deformation of whole plate, because integration of logarithm diverges to infinity. The measured elastic hole deformation varies with the ratio of the hole diameter and the width of test specimen. Therefore, $4\%d$ deformation cannot be attributed to the material property nor fracture mechanics. The value 4% is determined from fracture onset point in the past experience with the existing material and existing condition. But, it is not secured for new material and new condition in future. In airworthiness requirements for aircraft certification, the limit load is described as 'the structure must be able to support limit loads without detrimental, permanent deformation' [18]. The $4\%d$ deformation does not correspond to any specific stage of damage progression. Structural designer may use adequate safety factor to determine the limit load from bearing test results. But, the safety factors are not derived from authorized method. There is another criterion of bearing strength. Deviation from the linearity on the load-displacement curve may have good agreement with failure mechanics, because the non-linearity is always attributed to material damage as plastic deformation or microscopic fractures. Offset strength in ASTM D 5961[19] may give more convincing criteria. Some literature [14] use this criteria but not many as $4\%d$ deformation load. The problem of this criterion is that this method always gives higher value than true yielding strength because of the offset. Smaller offset lead to closer value to the yielding points, but sensitivity to measurement error also increases. Therefore, offset strength also has a problem.

In metal structure evaluation, the yielding load that is identified as kink point on load-displacement curve is extensively used, and may be the best criteria of the bearing strength. But, in bearing strength of composite, this criterion was not used well. The load-displacement curves with ordinal cross-head displacement do not show clear kink. It may be the reason why yielding load was not used for composite bearing strength. In this study, it is shown that clear kink can be observed by precise optical measurement of hole displacement. Then, the relationships between fracture and load-displacement curve were evaluated, and it will be proved that the kink point is considered as damage initiation point. In later section, effects of design factors as bolt-hole clearance and lateral constraints to the bearing strength will be re-evaluated.

2. Experiment method

Optical devices have good accuracy in measuring displacement. Xiao and Ishikawa [20,21] conducted precious measurements of load-displacement curve for double lap bolt joints using optical measurement. In their elaborate study of bearing strength, optical extensometre was used with targets attached on the specimen and the bolt head. Their load displacement curves have very clear kink point that can be considered as yielding. In this study, an additional technique was used to improve accuracy.

MIL-type configuration for bearing strength test [22] was adopted. The pins are SCM420 steel with hardness HV720–HV850. Standard pin diameters were 6.34–6.33 mm. 1.0 mm-pitch M6 screw was placed on both ends of the pin for clamping. The pin is supported by two SCM420 steel bushes and bushes are inserted into a bulky steel main fixture. The bushes are 14 mm in diameter and chamfered to 12 mm diameter on contact area to the specimen. The fixture configuration is very rigid so that the deformation of the fixture is negligible. The standard specimen size was 38.1 mm wide and 254 mm long. The stacking sequence was $[\{(0)/(45)\}_3]_S$ quasi-isotropic plies with Toray T300 plain woven prepreg F6343B-05P. The total thickness was around 3 mm. The loading hole was placed 19.05 mm from the end. The hole was drilled by 6 mm carbide drill and reamed into intended diameter. Water-soluble lubricant was used for drill and ream processes.

Relative displacement between pin and specimen was measured by two laser displacement gauges KEYENCE LB02 placed on the main fixture body. L-shaped targets were attached to both hole side edges of specimens. Each gauges measure relative motion of the target on the direction of loading by 2 μm resolution. The pin–specimen displacement was defined as the mean value of two gauges outputs. By averaging two gauges, rotation of the specimen around pin axis is cancelled. It was confirmed that the flapping motion of targets is negligible by another experiment using three laser gauges

