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BOLTED JOINT STRENGTH OF HEAT-RESISTANT 3-D COMPOSITES

Ippei Susuki [1], Yutaka Sato [2],
Yasumasa Hamaguchi [1] and Takahiko Sawada [1]

[1]*Structures and Materials Research Center, National Aerospace Laboratory, Mitaka-shi, Tokyo, Japan (181-0012)*

[2]*Institute of Industrial Science, University of Tokyo, Meguro-ku, Tokyo, Japan (151-8505)*

SUMMARY: The strength property and the mechanical behavior of bolted joint of a heat-resistant bismaleimide 3-D textile composite are investigated in this study. The static tensile tests for bolted joint specimen both at a room and at an elevated temperature conditions were conducted and the maximum loads and the bearing stresses of the 3-D textile composites were evaluated. The results were compared with those of the 2-D textile composites without out-of-plane yarn. On the other hand, relating to the decision of bolted joint strength, the method to estimate the fastener hole deformation is proposed from both a numerical and an experimental point of view. The finite element numerical analysis for a multi-fastener joint model, in which the frictional contact is fully taken into consideration, was carried out, and the effect of the friction on the mechanical behavior including the fastener hole deformation was evaluated. Furthermore, the advanced measurement system using a laser extensometer, which enables us to measure the fastener hole deformation rather directly than a conventional method, was also demonstrated.

KEYWORDS : Bismaleimide heat-resistant composites, Mechanical joint, Bearing strength , Finite element analysis, Contact problem

INTRODUCTION

One of the key technologies to realize the next-generation supersonic transport (SST) is the development of a lightweight structural material that satisfy the requirements including the long-term durability under high-temperature condition due to aerodynamic heating. Some kinds of graphite fiber reinforced heat-resistant polymeric matrix composites are expected to apply to this purpose. In the practical application of these composites to the aircraft structures, it will have many portions to join the composite and the metallic parts together. So an extensive experiments and analyses for bolted joint composite laminates have been carried out

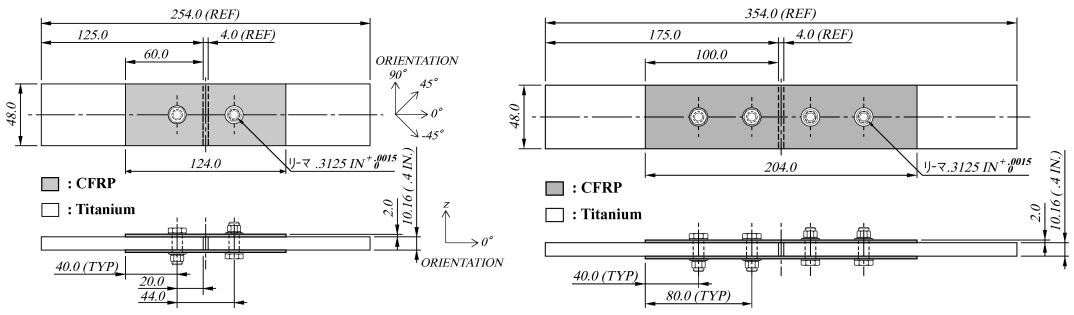
to evaluate the strength and failure properties. They are well reviewed at Refs.[1-3] for examples. On the other hand, the use of three-dimensional (3-D) fiber architecture is one of the most promising methods to improve low out-of-plane properties of usual laminated composite structures. Our previous studies showed the 3-D composites had more than 40% higher compressive strength after severe out-of-plane impact damages than that of two-dimensional (2-D) laminated plate's [4]. The heat-resistant composites are also expected to have some advantages in joint structure, but it is also found that the very limited data are available for the 3-D composite joints. In this report, the strength properties of bolted joint structure of 3-D bismaleimide heat-resistant composites are investigated. The maximum strength properties are compared with those of the 2-D composites through the static loading test results both at a room temperature and at an elevated temperature conditions.

The bolted joint strength is usually defined as a bearing stress criterion that relates to the fastener hole deformation such as a stress when a fastener hole is deformed with 4% strain. But, in practice, it is hardly to measure the fastener hole deformation of the fastener joint itself during the experiment different from simple pin loaded testing. And, especially for multi bolted fastener joint, the deformation of each fastener hole seems to be closely related to the load distribution properties. So here we try to investigate the estimation methods of fastener hole deformation. The finite element numerical analysis for a multi-fastener joint model, in which the frictional contact is fully taken into consideration, was carried out, and the effect of the friction on the mechanical behavior including the fastener hole deformation was evaluated. Furthermore, the advanced measurement system using a laser extensometer was tried to apply for the experiment, and we show its capability to measure the fastener hole deformation rather directly than conventional method.

