BASIC STUDY ON MECHANICALLY FASTENED JOINTS OF CARBON FIBER REINFORCED THERMOPLASTICS

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Abstract
In recent years, CFRTP (carbon fiber reinforced thermoplastic) has been researched to reduce the weight of mass produced automobile. To realize CFRTP application, establishing joining technology on CFRTP is considered an essential issue. We have conducted tensile strength experiments on mechanically fastened joints of CFRTP specimens in order to identify their mechanical properties. In this paper, we specifically used several types of the new CF/PP (carbon fiber reinforced polypropylene) developed by the Japanese METI-NEDO project. We have measured the maximum loads they can bear and analyzed the failure modes. As a result, we have learned that the developed CF/PP have a larger capacity to redistribute loads than the conventional CFRTS (carbon fiber reinforced thermosetting plastic), due to their ductility.

1 Introduction
1.1 CFRTP Application to Automobile
The establishment of lightweight technology and high-efficiency recycling technology for vehicles are urgently needed to cope with the global environmental problem. To pursue lightweight mass production automobile by CFRP (carbon fiber reinforced plastic), we have to find solutions for the existing problems of high cost and low productivity[1].
CFRTP (carbon fiber reinforced thermoplastic) is highly expected to solve these problems. CFRTP has the potential to achieve goals of cost savings, high-speed moldability, and high recyclability. Such high-workability CFRTP is being researched based on the Japanese METI-NEDO project. Along with the development of these new materials, establishment of the surrounding technologies like joining, repair, and recycling have also become important.
Of these, we have focused on the joining technology of CFRTP. In order to complete a large vehicle, subassemblies must be joined together by using methods such as mechanical fastening, adhesive bonding, and welding[2]. Although many assembly problems can be solved by adhesive or welding techniques, there are still many cases where only mechanically fastened joints are capable of meeting certain design requirements [3]. Unlike other joining methods, mechanical fastening facilitates disassembly of the parts when in need of inspection, repair, or recycling. Also, when it comes to actually installing CFRTPs to automobiles, they are likely to be combined with the conventional steel parts. When dissimilar materials need to be joined, mechanical fastening is an appropriate method to adopt.

1.2 Objective and Overview
Due to the reasons above, mechanical fastening is an unavoidable method on CFRTP and needs to be researched thoroughly. In view of drawing out an appropriate design criterion for mechanical fastening of CFRTP in the future, we conducted tensile strength tests on mechanically fastened joints of CFRTP. As a primary research, we have observed the fundamental properties of their fracture process by examining the maximum load reached and the failure mode. We specifically used the new type of carbon fiber reinforced polypropylene (CF/PP), developed by the Japanese METI-NEDO project "Development of Sustainable Hyper Composite Materials Technology".

2 Parameters Affecting Joint Strength
2.1 Joint Strength and Failure Modes
When fasteners are required, CFRTP present special design considerations since they possess different characteristics than the conventional CFRTS (carbon fiber reinforced thermosetting plastic). Thus, it is important to identify critical factors for the selection of the correct fastened joint. In order to draw the correct selection, we evaluated the joint strength and observed the failure modes.
Here, joint strength is defined as the strength obtained from the maximum load the joint bears through its fracture process. Different types of failure modes can be seen depending on the material and the load distribution, and the two major ones are net tension and bearing, as shown in Fig.1[4]. Net tension failure mode occurs when w/d (width-to-diameter ratio) is small and causes high-stress concentration, leading to a sudden breakage. It is principally influenced by the tensile strength of the fibers at fastened joints. Its net tension stress can be calculated by Equation (1). Bearing failure mode occurs as the bearing damage proceeds and the hole diameter stretches. This occurs gradually, and therefore is considered as the critical failure mode when it comes to designing a structure. Its bearing stress can be calculated by Equation (2).

