A STUDY ON THE FORMING PROCESS AND MECHANICAL PROPERTIES OF CENTER-PILLAR REINFORCEMENT WITH CR420/CFRP HYBRID COMPOSITE MATERIALS

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Abstract

In this study, a hybrid composite material was fabricated by stacking carbon fiber-reinforced plastic onto CR420 plates to increase the specific strength and stiffness relative to those of thick boron steel plates and dual-phase steels. Two forming processes were first compared and evaluated in terms of their ability to manufacture appropriate center-pillar reinforcement through simulations. Die was then prepared after deciding on the better process through computer aided engineering (CAE), and a center-pillar reinforcement was formed with a carbon fiber-reinforced plastic (CFRP)/CR420 hybrid composite. After forming, the differences in the mechanical properties of the specimens were investigated according to position through simulation. Further, the causes of deterioration of the mechanical properties were elucidated by observing the micro-structure. Large quantities of voids greater than 50 μm in size were found in those specimens that had contact pressure lower than 0.5 MPa. The results obtained confirm that large quantities of voids cause the mechanical properties of CFRP composites to deteriorate.

1. Introduction

In recent times, the development of environmentally friendly materials to improve the safety and fuel efficiency of automobiles has come to the fore in the automobile industry. As the demand for technological developments that result in high performance and high efficiency continues to increase, research into the manufacture of parts composed of advanced high-strength steel developed via the hot press process is actively underway (Caballeroa et al., 2007; Fan et al., 2009). Karbasian (2010) introduced elements of the hot stamping process, such as coating, quenching, cutting, and corrosion, which engendered significant potential for further investigations and innovations in the field of hot stamping. Further, fuel efficiency research and development through additional weight reduction using tailor welded blank (TWB) and partial quenching (PQ) quickly became widespread in the automobile industry as a result of studies by researchers such as Stöhr (2009) and Xu (2014). The mechanical behavior of TWBs was reviewed and the major strain on the forming limit diagram (FLD) curve with respect to the transition zone was investigated by Zadpoor (2007). Furthermore, various strategies for partial hot stamping were investigated by Stöhr (2009). Lee (2014) investigated the HAZ of TWB specimens and found that when TWB specimens coated with Al–Si are welded, intermetallic compounds such as FeAl3 and Fe2Al5 are created at HAZ, which decreases the hardness of TWB specimens. For Zn-coated boron steel, the hardness in the welded area did not fall below 450 HV, even when it was welded without laser ablation of the coating layer. In contrast, the coating layer of Zn-coated boron steel was observed to peel off when the material was heated for 5 min at 950℃. Research into hot stamping is currently still actively underway.

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To conform to the increasingly stringent environmental regulations associated with the automobile industry, automobile companies worldwide are currently developing biotechnological, natural fuel, and eco-friendly automobiles such as electric, fuel cells, and gas-electric hybrid cars. However, unfortunately, environmentally friendly automobiles tend to be heavier than conventional automobiles owing to the need for additional parts such as motor, battery, and electronic devices. Making a vehicle lightweight is of utmost importance in order to increase fuel efficiency. However, this is very difficult to achieve with high-strength steel materials and TWB technology. Therefore, lighter materials than those currently in use, and that also possess good strength-to-weight ratio and specific strength, are required in order to develop future automobiles.

Consequently, next-generation materials such as high-strength aluminum alloy, magnesium, and fiber-reinforced composite materials have been developed and are currently utilized in various automobile parts. Among these new-generation materials, fiber-reinforced composite carbon fiber-reinforced plastic (CFRP) has excellent strength-to-weight ratio and specific strength, and is consequently actively being studied by researchers such as Paepegem (2006) and AL-Zubaidy (2011). However, the low elongation rate and low fracture toughness of the CFRP composite result in various constraints on the types of automobile parts in which it can be utilized.