STRENGTH OF BOLTED JOINT SPECIMENS

Materials and specimens

The mechanical fastener joint specimens used in this study consist of a couple of titanium plates with 10mm thickness and a couple of CFRP plates with 2mm thickness. The CFRP plates were made by peculiar 3-D textile procedure with a middle elastic carbon fiber MR-50K for in-plane yarn and T-900 for out-of-plane yarn (Z-yarn) [4]. In-plane layers were composed by equal amount of 0°, 45°, -45° and 90°directional yarn, and the Z-yarn is



(a) Single fastener (b) Double fasteners-in-tandem

Fig.1 Ti/CFRP bolted joint specimens.

located with 3mm pitch. The dry fabric preform was molded by heat-resistant bismaleimide resin 5250-4-RTM with resin transfer molding (RTM) method. A couple of titanium alloy plate was joined together with a couple of composite plates on both sides using titanium fasteners as a tension specimen shown in Fig.1. Figure 1(a) and (b) are the single fastener type and the double fasteners in tandem type tension specimens, respectively. To compare the mechanical properties, we also prepared the specimen with 2-D composites that was made by completely same procedure except for excluding Z-yarn.

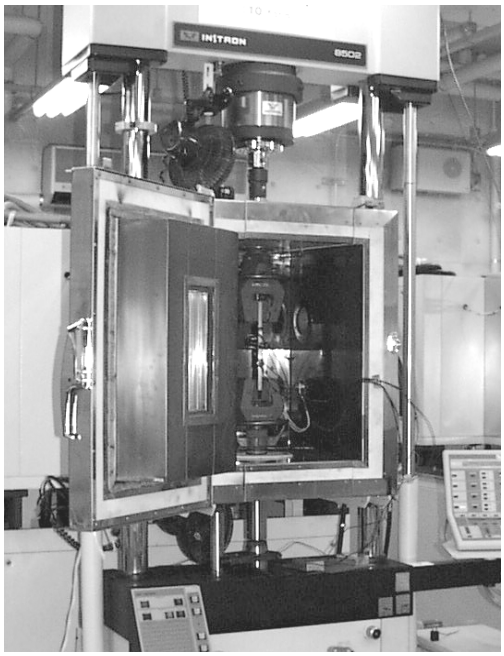


Fig.2 Hydraulic material testing machine with furnace.

Static tensile test

The actuator speed controlled static tensile tests were carried out using hydraulic material testing machine both at a room temperature (23 °C) and at an elevated temperature (150 °C) conditions. Figure2 shows a experimental setup for the tests at the elevated temperature condition. The variation of the relative displacement between upper and lower titanium plates was measured by conventional type extensometer attached on the side of specimen as shown in Fig.3.

Fig.3 Extensometer

Maximum loads and bearing stresses

Figures 4(a)-(d) show the load-relative displacement curve relations obtained by the experiments. The maximum load levels can be seen in the figures. The differences of the load-relative displacement behavior between 3-D and 2-D specimens are shown in Figs.4 (a) and (b) for 23 °C and 150 °C, respectively. It can be seen that the maximum loads for 3-D specimens are reduced about 5% compared with those for 2-D specimens for both temperature conditions. And the stiffness of the 3-D specimen at elevated temperature seems to reduce. The retentions of maximum strength at an elevated temperature are calculated about 88% for the single fastener joint and about 86% for the double fastener joint, respectively, from Figs.4 (c) and (d).

