A NEW COMPRESSION-MOLDING APPROACH USING UNIDIRECTIONALLY ARRAYED CHOPPED STRANDS

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SUMMARY

In this study, we propose a new compression-molding approach using a sheet-like molding material made by regularly and unidirectionally arrayed chopped strands (UACS). UACS achieves both excellent flowablity during molding and distinguished mechanical properties comparable to continuous fiber composites.

Keywords: Compression molding; Sheet molding compound; Strength

1. INTRODUCTION

Sheet molding compound (SMC) is used for compression molding in many engineering fields. SMC is composed of randomly distributed chopped strands and unsaturated thermosetting resin. Complexly shaped products, such as bathtubs, can be easily fabricated using SMC. However, products made of SMC are relatively weak due to the fiber agglomeration and orientation. Therefore, its application has been limited to non-structural use for safety concerns.

This study proposes a new compression-molding approach using unidirectionally arrayed chopped strands (UACS) [1]. UACS is a sheet-like molding made of regularly and unidirectionally arrayed discontinuous carbon fiber strands impregnated thermosetting resin. The products, components and laminates are made by stacking UACS and curing them with hot pressing. As a result, complexly shaped structural components, such as rib structures, can be fabricated by using the UACS due to its superior flowability. Furthermore, the layer structure is still maintained, and there are few resin-rich regions. This implies that UACS has a potential to extend FRP applications to the structural components.

2. UNIDIRECTIONALLY ARRAYED CHOPPED STRANDS

UACS ply in this paper is made of carbon fiber T700S (Toray Industries) and epoxy resin #2500 (Toray Industries). UACS laminate is fabricated by curing stacked UACS plies under pressure at high temperature. Figure 1 presents an example of the flowability of a flat UACS laminate. In this case, the dimension of chopped strands is 25mm fiber length and 12.5mm wide. The UACS plies were prepared by cutting in 250x250mm and stacking them in the laminate configuration of $[45/0/-45/90]_{2s}$. The stacked UACS plies were set in the mold cavity in 300x300mm and cured at 3MPa pressure and 150ºC for 30min. The UACS laminate (Vf58%) exhibits excellent flowability as illustrated in Fig. 1. The fiber orientation in UACS laminate remained the same after its area was increased. We found that the flowability was almost the same as that of SMC (Vf40%) made by randomly distributing chopped strands (25mm fiber length) in the resin.

One important feature of UACS is that the layer structure is maintained even when complexly shaped components are fabricated from a flat plate of quasi-isotropic UACS laminate. Figure 2 depicts a rib structure fabricated using UACS as an example of a complexly shaped structural component. For comparison, a rib structure made from ordinary prepreg is also presented in Fig. 2. In both cases, flat plates of quasi-isotropic laminates were set in the cavity of the rib-structure mold and cured under the conditions above. Resin-rich regions could be seen in the ordinary prepreg, as illustrated in Fig. 2. In contrast, the chopped strands in UACS sufficiently filled the rib part. Furthermore, the layer structure was still maintained even in the rib part. To our best knowledge, this is the first such molding compound.

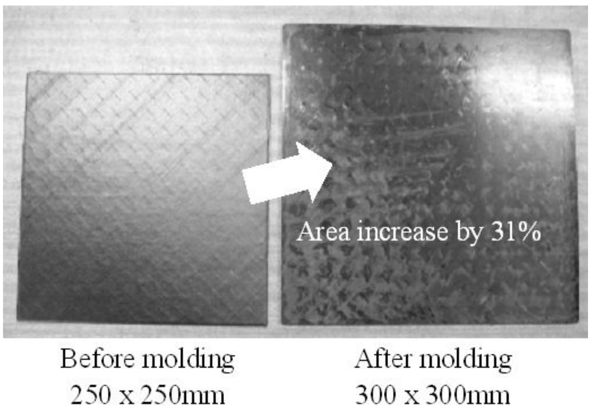

Fig. 1 Example of flowability of a flat plate with quasi-isotropic UACS laminate.