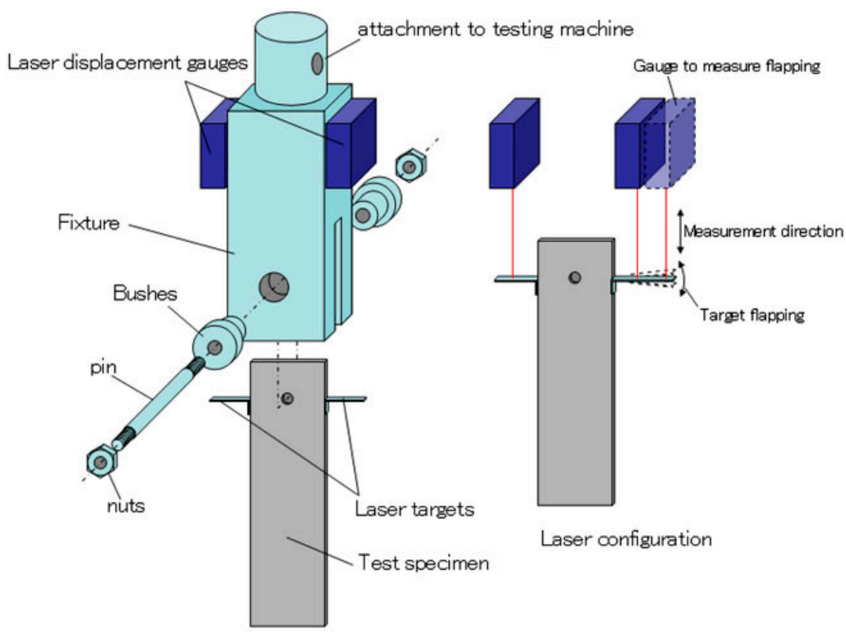

Figure 1. Test set-up.

measuring two spots on one side of the target. The configuration of the test set-up is shown in Figure 1.

3. Definition of strength

Shimadzu Autograph AG5000 was used in this study. Loading rate was 1 mm/min cross-head speed. Typical load-displacement curve of standard condition is on Figure 2. The curves are almost in a perfect straight line in the middle range of loading. Apparent kinks of the load-displacement curve can be seen.

Xiao and Ishikawa classified the fracture process of bearing damage into four stages as damage onset, damage growth, local fracture and structural fracture [21,23] supported by extensive simulation and experiments [10,24,25]. In their experiments, AE due to damage start slightly before the 'knee point' – kink of the load-displacement curve, and AE counts show sharp increase at the knee point (see Figures 4 and 6 in [23]). This start point of AE and the knee point with AE counts increase may correspond to the start of damage onset and start of damage growth, respectively. Around the start point of AE (very close to $4\%d$ point), the load-displacement curves have a subtle kink. Back to Figure 2, the kink of the curve consists of two small kinks. These two kinks were always observed in all the data in this study. First, kink is quite small but obviously the curve diverges from linearity from this point. From similarity of this load-displacement curve and study by Xiao and Ishikawa, it can be said that the first kink point and the second kink point correspond to the damage onset and the start of damage growth, respectively.

There is a question, what is the practical method to determine the bearing strength. The load of first kink point may be the most conservative value because it corresponds to the damage onset. But, the kink of this point is quite small, so that it is hard to

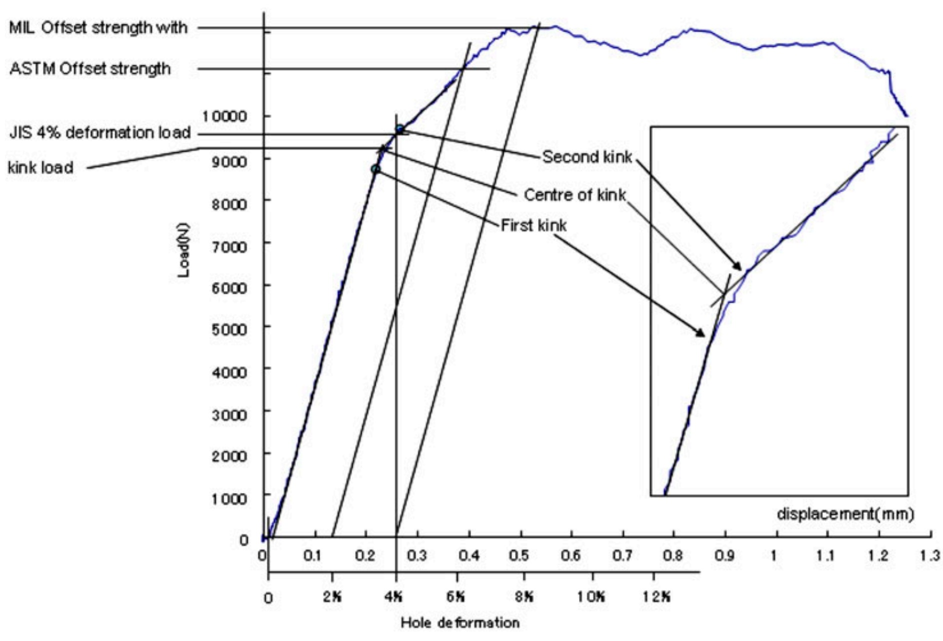

Figure 2. Load-displacement curve.

identify. The second kink point is relatively legible to identify but still not clear enough. It is not easy to identify two individual kink points in the load-displacement curve; so, there is a problem of personal error in practical application. Thereupon it is useful to define 'centre of kink'. The centre of kink is defined as follows: first, draw a straight line aligning first straight part of the load-displacement curve. 'First straight part' means the part where the load is more than 70% and less than the kink. The kink is preliminarily defined before. Second, draw a straight line aligning the second straight part of the load-displacement curve. 'Second straight part' means short straight part after the kink. The centre of kink can be defined as the cross-point of the two lines. An example is shown in Figure 2 (magnified image is in inset). The personal error of this method is quite small; even those kinks are subtle because determining straight lines is easy and accurate. Conventional 4%*d* load is also not free of personal error. There is a problem to determine zero point of displacement. The 'kink load' can be defined as the load on this point for the representative value.