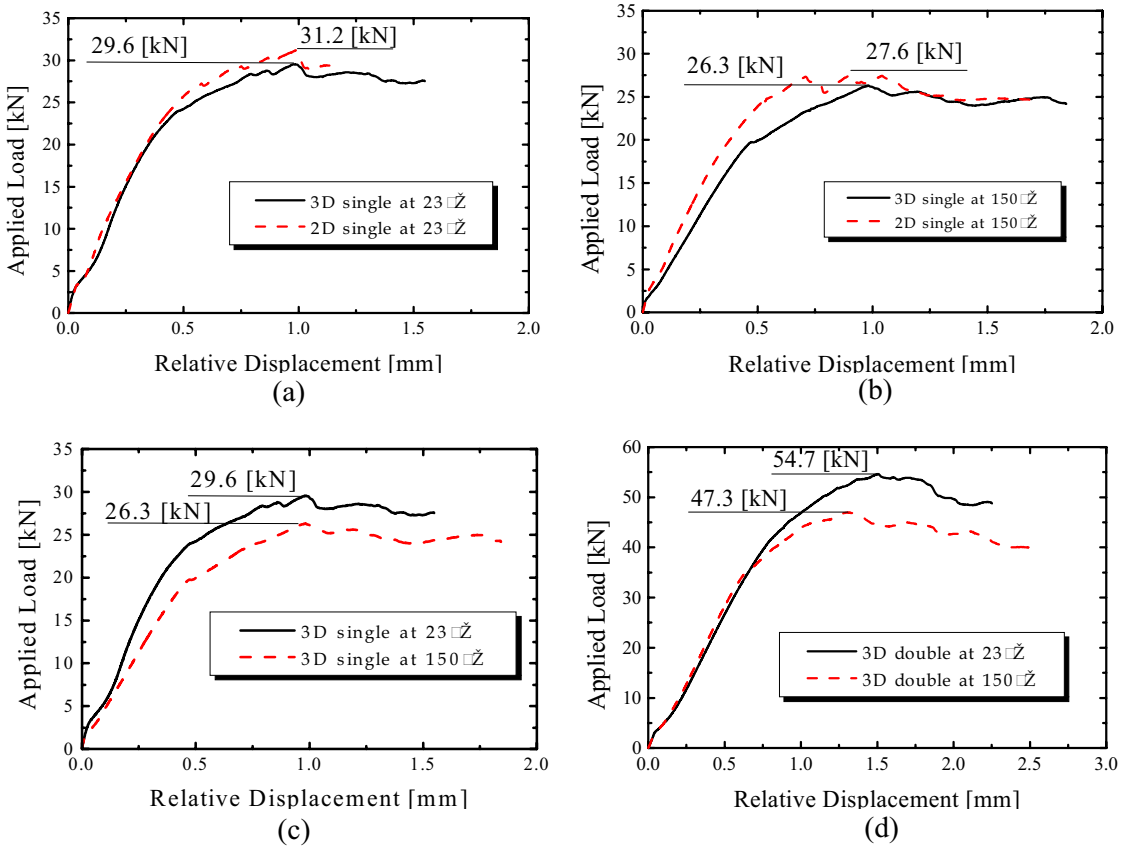


Fig.4 Comparison of load-relative displacement curves and maximum load.

Table 1 Comparison of maximum loads [kN].

	23℃		150℃	
	Single	Double	Single	Double
3-D	29.6	54.7	26.3	47.0
2-D	31.2	-	27.6	-

Table 2 Comparison of maximum bearing stresses [MPa].

	23℃		150℃	
	Single	Double	Single	Double
3-D	789	783	693	673
2-D	840	-	737	-

The maximum loads and the maximum bearing stresses σ_b estimated by

$$\sigma_b = \frac{k \cdot P_{\max}}{2t \cdot d}$$

$P_{\max}$: Maximum load
t : Thickness of composite
d : Diameter of hole
k : Load distribution coefficient
(single:1.0, double:0.5)

are tabulated in Table1 and 2, respectively. These results show that the strength of the 3-D textile composites can compare favorably with those of the 2-D when we take the advantage of out-of-plane failure resistance into consideration. The maximum bearing stress for the double-fastener joints are estimated by the above equation assuming that the load distribution for each fastener is equal (k=0.5 in the above equation). This assumption seems to be right around the maximum load level because that the estimated values are almost equal to those of 2-D's. This is caused by the material non-linearity of the composites around the fastener holes. Within the extent of usual operating load level, the distribution of multi-fastener joint are not uniform and changes with somewhat complicated manner.

EVALUATION OF FASTENER HOLE DEFORMATION

Numerical simulation

The structural discontinuities of the mechanical fastener joint make problem difficult to analyze. Most of analytical and numerical approaches have been focused mainly on a simple pin-loaded fastener hole model where the effect of the fastening of the bolt is not considered [5-9]. But it was reported that the maximum load of the bolted composite joint was strongly affected by a pretension force of the fastener bolt. The frictional contact effect due to the pretension around the fastener hole should be considered when we evaluate the problem concerning with the strength properties and/or the precise mechanical behavior of bolted joint by the analysis.