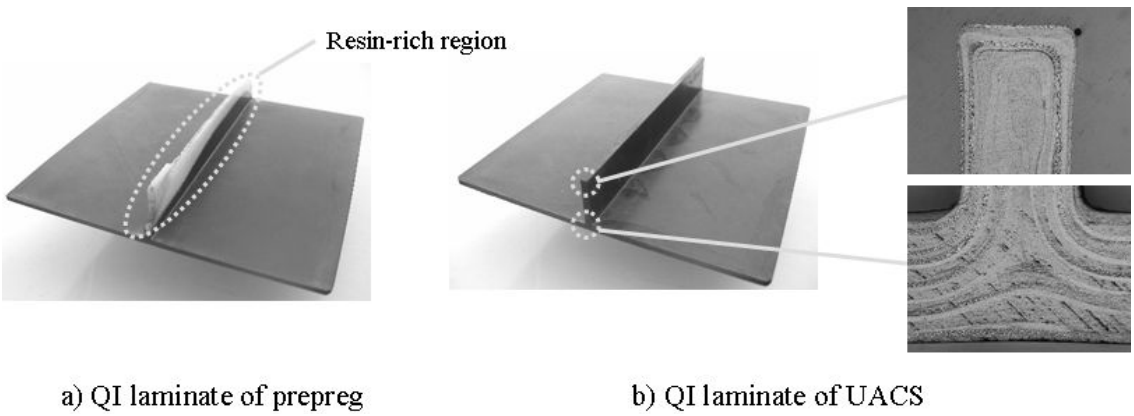

Fig. 2 Example of flowability of a rib structure with quasi-isotropic UACS laminate.

3. MECHANICAL TESTING AND RESULTS

3.1 Measurement of the Mechanical Properties

We measured the mechanical strength and modulus of UACS laminate and compared them with those of SMC and conventional laminates made of ordinary prepreg. UACS was made of chopped strands in 25mm fiber length and 12.5mm wide. The UACS plies were then stacked in the quasi-isotropic lamination of $[45/0/-45/90]_{2s}$ and cured by hot pressing. Conventional laminate was also made by stacking the ordinary prepreg in the quasi-isotropic lamination of $[45/0/-45/90]_{2s}$ and curing. The volume fraction of both UACS and ordinary prepreg was about 58%. SMC was made of randomly distributing chopped strands (25mm in length) into vinyl ester resin. The volume fraction of SMC was about 40%.

Figure 9 presents the experiment data of the tensile modulus and strength according to ASTM D3039 (error bar corresponds to $\pm\sigma$). The strength of UACS laminate was twice that of SMC. We also confirmed that the modulus of UACS laminate was higher than that of SMC and close to that of conventional laminate. It should be noted that the maximum fiber volume fraction of SMC is almost 40% due to the flowability.

3.2 Unidirectional UACS Laminates

To understand the detailed failure mechanism in UACS laminate, we performed a tensile test for the unidirectional UACS laminate. Multiple UACS plies were stacked parallel to each other and cured in the unidirectional lamination. In particular, we evaluated how the chopped strand sequence and dimensions affect the strength of UACS laminates.

First, we studied the effect of the chopped strand sequence on the tensile strength. In the same way as in the previous section, the dimension of chopped strands is 25mm fiber length and 12.5mm wide. Eight UACS plies were then stacked and cured in the unidirectional laminate. We studied two different chopped strand patterns (Cases I and II) as depicted in Fig. 3. In Case I, we can easily see that the interlaminar delamination generated from the ends of chopped strands causes the final failure of the coupon (Fig. 4). In contrast, in Case II, the splitting generated from the side-ends of chopped strands causes the final failure (Fig. 4). To quantitatively discuss the tensile strength of UACS laminate, we applied the fracture mechanics model [2-4] to these experiments. The model used here is quite simple and is just one-dimensional. As shown in Fig. 5, the model is expressed as a laminate of columns. The crack seen in Fig. 5 a) represents the delamination in Case I and that in b) represents the splitting in Case II. The height h_1 in the region above the broken line corresponds to the thickness of chopped strand in Case I and the width of chopped strand in Case II. We assumed that end region of chopped strand does not carry any load.