In an effort to overcome the limits on the single CFRP material, active research is currently underway into hybrid composites in which CRFP is amalgamated with metals. Teng et al. (2012) conducted research on the fracture mode of CFRP-reinforced metal structures. El-Tawil et al. (2011) showed that metal hinges covered with CFRP are good for lower frequency fatigue behavior and delayed distortion as partial buckling is restricted. Hankeln and Mahnken (2013) evaluated the formability of unidirectional single material CFRP through simulation. They designed the CFRP by dividing it into reinforcing material and matrix, and studied the effect of the anisotropy of CFRP on the deformation behavior according to viscosity and temperature. Ghasemnejad et al. (2010) studied the crashworthiness and failure modes of laminated composite boxes made of twill-weave and unidirectional CFRP composite materials. Lee et al. (2016) investigated the epoxy flow behavior and formability of CFRP/CR340 hybrid materials through a deep drawing process according to process parameters.

However, research on CFRP/steel hybrid composites is still at the basic experimental stage, and is concerned with mechanical properties, contact strength, and evaluation of formability; further, the research primarily involves flat plates or basic shapes, as opposed to large and complicated shapes. Therefore, research into automobile parts that incorporate these next-generation materials must focus on lightweight materials in actual future automobiles.

In this study, two forming processes were compared and evaluated through simulations in order to manufacture appropriate center-pillar reinforcements that absorb impact when vehicles crash. Die was prepared after deciding on the better process through computer aided engineering (CAE), and center-pillar reinforcement was formed with a CFRP/CR420 hybrid composite. After forming, test specimens were machined per position and the mechanical properties of the specimens investigated. The reasons for variances in the mechanical properties according to position were ascertained by investigating the contact pressure through simulation analysis. Further, the causes of deterioration of the mechanical properties were elucidated and verified via photographs of the micro-structure.

2. Experiment and Simulation

2.1 Materials

Carbon fiber from Toray comprised the plain weave CFRP used in this study. Prepreg sheets, each 0.25 mm thick, and thermo-setting resin with initial epoxy weight at 35% were used.

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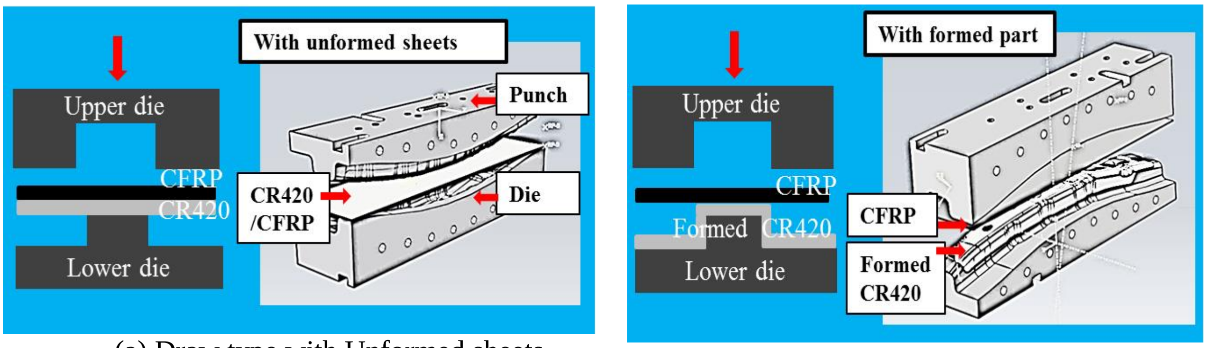
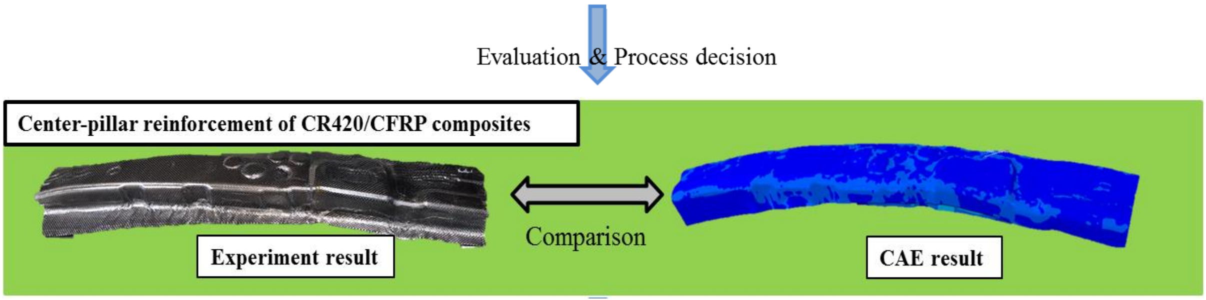
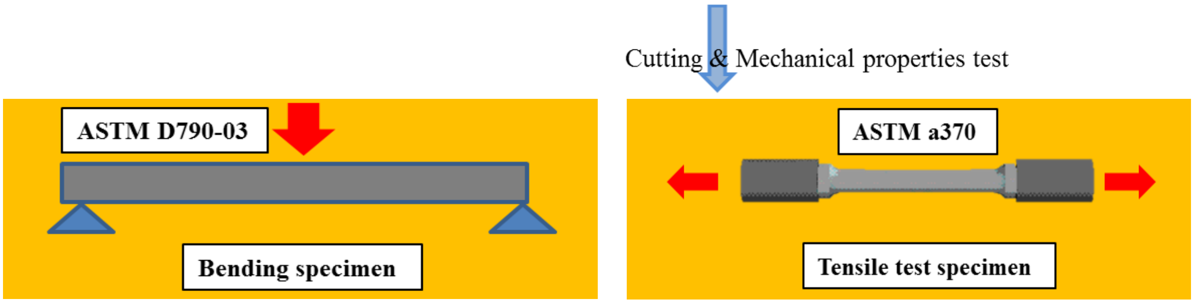