Three dimensional finite element non-linear analysis, in which the frictional contact effect during increasing tensile load was fully taken into consideration, was carried out to evaluate the fastener hole deformation of the multi-fastener joint specimen depicted in Fig.2(b). An eighth part of the specimen was taken up for numerical analysis model because of symmetry

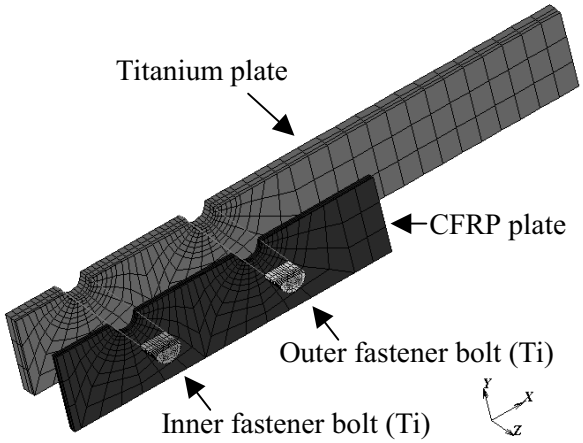


Fig.5 Finite element model of double fastener joint specimen.

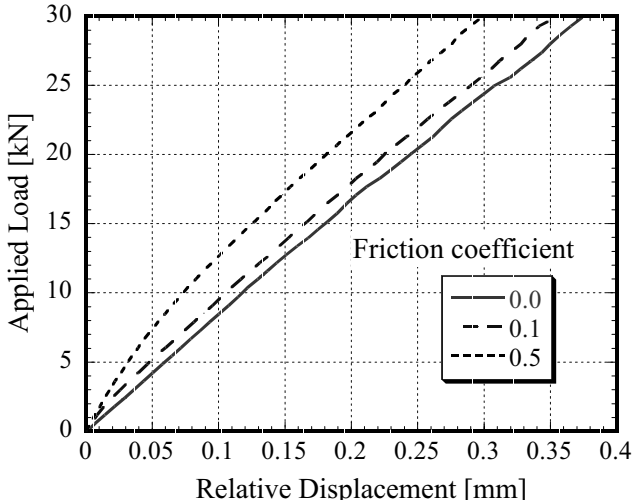


Fig.6 Effect of friction coefficient on non-linear behavior of load-relative displacement curves.

as shown in Fig.5. The effect of a pretension of the fastener bolts was also introduced as a pressure uniformly acting on the washer region, which was estimated from the other experiments using a fiber-optic strain gauge embedded in the titanium fastener bolt. The frictional stick and slip mechanism was modeled using coulomb friction between titanium and composite plate around the fastener holes. The material constants used for the analysis are shown in Table 3.

Figure 6 shows the load-relative displacement curves for different friction coefficients. It can be seen that a larger friction coefficient produces a stronger non-linearity on the macroscopic mechanical behavior. The difference of the distributions of axial stress component around the fastener holes is depicted as Fig.7 for different friction coefficient at 30[kN] as an applied load level. The magnitude and the distribution properties of compressive stresses at the region where the fastener bolt and composites contact each other are obviously different for each case, and, consequently, it can be said that the load distribution ratio for each fastener affected by the frictional mechanism. Figure 8 shows the variation of the load distribution ratio for the inner fastener estimated by the deformation of fastener holes with increasing load. In the case that has larger friction coefficient (μ=0.5), the load distribution ratio changes more rapidly than the other case.

Table 3 Material constants used in analysis

FRP (CF/BMI)		Titanium	
E_f	ν_f	E_m	ν_m
60 [GPa]	0.25	110[GPa]	0.30

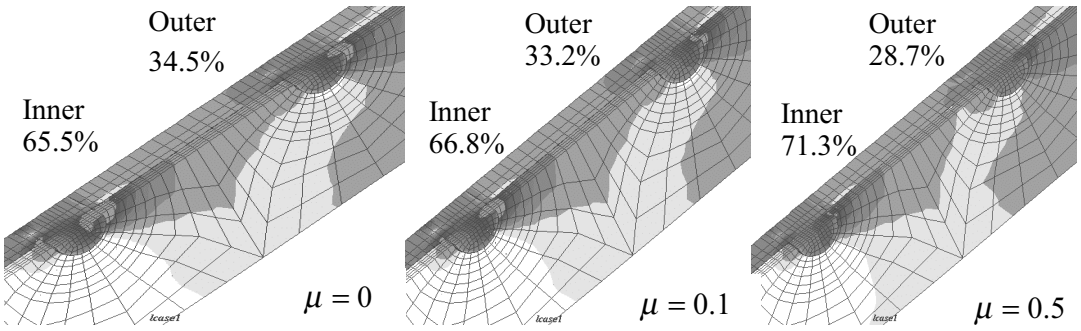


Fig.7 Stress distributions around the fastener holes at 30[kN].