The energy release rate G for the propagation of delamination or splitting is then given by

$$G = \frac{E_1 h_1 P^2}{2E_1 h_1 (E_1 h_1 + E_2 h_2) d^2} = \frac{E_1 h_1 (h_1 + h_2)^2}{2E_2 h_2 (E_1 h_1 + E_2 h_2)} \sigma^2 \qquad (1)$$

where P is the tensile load applied to the model, h_1 and h_2 are defined as in Fig. 5 (h_1 corresponds to chopped strand thickness or width), d is the thickness of the model, E_1 is the modulus in the region above the broken line in Fig. 5, E_2 is the modulus in the region below the broken line, and σ is the average applied tensile stress of the model.

Since the crack propagates when the energy release rate G reaches the fracture toughness G_c, the critical stress σ_c at the crack propagation is given by

$$\sigma_c = \frac{1}{h_1 + h_2}\sqrt{\frac{2E_2 h_2 (E_1 h_1 + E_2 h_2) G_c}{E_1 h_1}} \qquad (2)$$

This equation suggests that the growth of delamination or splitting is unstable since σ_c is independent of a.

Table 1 compares the experiments and predictions. The moduli for the regions above and below the broken line are assumed to be the same (i.e. $E_1 = E_2$). In this calculation, we used G_c = 633J/m^2 deduced from the strength of Case I. This G_c value is reasonable compared with other experiment results of mode II fracture toughness [5-8]. The predicted strength ratio of Case I to Case II is 12.3 and is very close to the experiment value; in the experiments, the strength in Case I was 13.0 times that in Case II.

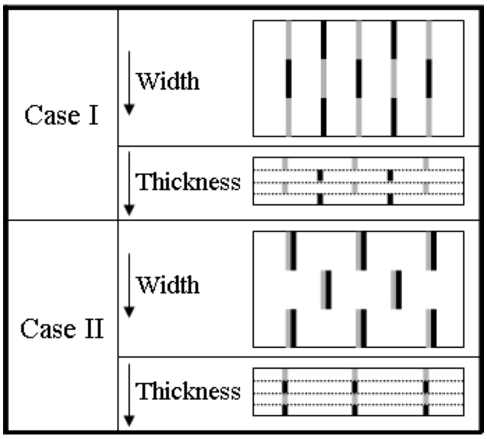

Fig. 3 Patterns of stacking for unidirectional UACS laminates.

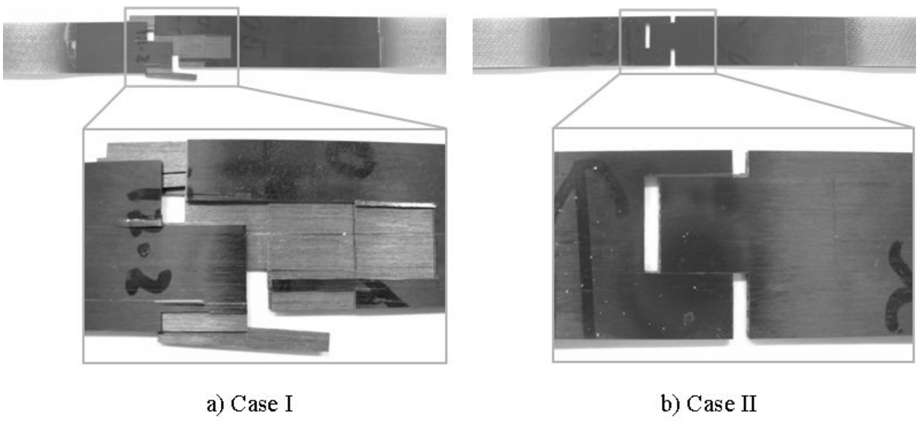

Fig. 4 Fracture coupons of unidirectional UACS laminates.