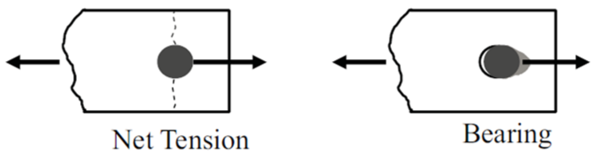


Figure 1. Failure Modes

$$\sigma_{nt} = P/\{(w-d)\}t \tag{1}$$

$$\sigma_b = P/dt \tag{2}$$

where σ_{nt} is the net tension stress (MPa), σ_b the bearing stress (MPa), P the load (N), w the width of the specimen (mm), d the diameter of the hole (mm), and t the thickness of the specimen (mm).

2.2 Parameters
There are several parameters that affect the joint strength, as shown in Table 1[5]. Of these, we narrowed our focus on how the parameters material and geometry affect the joint strength. Here, geometry refers to the variables of w/d, e/d (edge distance-to-diameter ratio), and the hole patterns of single-row and multiple-row, as shown in Fig. 2.
As for the conventional CFRTS, the optimal geometry has already been studied by many researchers. Smaller spacings result in the cutting of too many fibers, while large spacing

accordingly results in weight increase. The existing design criterion we have referred to is as follows: minimum w/d as 5; e/d as 2.5; and p/d (pitch distance-to-diameter ratio) as 4[3]. When these criteria are satisfied, it shows bearing failure mode on CFRTS.

Material	**Fastener**	**Design**
Resin type	Fastener type	Joint type
Fiber type and form	Fastener size	Laminate thickness
Laminate stacking sequence	Hole size	Geometry
Fiber orientation	Clamping force	Drilling technology
Volume of Fiber		

Table 1. Parameters affecting joint strength

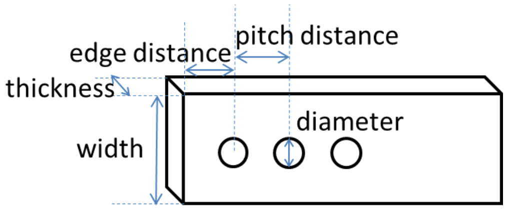


Figure 2. Geometry Variables

3 Base Material

3.1 Materials

We adopted three types of CFRTP for the experiment, which are composed of carbon fiber (CF, light fiber) and polypropylene (PP, cheap and general resin), as shown in Table 2. To make a comparison, we have also conducted experiments on CFRTS, which uses EP (epoxy) as resin.

While QISO-PP1 and QISO-PP2 use the continuous CF prepreg tape to form a quasi-isotropic plate, CMT is composed of the discontinuous CF reinforced isotropic plate. QISO-PP1 and QISO-PP2 are the same except the adhesion between PP and CF, where in QISO-PP2 both CF and PP are modified to have higher mechanical properties.

	Specimen Name	Base Material	V_f(%)	Stacking Sequence	Interfacial Shear Strength(MPa)
CFRTS	QISO-TS	TS Prepreg Sheet	50	$[(45/0/-45/90)_s]_2$	—
CFRTP	CMT	Carbon Fiber Mat Reinforced Thermoplastics Prepreg Sheet	20	—	13.3
	QISO-PP1	No-modified PP Prepreg Tape	45-50	$[(45/0/-45/90)_s]_2$	4.8
	QISO-PP2	Strongly acid-modified PP Prepreg Tape			17.7

Table 2. Materials Used

3.2 Molding process

As previously stated, QISO plates were obtained by laminated molding of UD prepreg tapes (0.1 mm thickness and 10 mm width) or sheets (0.15mm thickness) from MRC/TOYOBO. The CMT plate was made at TORAY from the discontinuous CF due to the advanced technique required in the molding process. The QISO laminate was fabricated through a process of stacking prepreg cut tapes or sheets in a quasi-isotropic layup, heating them up by hot plate, adding pressure concurrently, and cooling them down in the end, as shown in Fig. 3. CMT was also reheated and pressurized to obtain a plate of certain thickness.