To make sure of the validity to use the centre of the kink as the failure point and representative load to determine the strength, cyclic load tests were carried out. Figure 3 shows load-displacement curves where loadings were stopped just before the kink-point, then returned to zero load, and loaded again. Two load-displacement curves are completely same. This repeatability shows that the specimen does not have any damage. In another test shown in Figure 4, loadings were stopped immediately after the kink-point, then returned to zero and loaded again. In this case, second load-displacement curve does not trace the first one, and second load-displacement curve does not have a kink-point. To see the damage around the hole, another test was conducted. The loading was stopped and relieved immediately after the kink point. The photograph of the specimen of this test is in Figure 5. Light reflection allows seeing the surface flatness precisely. Swell on the compression side is clearly seen. This swell may be due to internal damage. No such swell was observed on specimens where the load did not reach the kink point. It has been pointed out that bolt tension increases after kink point

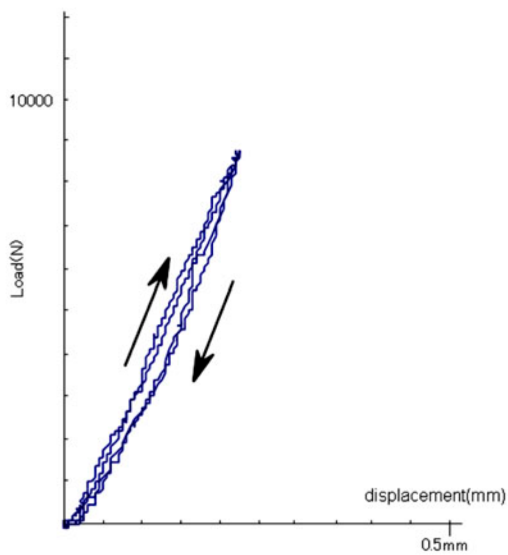

Figure 3. Load-displacement curve of cyclic load test – below kink load.

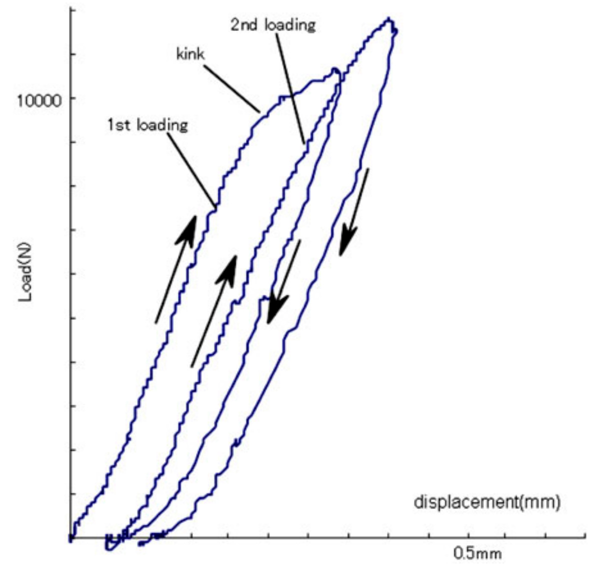

Figure 4. Load-displacement curve of cyclic load test – above kink load.

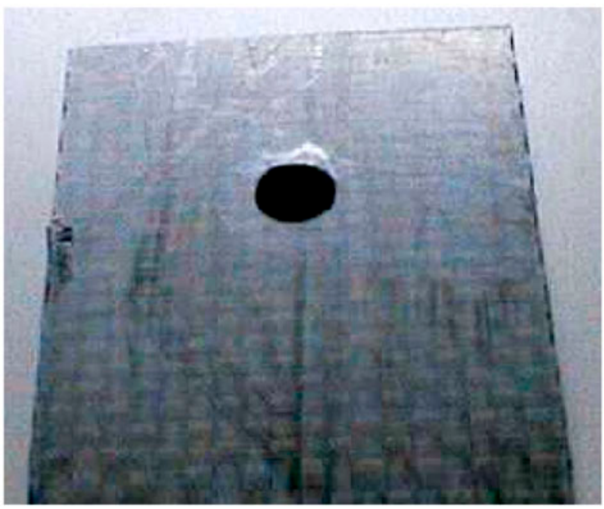

Figure 5. Specimen just after kink load.

because bearing damage cause out-of-plane deformation [9,13,26]. The swell seems to be a relative phenomenon. Figures 6 and 7 show the sectional micrographs of swell part of the specimen. The layer of 0 degree (parallel to the load direction – horizontal direction in the photograph) fibre is relatively lighter in colour in the photograph. Some damage of zero degree fibre can be seen. No such damage was found on the specimen where the load did not reach kink point. Thus, the validity of the new criteria to determine strength by kink point was proved. High-precision measurement of hole displacement enable the new criteria. Bearing strength should be re-evaluated by this criterion.