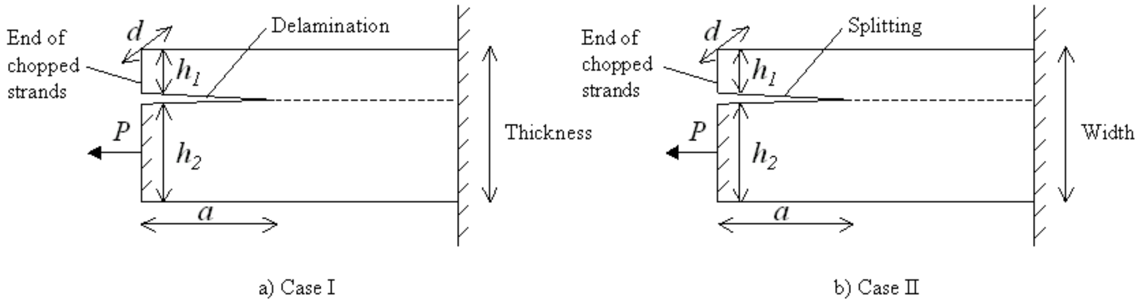

Fig. 5 Analytical model of cracking from end of chopped strand in UACS laminate.

Table 1 Tensile modulus and strength of unidirectional UACS laminates

ID	Experiments						Predictions
	Spec.	Specimen Width [mm]	Specimen Thickness [mm]	Tensile Modulus [GPa]	Tensile Strength [MPa]	CV. [%]	σ_c [MPa]
Ref.	Prepreg	-	-	130	2460	-	-
1	Alternate ends	25.0	1.166	119	950	4	950
2	Coincident ends	25.0	1.174	118	73	32	77

Second, we studied the effect of chopped strand dimensions on the tensile strength. The strength was evaluated in a unidirectional UACS laminate having chopped strands of different width and thickness. Let us consider only Case I hereafter. The strength of UACS laminates with different chopped strand widths was investigated. Comparisons between the experiments and predictions are summarized in Fig. 6 a). The same value of G_c (633J/m^2) was used in the prediction. From Eq. (2) the chopped strand width had no effect on the tensile strength. This was confirmed by the experiments.

We also evaluated the effect of chopped strand thickness on the strength. Comparisons between the experiments and predictions are summarized in Fig. 6 b). It is obvious from Eq. (2) that the tensile strength decreases with an increase in the chopped strand thickness h_1. This was also confirmed by the experiments.

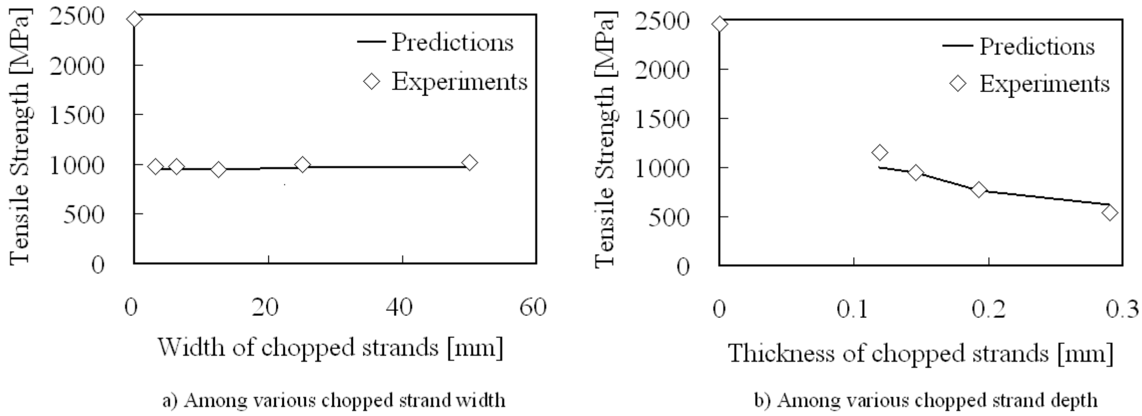

Fig. 6 Comparison of the tensile strength of unidirectional laminates between experiments and predictions.

Consequently, the strength in unidirectional UACS laminate is well predicted by fracture mechanics incorporating the delamination or splitting growth. We therefore suggest the tensile strength depends on the chopped strand sequence and dimensions, as easily seen in Eq. (2).