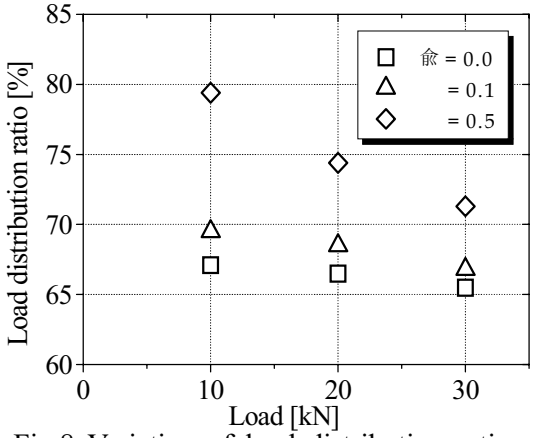


Fig.8 Variation of load distribution ratio of the inner bolt

Measurement system of fastener hole deformation

Here we try to apply a laser extensometer to measure the fastener hole deformation of the mechanical multi-fastener joint specimen. The laser extensometer enables us to measure the slight relative changes of the distances between targets placed on the specimen. A cubical glass rotating at a constant rate generates a parallel scanning laser beam toward the corded targets on the specimen. The variation of the brightness of reflecting light with time is detected by photo sensor and is transformed into the change of distance between the edges of the targets as shown in Fig.9. In the experiment, the corded targets were placed on the center of each bolt head and on the composite plate so as to represent the displacements at the point of both edges of the fastener holes as shown in Figs.10 and 11.

To confirm the validity of the method, we compare the relative displacements that are expected to obtain by measuring the distance of the target and the actual deformations of the

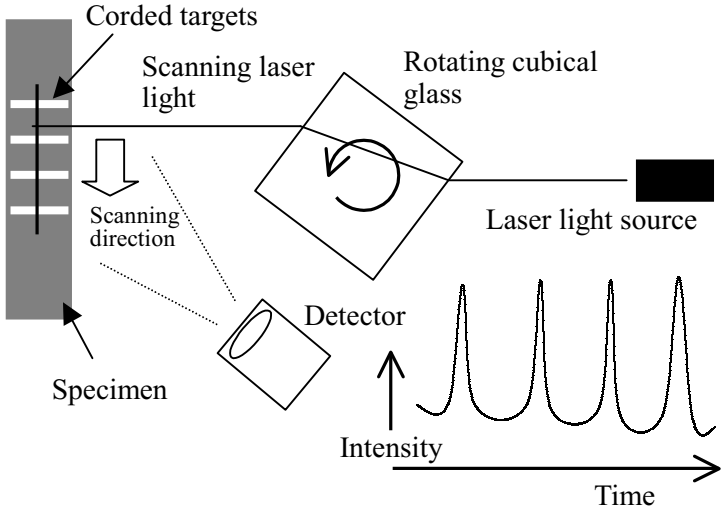


Fig.9 Principle of laser extensometer.

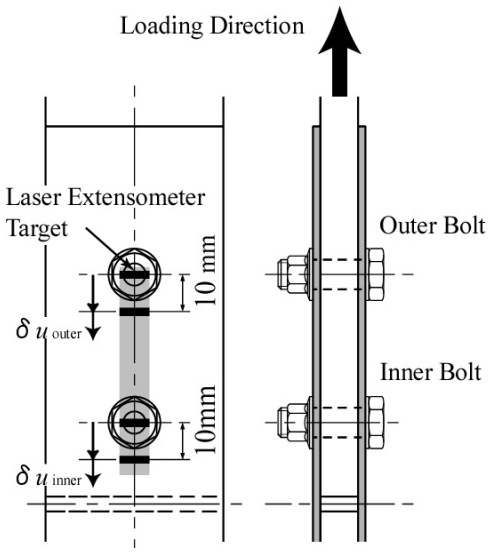


Fig.10 Location of targets to measure fastener hole deformation by using laser extensometer.