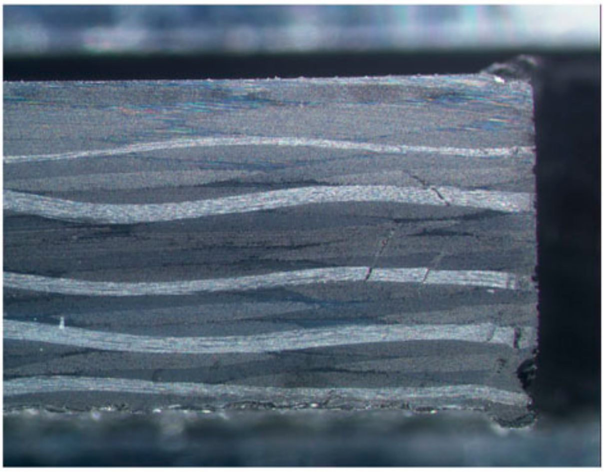

Figure 6. Micrograph section of specimen in Figure 5.

Figure 7. Micrograph section of specimen with high magnification.

4. Effect of thickness

The plate thickness is one of the most important design factors. Figure 8 shows bearing test results of 8, 12 (standard in this study) and 20 plies plates. The plate thickness were exactly proportional to the number of plies; the thickness of ply was 0.241 mm/PLY. The important point is that thick plates have larger deformation of kink points. And thin plate start kink earlier than standard condition. This results shows that $4\%d$ deformation load has a problem. Figure 9 shows bearing strength and hole displacement of kink point. The bearing strength σ is defined as

$$\sigma = \frac{P}{dt} \tag{1}$$

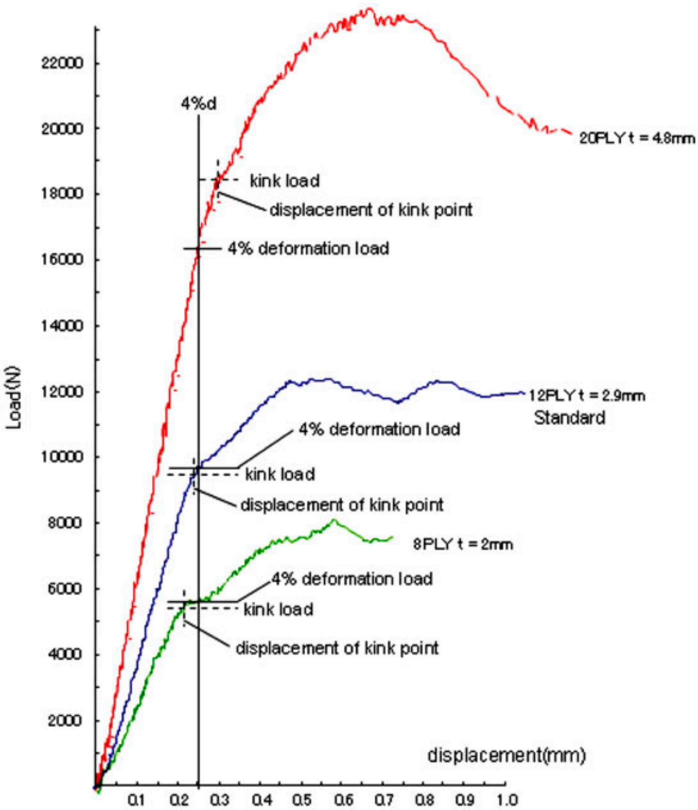

Figure 8. Load-displacement curve for several plate thicknesses.