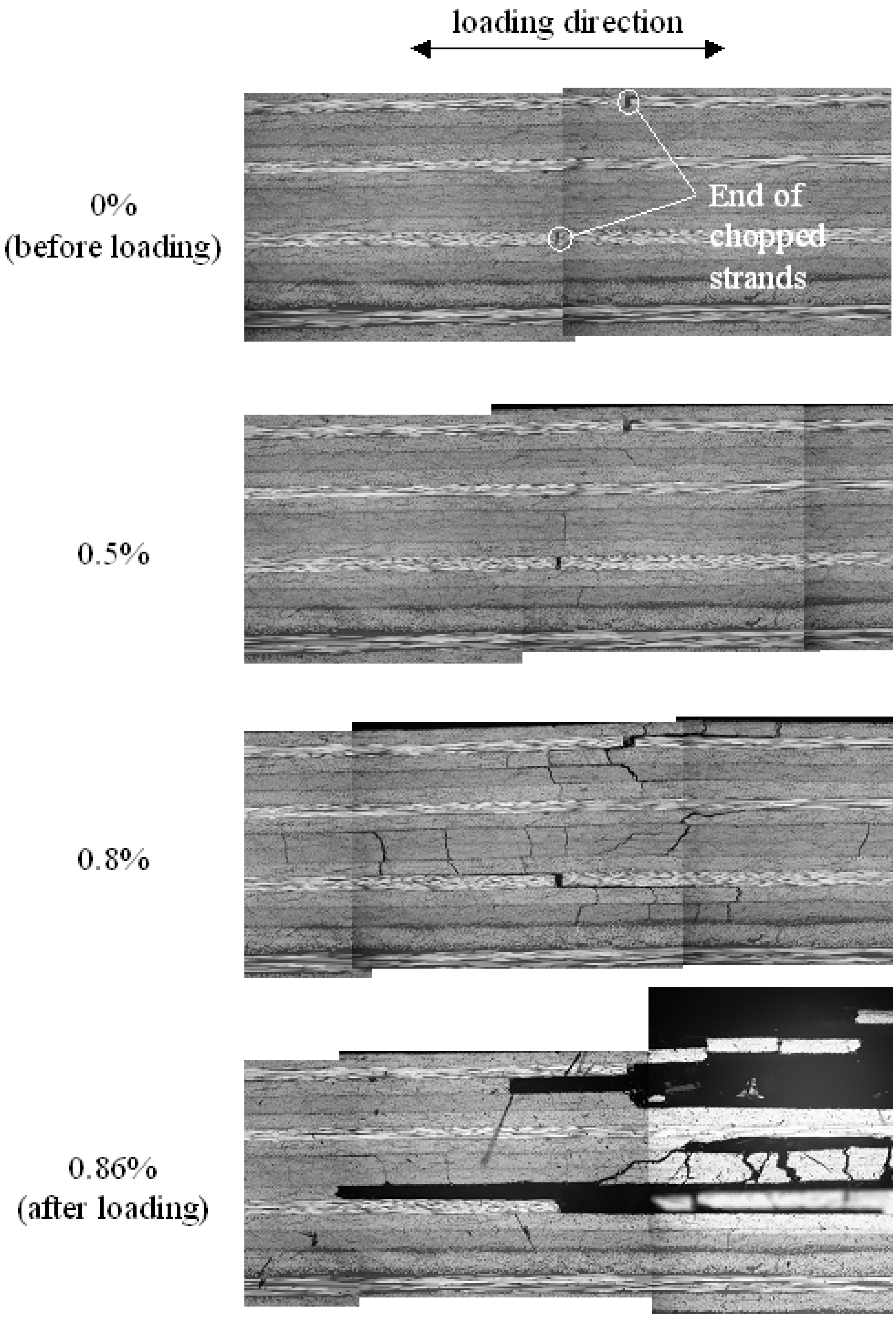

Fig. 7 In-situ observation of the damage process in a tensile test on a cross-section of quasi-isotropic UACS laminate.

3.3 Quasi-isotropic UACS Laminates

To clarify the failure mechanism of quasi-isotoropic UACS laminate, we implemented in-situ observation of the damage process in a tensile test on the cross-section as presented in Fig. 7. Multiple transverse cracks and some slight delamination were generated at the lower applied strain. The significant delamination was finally generated to connect these damages and led to final failure. Therefore, the delamination is the main damage even for the quasi-isotoropic UACS laminate.