(a) Draw type with Unformed sheets (b) Draw type with formed part



(c) Center-pillar reinforcement after experiment (d) Center-pillar reinforcement after simulation



(e) Three-point bending test (f) Tensile test

Fig. 1 Flow of experiment conducted using CR420/CFRP hybrid composites

In this study, CFRP was stacked onto the CR420 steel sheets with excellent elongation rate instead of high-strength steel sheets by using DP steel and boron steel plates in order to increase the strength-to-weight ratio, specific strength, and fracture toughness. The thickness of the CR420 steel plate was 1.4 mm and it was coated with Zn to prevent galvanic corrosion. Its mechanical properties are listed in Table 1.

Table 1. Mechanical properties of CR420

Tensile strength (MPa)	Elongation (%)	Vickers hardness (Hv)	Elastic modulus (GPa)
596	25	140	210

Figure 1 outlines the flow of the experiment conducted. Two CAE methods were first utilized to decide on the most appropriate center-pillar reinforcement preparation process. In the first method, forming was performed by stacking the CFRP onto the CR420, which was not formed on the die, as illustrated in Figure 1(a). In the second method, the CFRP was stacked onto preformed CR420 and the composite material cured, as illustrated in Figure 1(b). Both methods were then evaluated, and the process adjudged to be the better one was employed to prepare the actual die. The actual experiment was then performed and the experimental results compared to the simulation results, as shown in

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Figures 1(c) and (d). The mechanical properties of the bending and tensile test specimens were then obtained from each position in order to investigate the mechanical properties of the formed product, as illustrated in Figures 1(e) and (f).

2.3 Mechanical Properties used for CAE

In this study, simulations were conducted using ABAQUS software. The physical properties of CR420 used in the simulations are illustrated in Figure 2. Zone a–b at position 1 is an elastic zone with elastic modulus 210 GPa. Zone b–c at position 2 is a plastic deformation zone, for which the S-S curve based on the tensile test data of CR420 was entered. Zone c–d at position 3 is a fracture zone with ultimate strength. The slope of strain criterion for zone c–d, which is degradation response, is governed by damage evolution. If no damage theory is applied here, the fracture mechanism does not occur and the stress after necking responds as c–d. That is, the steel is not fractured, is elongated infinitely, and stress is also not reduced in the simulation. In this study, a fracture mechanism theory was applied in the forming limit diagram in order to obtain accurate sheet-forming simulation data.