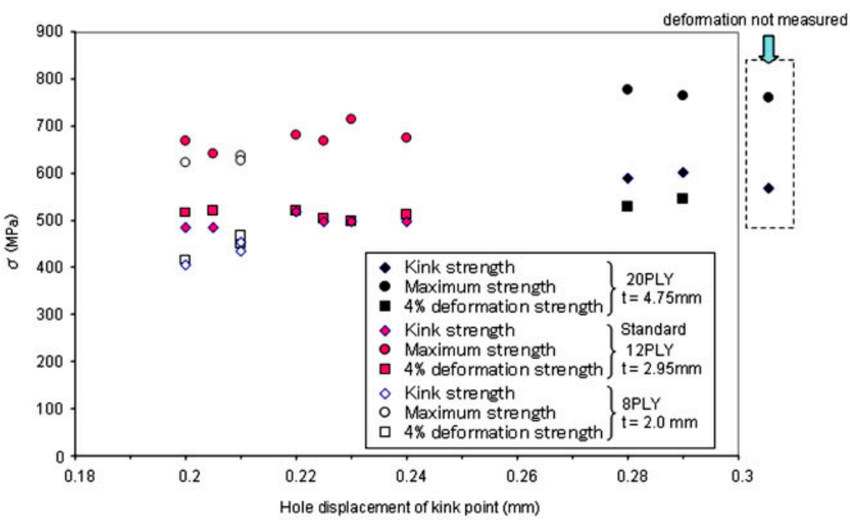

Figure 9. Bearing strength and kink point displacement with plate thickness.

where P is each load, d is representative hole diameter ($d = 6.35$ mm) and t is the plate thickness. Obviously, thicker plates are stronger. The kink load is not proportional to the plate thickness. There are two exceptional cases for standard condition having smaller hole displacement. It may be due to measurement error of displacement around low loading area. One case of 20 PLY is missing $4\%d$ load due to excessive measurement error of hole displacement caused by chucking problem. Even those cases, load-displacement curve showed clear kink, and the kink load were well determined. As discussed with Figures 6 and 7, bearing strength is determined by microscopic buckling of zero degree fibre but not the buckling of the plate. So, buckling property cannot explain higher bearing strength of thicker plate. This issue will be discussed later.

5. Effect of bolt: hole clearance

In this study, bolt-hole clearance was controlled by changing pin diameter. Hole diameters were also precisely measured. The bolt-hole clearance is defined as difference between the hole diameter and the pin diameter. Figure 10 shows typical load-displacement curve for each bolt-hole clearance. In the case of larger bolt-hole clearance, the kink tends to be more distinct. But, significant difference was not observed in load-displacement curve. Figure 11 shows the relationship between each strength and bolt-hole clearance. The representative hole diameter d is 3.65 mm and the plate thickness t is 0.295 mm. The later cases are also the same. Hole fit class in ISO [27,28] and NAS618 [29] is also shown in the figure. The kink load decreases at larger bolt-hole clearance more than 0.1 mm (1.5% of hole diameter). But maximum load was not changed. No strength reduction was observed for less than 0.04 mm bolt-hole clearance. This bolt-hole clearance is equivalent to class H9/h9 hole fit in ISO and FIT B-A in NAS618. Eventually, the difference between

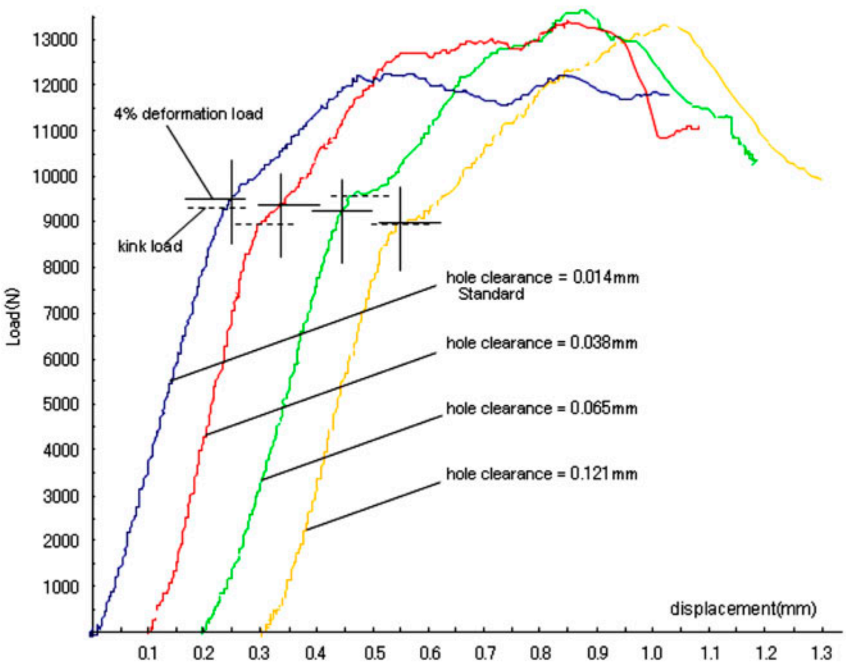

Figure 10. Load-displacement curve for several hole clearances.