We also studied the effect of chopped strand dimensions on the tensile strength in quasi-isotropic UACS laminates, and summarized experimental results in Fig. 8. Even if the damage process seen in the quasi-isotropic laminate is extremely complicated, final failure was caused by significant delamination, in the same way of unidirectional UACS laminates. That is why the tendency for the tensile strength to depend on the chopped strand thickness but not on the chopped strand width is still maintained.

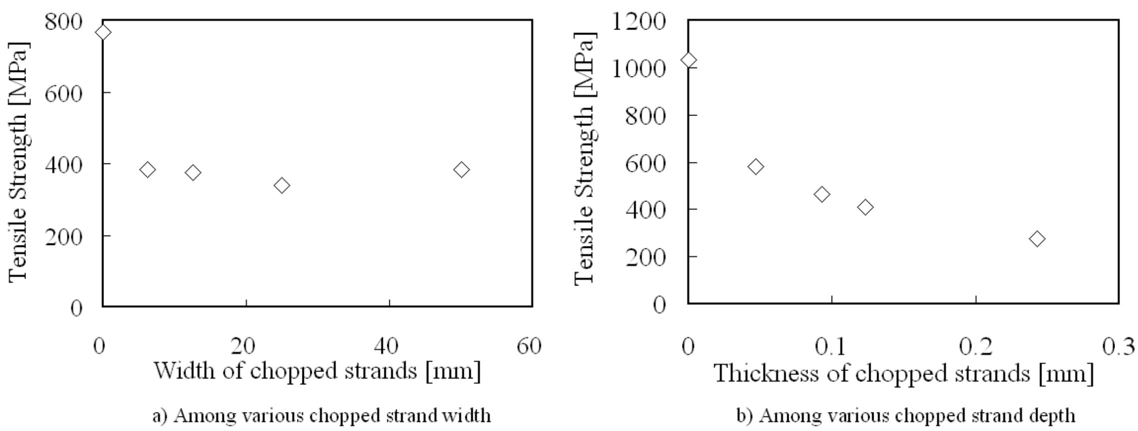

Fig. 8 Comparison of tensile strength of quasi-isotropic laminates in experiments.

4. ENHANCED UACS

UACS laminate was found to be fractured by unstable delamination growth. Thus the tensile strength of UACS is still limited by approximately a half of that of continuous fiber prepreg as shown in Fig. 9. To control the final failure with fiber breakage, we optimized the material configuration of UACS and obtained further more strength than the UACS (hereafter, described as Enhanced UACS).

The comparison of mechanical properties between SMC, prepreg, UACS and Enhanced UACS are summarized in Fig. 9-14 (error bar corresponds to $\pm\sigma$). SMC was made of randomly distributed fiber strands (T700S) and vinyl ester resin (Vf40%). Prepreg, UACS and Enhanced UACS were made of same fiber/resin system (T700S/#2500) and stacked in quasi-isotropic lamination of $[45/0/-45/90]_{2s}$ (Vf58%). Tensile tests (ASTM D3039), compression tests (JIS K7076; shear loaded), flexural tests (ASTM D790), tensile fatigue tests (JIS K7083; R=0.1, 10Hz), Sharpy flatwise impact tests (JIS K7077; without notch) and Izod edgewise impact tests (ASTM D256; notch A) were implemented. The Enhanced UACS is very promising for the molding material which achieves both excellent flowability and distinguished mechanical properties comparable to the continuous fiber prepreg.