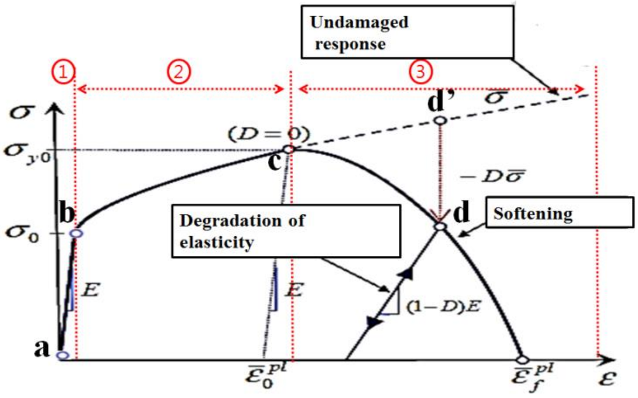

Fig. 2 Material input method with respect to region

Figure 3 shows the FLD curve obtained after a stretch test. Minor and major strain data were applied in the simulation, and damage evolution value was defined at 0.1 mm as a fracture value.

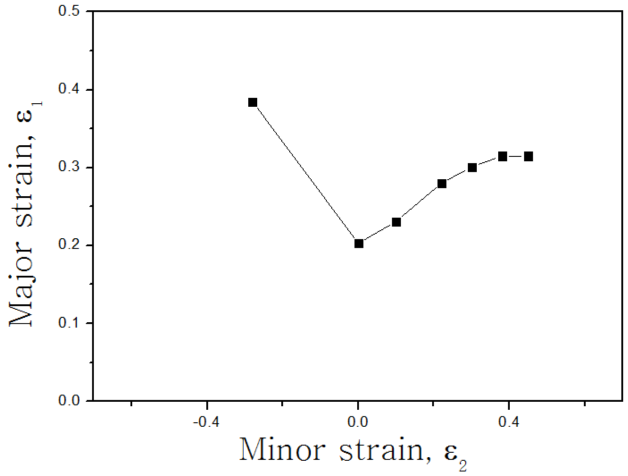

Fig. 3 FLD curve for CR420

2.4 Center-pillar Reinforcement Experiment

Figure 5 shows the die used to form the center-pillar reinforcement after CAE analysis. Blank was prepared by stacking CFRP 0.25 × 7 ply = 1.75 mm on the 1.4 mm CR420. A press with capacity 5,000 ton was used in the forming. Holes were made on the upper and lower die and heated to 140℃ using a cartridge heater. Pressure exceeding 0.5 MPa was imposed, followed by curing for 30 min to

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prepare the center-pillar reinforcement. After forming the center-pillar reinforcement, tensile and bending test specimens were cut according to region. Eight pillars were used to measure the mechanical properties.

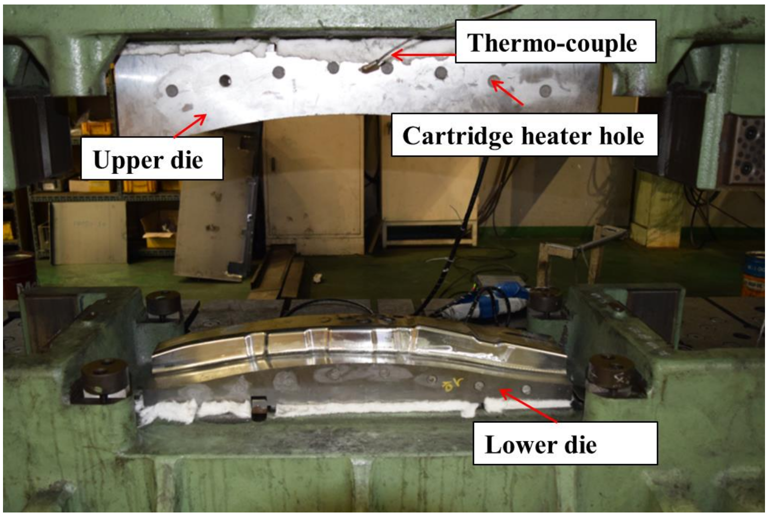

Fig. 5 Experimental apparatus employed for center-pillar reinforcement

2.5 Tensile and Bending Experiment

Tensile strength test was carried out using MTS with the specimen ASTM-A379 at a tensile speed of 2 mm/min. The test specimen used in the three-point bending test was ASTM D790-03 with a bending speed of 10 mm/min. Because elongation of CFRP is low, the tensile strength and bending tests were terminated the moment CFRP fracture occurred.