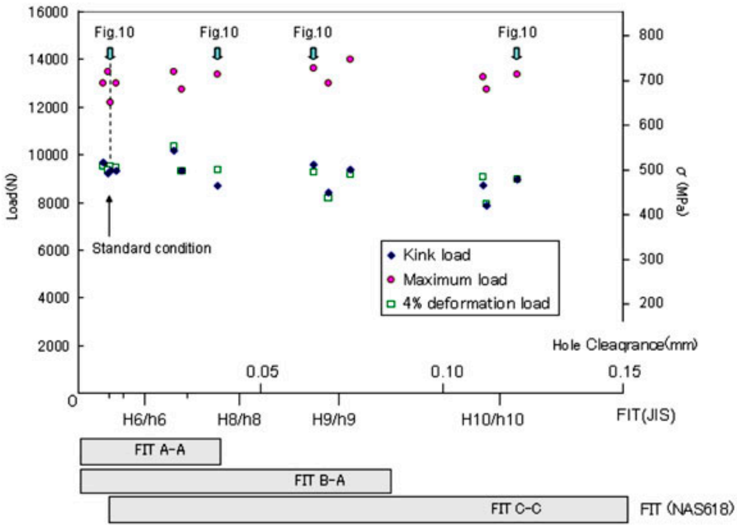

Figure 11. Bearing strength with hole clearance.

kink loads and 4%d deformation loads were very small. But, different material with different property may yield different results. Those results re-confirm the study of DiNicola and Fantle [5] that the hole clearance has small effect on the strength. But, one should notice that the scatter of kink load is remarkably large at loose fit. This fact means higher strength value for structural design can be available by employing tight fit, because the strength value for design is not simply average value of test data but minimum value derived from statistical process. It is roughly calculated by subtracting the dispersion from the average. Stress distribution on pin-hole contact surface may take role to cause larger scatter at loose fit. Unfortunately, the number of tests in this study is not sufficient for statistical treatment. Further study must be taken in future.

6. Effect of lateral constraint

6.1. Effect of clamp up force

For various bolted joints, the friction by strong clamping is expected to improve the rigidity of the joint, especially for automotive industry. But, in composite structures, creep of matrix resin causes reduction of clamping. Though the creep behaviour of laminate is not well known, it can be said that the residue clamping can be no longer sufficient after long duration. Considering these discussion, several tests were conducted under considerably light clamping. The tightening torque was set to 0–3 N · m controlled by bar-type torque wrench. 0.7 N· m was set for standard condition corresponding to 'finger tight' in [22]. The relationship between the tightening torque T and the initial clamping force F is estimated as follows:

$$F = T / \left(\frac{\mu_s d_s}{\sqrt{3}} + \frac{P}{2\pi} + \frac{d_w \mu_w}{2} \right) \quad (2)$$

where μ_s, μ_w are friction coefficient of thread to nut and nut to washer, respectively, and d_s, d_w are effective diameter of screw and nuts. P is thread pitch. $\mu_s = \mu_w = 0.11$,

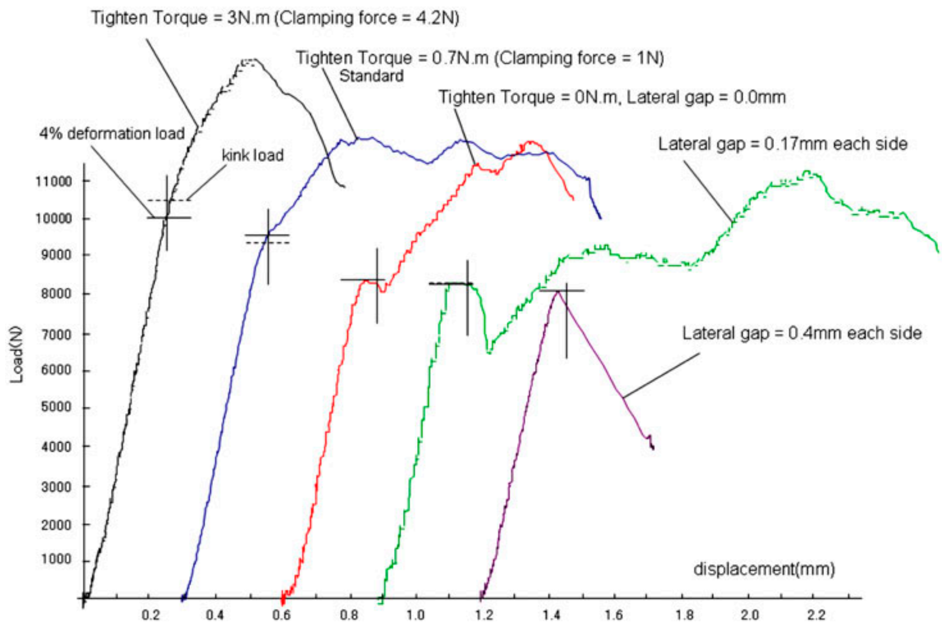

Figure 12. Load-displacement curves with several tightening torque or lateral gap.