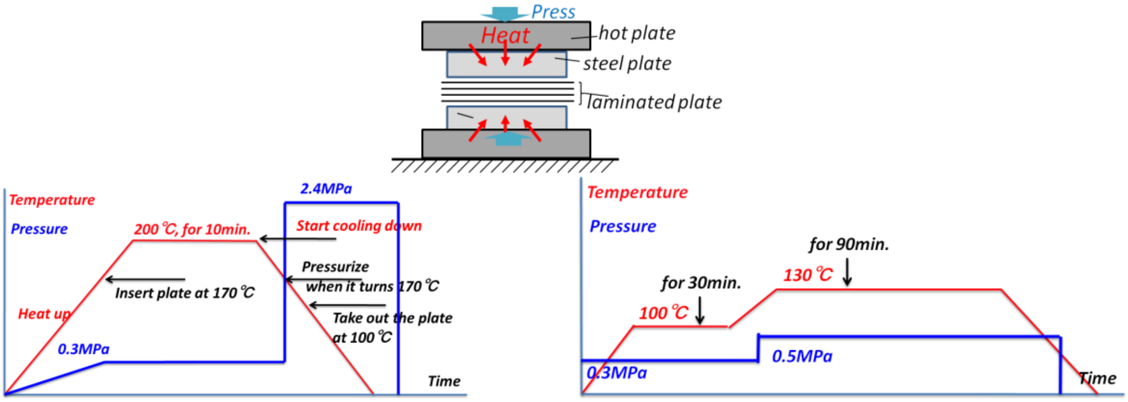


Figure 3. Curing Procedure (Top: Hot Plate, Left: CFRTP, Right: CFRTS)

4 Test Method

We evaluated the performance of the mechanically fastened joints by conducting tensile strength tests based on the simple "Method B" on JIS K7080, measuring the load and the displacement of the crosshead[6]. Fig. 4 shows the overview of the experiment. The bearing strength (or the net tension strength) is calculated from the Equations stated above by fitting the maximum load as P . We set the specimen size as follows: d (diameter)=4 mm; t (thickness)=2 mm; e/d=2.5; and w/d varying from 4 to 7. Also, to evaluate multiple row effects, we conducted experiments on three-row specimens with p/d (pitch distance-to-diameter ratio)=4 and w/d varying from 4 to 10, depending on the material. By using this method, we changed the parameters of material and geometry to study their effect on joint strength.

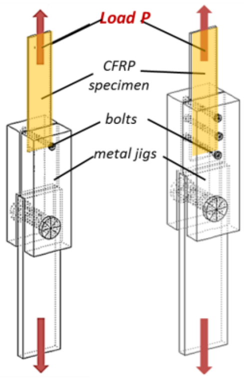


Figure 4. Tensile Strength Test

5 Results and Analysis

Here, we will site some of the prominent results gained from the experiment.

5.1 Fracture Process

Fig. 5 shows the load/thickness-displacement curves and Table 3 shows the failure modes of each material, at w/d=5. As you can see from the images of the broken specimens, all materials showed bearing failure, but CMT's final fracture was caused by net tension failure.
QISO-TS bore the highest load, but once it reached the maximum load, its fracture process happened very quickly compared to the CFRTPs. This is due to its brittleness. CMT showed the lowest load, but we have to keep in mind that V_f is the lowest among all the other materials. CMT seems to show a fairly gradual process of bearing failure at an early stage, but the final fracture is caused by net tension failure. On the contrary, QISO-PP1 and QISO-PP2

showed a ductile feature. QISO-PP1 resulted in an especially large ductility since the attachment between CF and PP is weaker than that of QISO-PP2. QISO-PP2, with a higher mechanical property, bore higher load, almost as high as QISO-TS. The other specimens with different w/d value showed similar fracture processes.