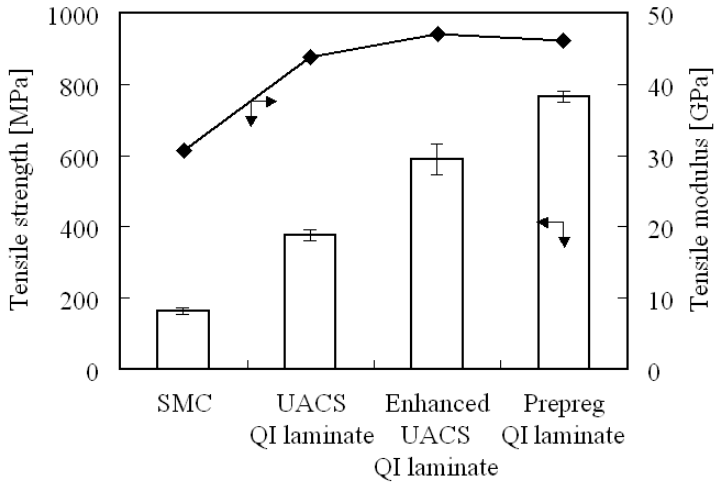

Fig. 9 Comparison of tensile modulus and strength.

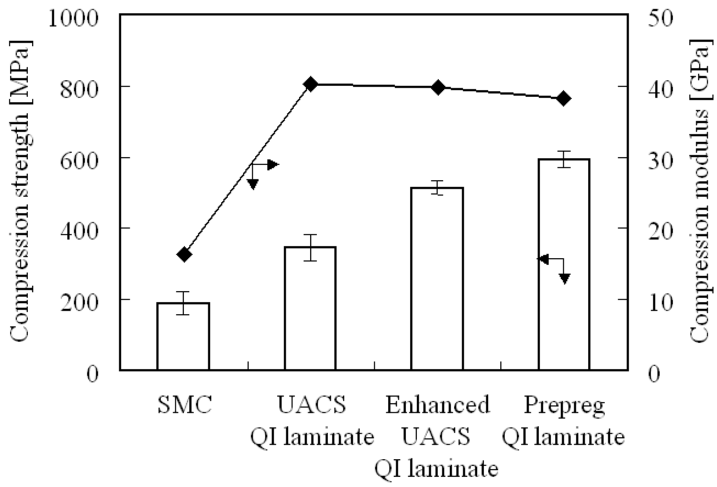

Fig. 10 Comparison of compression modulus and strength.

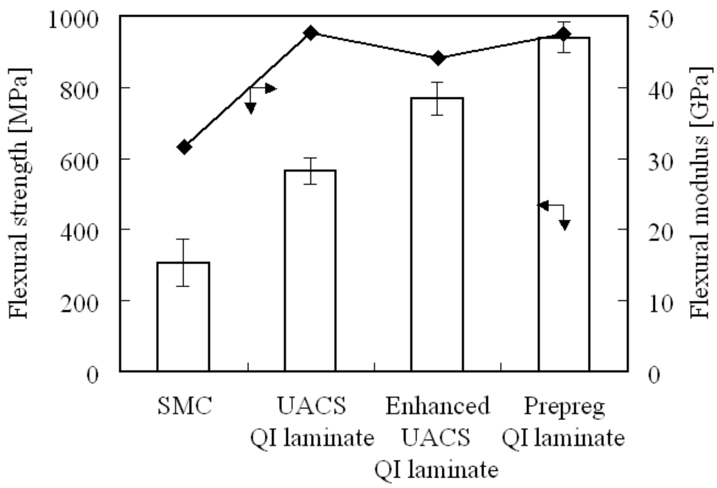

Fig. 11 Comparison of flexural modulus and strength.