$d_s = 5.5$ mm and $d_w = 6.0$ mm were estimated in this study. Figure 12 shows comparison of load-displacement curve with various clamping forces. The kink point becomes clear as the clamping force reduces. At very small clamping force, the load slightly drops after the kink. $4\%d$ deformation loads did not coincide with kink loads. Usually, $4\%d$ deformation loads are slightly larger than kink loads. Since non-linearity of the load-displacement curve is in low loading area, personal error to re-define the zero point of displacement can be a big issue to determine $4\%d$ deformation load. The load-displacement curves with higher tightening torque have the tendency to have calm higher kink with larger displacement. Figure 13 shows the relationship between the initial clamping force and each load. All the maximum loads, kink loads and $4\%d$ deformation loads increase as clamping force increases. But, those increments of loads is no more above 4N · m of clamping force (only four times of 'finger tight').

It has to be noticed that 'clamping force' in this discussion is limited to the initial value. Due to the out-of-plane expansion on compression side of the bearing hole, the clamping pressure increases with load increase.

6.2. Effect of lateral gap

Another case of lateral constraint on bolted joint is no clamping up but giving gap between jointed parts. In bolted joints, clamping force works not only for restraint of parts, but also for retaining bolt and nut by friction. But, the creep deformation reduces the clamping as mentioned. To avoid creep loosening, insertion of metal collars to take clamping forces may be adopted. To take clamping force properly, it is best to design the collars as same thickness of the composite parts. But, precise control of laminate thickness is very difficult; so slightly thicker collars are favourable. In this case, composite parts are placed with small gap. Due to the out-of-plane expansion in high loading condition, those gaps may be filled by the expansion and clamping force may

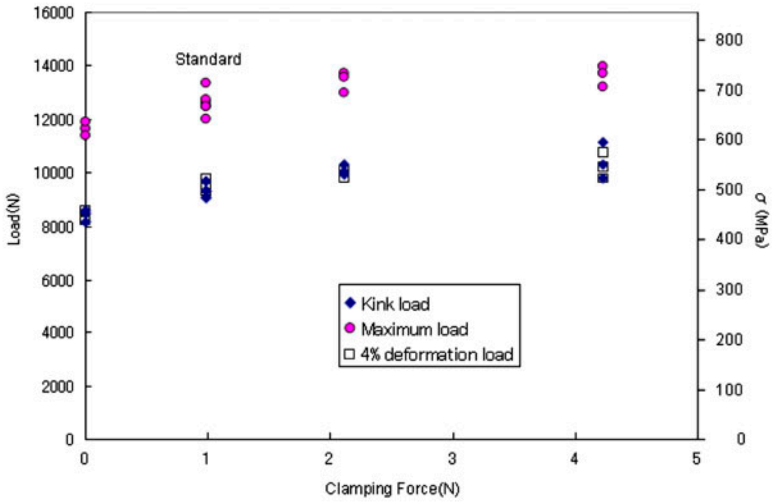

Figure 13. Bearing strength with clamping force.

take place. So, this structure cannot be regarded as free pin. There are very few previous studies concerning this structure. DiNicola and Fantle [5] conducted experiments with controlled lateral gap of 0.25 mm. But, the effect of the lateral gap was not investigated. In this study, lateral gaps were controlled by the following procedure. The fixture and test specimen were set up with standard condition; the pin and nuts were tightened with finger tight torque. Then, both nuts were loosened by certain angle; then bushes were slid towards outside to make the gap. The load-displacement curve with several lateral gaps is also shown in Figure 12. In case of 0.35 mm or larger gap, load did not recover after sudden load drop; so this condition can be regarded as free pin, and the kink load and maximum load are same. In the case of the load dropped before $4\%d$ deformation, $4\%d$ load were defined as maximum load before $4\%d$ deformation. In this series of joint with lateral gap, $4\%d$ loads and the kink loads were almost same.