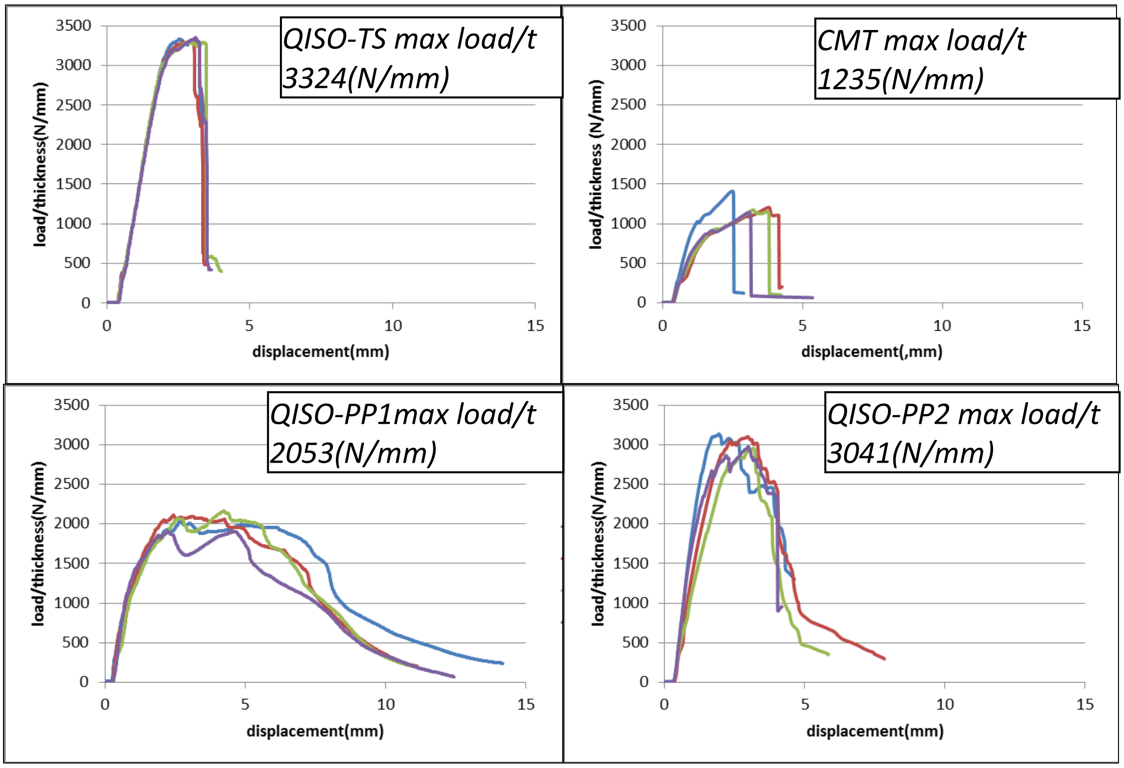


Figure 5. Load/Thickness-Displacement Curves (w/d=5)

QISO-TS	*CMT*	*QISO-PP1*	*QISO-PP2*
			
bearing	bearing + net tension	bearing + tension area breaking	bearing+ tension area breaking

Table 3. Failure Modes (w/d=5)

5.2 W/D Comparison

QISO-TS, QISO-PP1, and QISO-PP2 showed bearing failure mode at all w/d values. In contrast, CMT showed net tension failure until the w/d was raised to 6, different from the minimum w/d for CFRTS.

Fig. 6 shows the bearing stress calculated from Equation (2). The bearing stress here can be treated the same as the bearing strength for QISO-TS and QISO-PP2. As for CMT, it broke by net tension when w/d was 4 and 5, so the bearing stress on the Figure is not equivalent as the bearing strength. As for QISO-PP1, the bearing stress is higher when w/d is larger, even though σ_b should not be dependent on the width. This is thought to be because the CF and PP drastically comes off each other around the hole as seen in Table 3, resulting in less space on the sides to bear load.