3. Test Results and Discussion

3.1 Evaluation of Center-pillar Reinforcement

(a) Before piercing and trimming

(b) After piercing and trimming

Fig. 12 Center-pillar reinforcement before and after piercing and trimming process

Figure 12 shows the final part of the center-pillar reinforcement before and after the hole piercing and trimming process. When the milling process is conducted, tool geometry on delamination is not significantly affected (Wolfgang et al., 2015). Following the hole piercing and trimming, no wrinkle or crack occurred, and the final product was trimmed well or cleaned.

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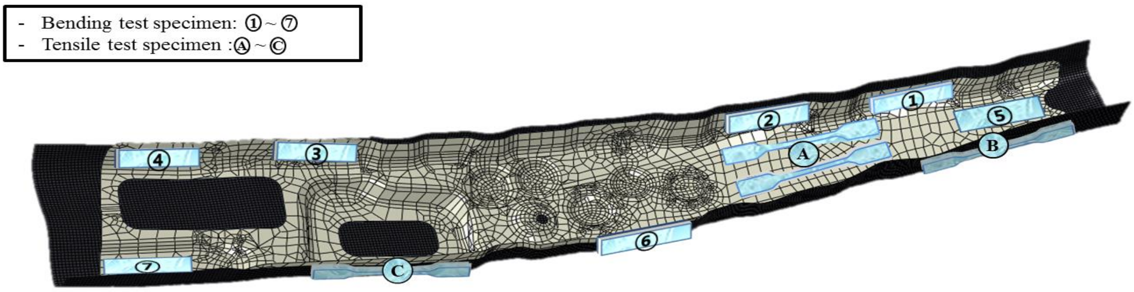
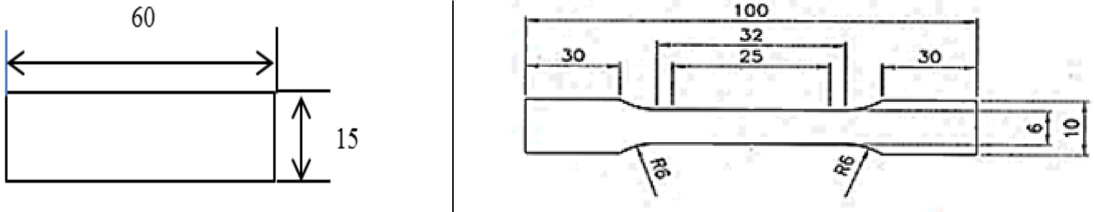
3.2 Tensile Test and Bending Test According to Location

Figure 8(a) shows the cut specimen of CR420/CFRP hybrid composites from each position of the finished product, and Figures 8(b) and (c) show the size of each bending test specimen and tensile test specimen. The bending and tensile test specimens were cut at each position and tensile strength test and three-point bending were performed.



(a) Bending and tensile specimen of center-pillar reinforcement according to position



(b) Bending specimen (Positions 1–7) (c) Tensile specimen (Positions A–C)

Fig. 8 Bending and tensile specimens according to position and specimen dimensions