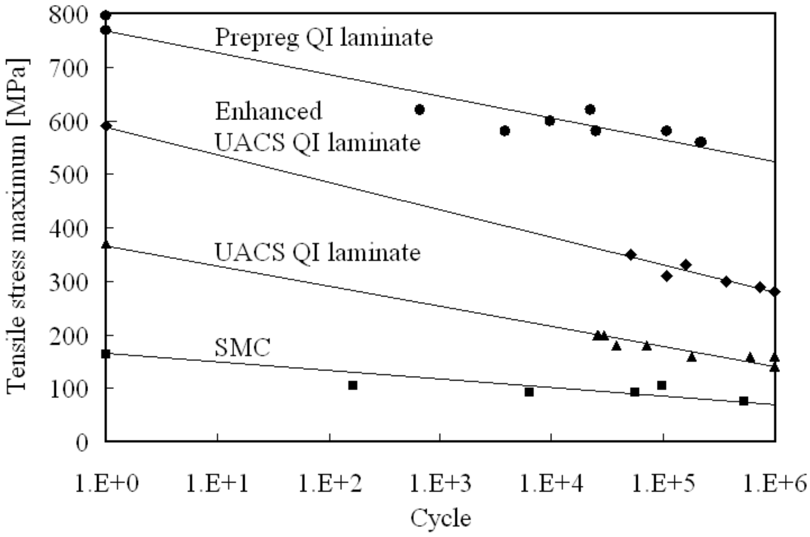

Fig. 12: Comparison of tensile fatigue strength.

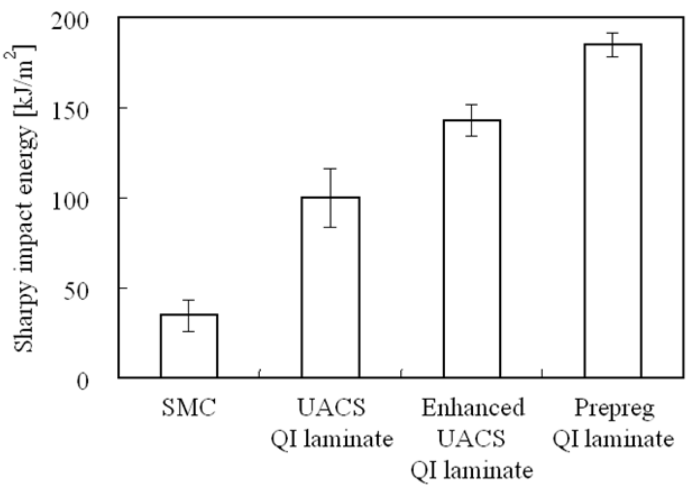

Fig. 13 Comparison of Sharpy flatwise impact energy.

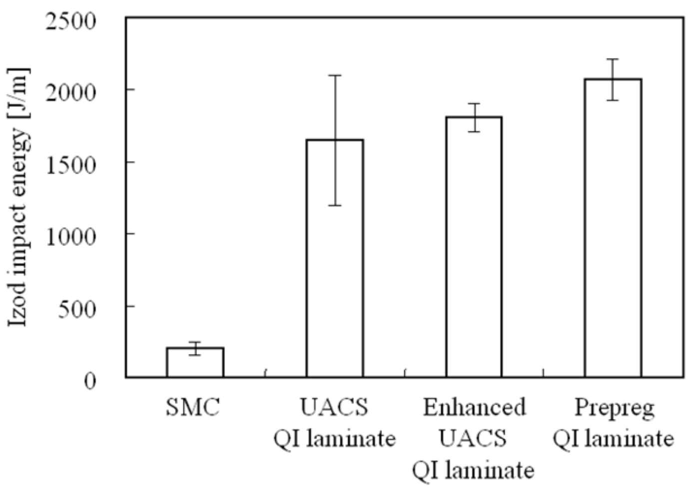

Fig. 14 Comparison of Izod edgewise impact energy.

5. CONCLUSIONS

This study proposes a new compression-molding approach using unidirectionally arrayed chopped strands (UACS). UACS a sheet-like molding material made of regularly and unidirectionally arrayed discontinuous carbon fiber strands impregnated thermosetting resin. Products, complexly shaped components, and UACS laminates are made by stacking UACS plies and curing them with a hot press. We demonstrated that UACS had much better flowability than ordinary prepreg. As a result, a rib structure made with UACS was highly uniform, its layer structure was well maintained, and only a few resin-rich regions existed. We performed tensile tests to measure the mechanical properties of UACS laminates and confirmed that the UACS laminates have higher strength and moduli than SMC laminates. Observations revealed that the final failure was mainly controlled by the onset of unstable delamination growth. Finally, we demonstrated that the strength of UACS could easily be deduced by a simple model based on fracture mechanics. As a result, we optimized the material configuration of UACS and proposed an enhanced UACS which achieved excellent strength comparable to continuous fiber prepreg laminate.

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