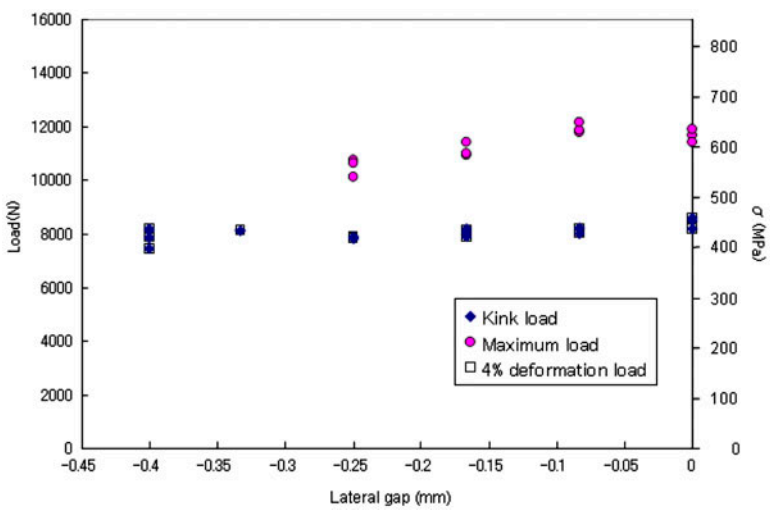

Figure 14. Bearing strength with lateral gap.

Because, load-displacement curves have broad plateau after the kink, and the $4\%d$ deformation points were in the plateau zone. Figure 14 shows the relationship between lateral gap and each load. In this figure, the lateral gap is shown as negative value. Because joint with lateral gap is 'loosened tightening,' it can be regarded as 'negative tightening.' One can join Figures 13 and 14 and see them as a single figure. Note that data for zero lateral gap are common with them for zero tightening torque. The maximum load decreases as lateral gap increases. But, the kink point load does not vary with lateral gap. As mentioned above, the out-of-plane expansion is quite strong, so that it can cause measurable strain on the bolt head [9]. The out-of-plane expansion does not occur until local fracture begins; so, lateral gap does not affect kink point load. After the local fracture begins, damaged components can still carry load more than the load of damage onset. According to an analysis by Hsien-Tang et al. [13], damaged material can be modelled like a incompressible liquid surrounded by undamaged material so that it still carries loading pressure. Though their analysis does not include the case of lateral gap, it may be easily expanded to this configuration. Smaller lateral gap lead to earlier gap filling; then the pressure suppresses damage progress and allows carrying larger load. This result shows that thickness control of collar and composite part or gap between jointed parts may take important roles in survivability of vehicles. Even if the structure are 'damaged' after the load exceeds the limit load, the joints still have margin to carry larger load; so the joints still sustain the connection. The vehicle may return to safe place before catastrophic failure. With controlling lateral gap, designer can adopt increased residual bearing strength than that of free pin. Hence, more weight reduction can be available.

7. Conclusions

Bearing strength of quasi-isotropic stack graphite epoxy composite were re-evaluated with new criteria under various conditions of plate thickness, hole clearance, clamping force and lateral constraint. The new criterion based on kink of the load-displacement curve was proposed with consideration of fracture mechanism. The load-displacement curves were precisely measured using laser extensometre. The effects of hole clearance were similar as previously studied using $4\%d$ deformation load on several literature. Bearing strength are reduced at more than 0.1 mm (1.5%) hole clearance, but no affection less than 0.04 mm hole clearance. Hole clearance may influence the scatter of strength. Strength value for design can be increased using tight fit. Lateral constraints affect both the kink and maximum loads. Higher initial clamping force leads to higher kink point. Special cases of lateral constraint with small gap were also studied. It was found that the gap affects the maximum load but not the kink load. This result shows that control of lateral gap can contribute to securing residue strength and improve safety of structure. Thicker plate showed higher kink point. The kink load is not proportional to the plate thickness. This result needs some discussion. Out-of-plane expansion of compression side of the bearing hole may be proportional to the plate thickness, and the thickness-wise stiffness of the plate is inverse proportional to the plate thickness. So, building up of lateral clamping pressure seems to be independent of plate thickness. But, in actual testing, the surface roughness of the plate causes non-linearity of the thickness-wise stiffness. Maybe this is the reason why thick plates show higher kink point. Surface roughness caused by texture of peel ply may influence, but this issue needs further study. In most of cases, the kink load – the representative load for strength – were very close to $4\%d$ load. But, significant deviations were found in several conditions of thicker plate and higher initial clamping force. This fact directs questions at the validity of conventional 4%*d* load. To clarify this issue, more accumulation of experience data are needed for more various conditions, especially for different materials with different fibre or different resin like thermoplastic resin (relatively soft and lager elongation), RTM resin (brittle feature) or other various types of materials. Consideration of fracture mechanics is always important.

Acknowledgements

The author greatly appreciates Prof. Suemasu, department of engineering and applied sciences, faculty of Science and Technology of Sophia University and Prof. Ishikawa, chairman of Composite Engineering Research Center, Nagoya University for their gracious support for this study by giving advice and encouragement even in their extremely busy condition.

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