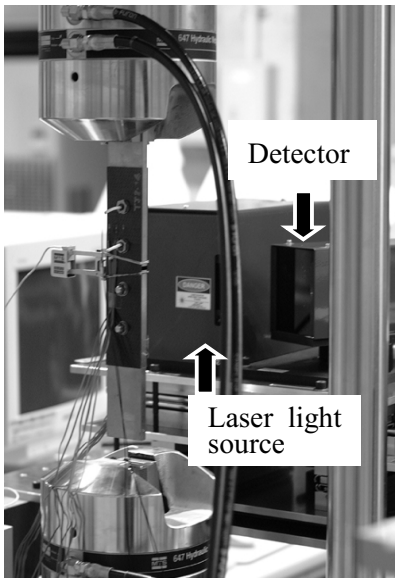


Fig.11 Measurement system using laser extensometer.

fastener hole itself by an aid of the finite element numerical simulation same as previous section. As shown in Fig.12, though the relative displacements, which are expected to measure by the experiments, are somewhat larger than the values that we want to estimate, it can be said that the proposed measurement method will be applicable to represent the fastener hole deformations.

Figure 13 shows the experimentally measured relative displacements for both fasteners during an increasing loading process. In the figure, the change in the slopes for each line is corresponded to the transition of the deformation mechanism, that is, the frictionally stuck state around the fastener changes frictional slip state. The variation of the load distribution ratio calculated by the value of deformations with applied load is depicted in Fig.14. Although, within the extent of relatively low load level, the evaluated value is tend to fluctuate because of the resolution of the measurement system, the transition of the load distribution ratio with increasing load is estimated fairly good.

CONCLUSIONS

In this paper the bolted joint strength of heat-resistant bismaleimide 3-D textile composites at

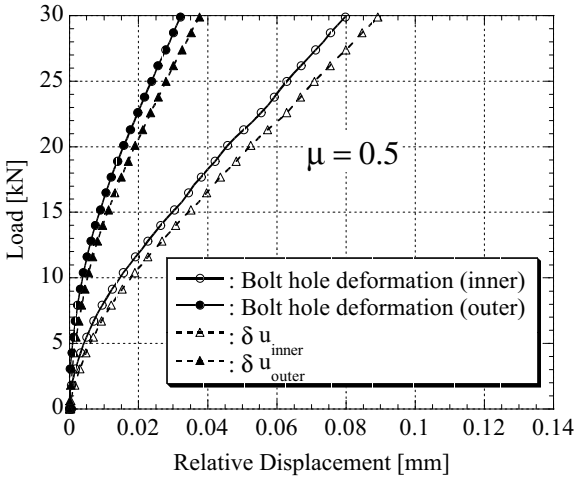


Fig.12 Comparison of actual fastener hole deformations and relative displacements expected to measure by laser extensometer.

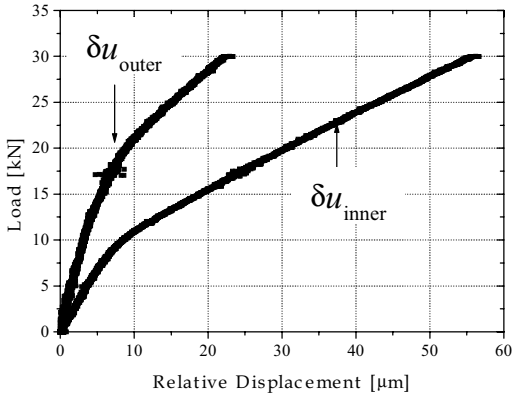


Fig.13 Deformations of fastener holes measured by laser extensometer.

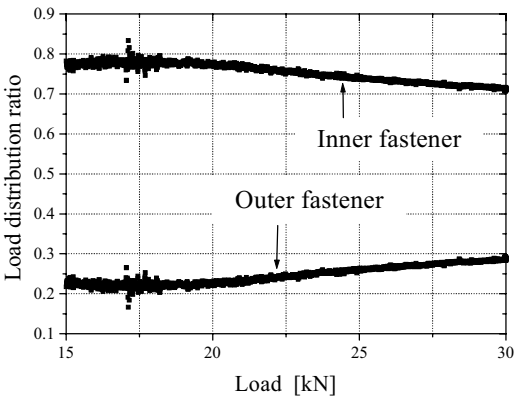


Fig.14 Load distribution ratio estimated from fastener hole deformations.

the room and the elevated temperature conditions has been evaluated experimentally. The maximum strength and the bearing stress have compared with those of 2-D textile composites. On the other hand, both numerical and experimental methods to estimates the fastener hole deformation of the multi-fastener joint specimen have been demonstrated.

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