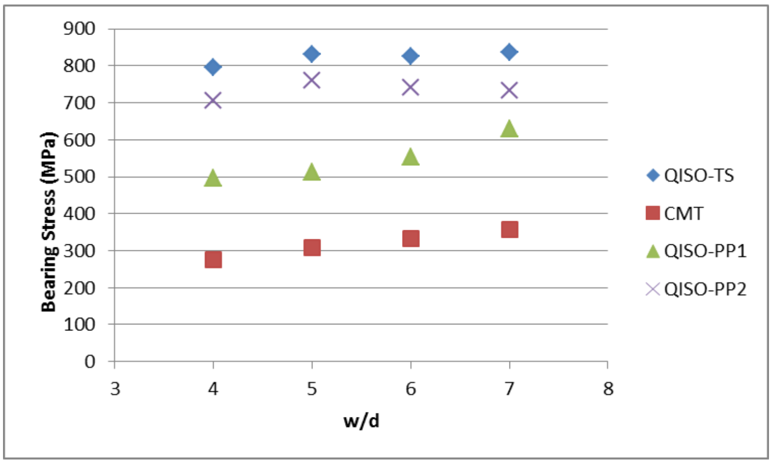


Figure 6. W/D Comparison

5.3 Multiple Row Effect

By using three fasteners in a row, the joint strength is supposed to increase. However when brittle materials like the conventional CFRTS is fastened to metal or some kind of material with larger stiffness, the load distribution does not work out effectively and causes extremely high concentration specifically in one hole[7]. On the other hand, CFRTPs with large ductility had the potential to redistribute load onto the second and third holes as well. This led CFRTPs to have higher multiple row effect. The failure modes of specimens with adequate w/d are shown in Fig.7. Fig.8 shows maximum load/thickness of w/d with the minimum value that the specimen showed bearing failure. QISOs showed bearing failure modes on each hole when w/d became larger, whereas CMT continued to show net tension failure mode even at w/d=10. CMT has little multiple row effect because of its net tension failure at one hole. QISO-PP1 and QISO-PP2 showed a high multiple row effect due to their ductility, having a larger capacity to redistribute loads than QISO-TS.

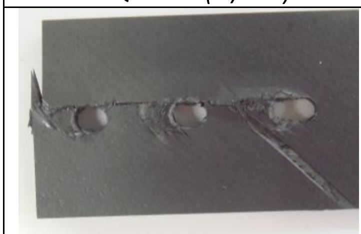
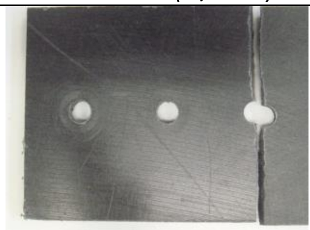
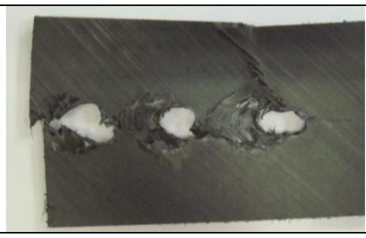
QISO-TS (w/d=8)	*CMT(w/d=10)*
	
QISO-PP1(w/d=8)	*QISO-PP2(w/d=8)*
	

Figure 7. Failure Modes (3 row)

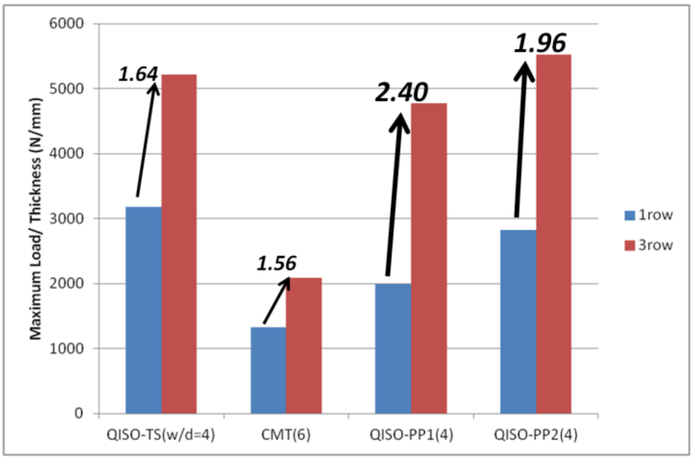


Figure 8. Multiple Row Effect

6 Conclusion

This research was significant in the sense of being a primary study on the understanding of the fundamental fracture process on new materials. We think that the results we obtained from this research will be a key to establishing a critical structural design in detail.

We have gained a conclusion that among the three CFRTPs we have tested, QISO-PP2 has the best workability in terms of mechanical fastening. It has high mechanical properties, almost as high as that of QISO-TS. At the same time, it shows ductility, which is a feature proper to CFRTP, and suggests possibility for multiple row fastener designs. On the contrary, since CMT was brittle and prone to showing net tension failure mode, we can presume that CMT has a relatively higher bearing strength than its tensile strength. This, however, can be said that CMT is not a preferable material in the aspect of mechanical fastening.

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