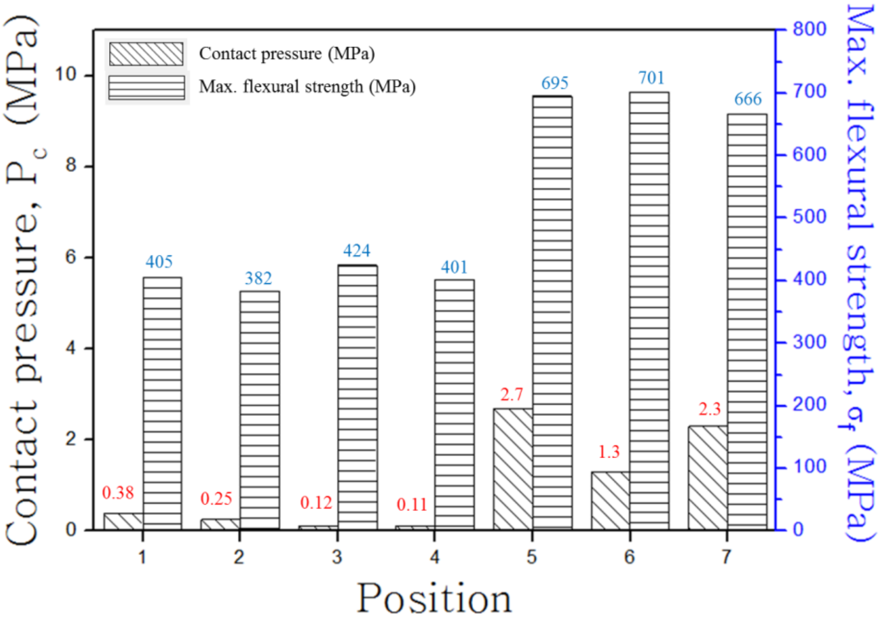


Fig. 9 Maximum flexural strength and contact pressure according to position

Figure 9 shows the contact pressure and flexural strength according to position. As can be seen from the graph, at positions 1–4, where the pressure was lower than 0.5 MPa, the flexural strength was in the range 380–420MPa, whereas at positions 5–7, where the contact pressure was higher than 0.5 MPa, the flexural strength was higher than 660–700 MPa. This trend can also be observed in Figure 18.

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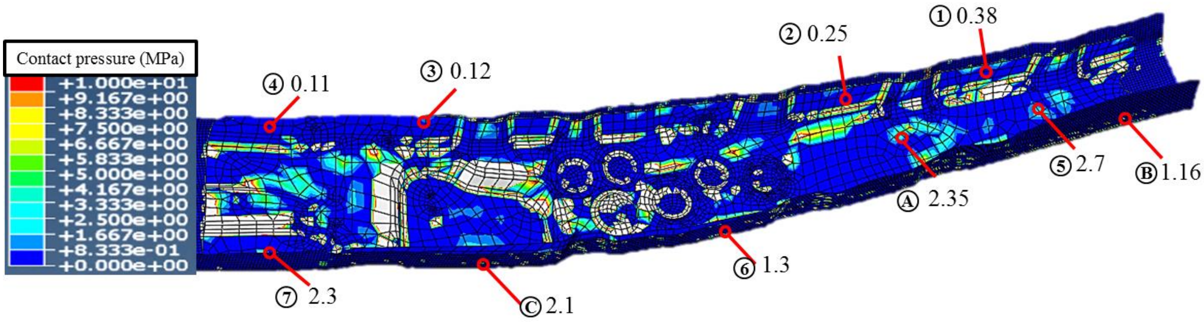

Fig. 10 Contact pressure of center-pillar reinforcement according to position

Figure 10 shows the contact pressure points. The contact pressure was very low at points 1–4, the upper side, measuring just 0.11–0.38 MPa. Meanwhile, at point 5, in the center of the specimen, the contact pressure was 2.7 MPa. Contact pressures of 1.3 and 2.3 MPa were imposed at points 6 and 7, on the lower sides of the specimen. These results indicate that good physical property was obtained only when CFRP was cured under a pressure higher than 0.4 MPa, as was reported by Zhu et al. (2011). Zhu et al. (2011) reported that when pressure was higher than 0.4 MPa, porosity became less than 1% and did not affect mechanical properties.

4. Conclusions

1.Center-pillar reinforcement with the formed part performed well for hole piercing and trimming, and, as in the simulation results, good results were obtained.
2.In regions where contact pressure was lower than 0.5 MPa, the mechanical properties of the product deteriorated, indicating that the clearance at the side had to be adjusted during die designing in order to increase the contact pressure.

Acknowledgments

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