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Design of Repeat-Antenna Package for Mobile Communication Made of Ferrite-Loaded Glass-Fabric/Epoxy Composites

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Abstract

This paper presents the material design and structural analysis of the repeat antenna used in mobile communication and shows the possibility of replacing the aluminum package of the repeat-antenna system by ferrite-loaded glass-fabric/epoxy composites. The three-phase composite material provided high strength and electromagnetic shielding at 1.8–2.0 GHz, one of frequency ranges used for mobile communication. The Ni–Zn ferrite as an absorbing material was fabricated, and Ni–Zn ferrite/epoxy composite was measured with a network analyzer to obtain complex permittivity and permeability. The characteristics of Ni–Zn ferrite specimens with conductive carbon black were studied, and the matching frequency was adjusted to 2 GHz frequency by controlling the amount of conductive carbon black. The ferrite-loaded glass-fabric/epoxy composite specimens were fabricated, and tensile and bending tests were carried out to evaluate mechanical properties. The structural analysis of antenna package of ferrite-loaded glass-fabric/epoxy composite was conducted for under wind pressure and compared with that of aluminum antenna package.

Keywords

Composites, glass-fabric, Ni–Zn ferrite, repeat antenna, structural analysis

1. Introduction

Electromagnetic wave (EM wave) absorbing material is widely used as an EM wave absorber in electrical and aerospace industry as a method to minimize unwanted signals [1, 2]. As electric instruments become more complicated, it becomes more

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necessary to reduce possible interference among them by using an EM wave absorber [3, 4].

Magnetic materials such as ferrites are being used for absorbers which attenuate EM waves by magnetic moment loss. The absorbing property of these materials can be designed by changing material characteristics, such as thickness, complex permittivity, permeability, and frequency [5–7]. Conductive materials such as carbon black, graphite, and metal powder can reduce EM waves by ohmic loss of dielectric properties [2]. The loss is also caused by high conductivity that may be achieved by using high content of conductive material [8]. Even though magnetic and conductive materials have different characteristics in wave absorption, mixtures of magnetic and conductive materials have been studied for the purpose of controlling the material properties and attenuating abilities in the high frequency range including the X-band (8–12 GHz) [9–11].

There has been extensive research into the use of EM wave absorbers made of composites for communication and radar systems because fiber-reinforced composite material is both light and strong. Especially, glass fiber composites with EM wave absorbing materials have been extensively researched [12].

The repeat antenna is a system to improve the quality of mobile communication and to enlarge the coverage area of the base station. The antenna is mostly installed outdoors, and its package requires high strength, electromagnetic shielding, corrosion protection, and small weight. To meet these requirements, aluminum packages have been widely used in the repeat-antenna system. A repeater is a system to improve telephone service quality and to enlarge the base station coverage area when there is a signal hole which is blocked by topographic barriers and it is difficult to access wireless service. This system amplifies weak signals in this hole effectively and repeats it, when installed between a base station and a mobile terminal. The communication of the repeater system is a FA (Frequency Allocation) type which amplifies a whole wireless operator's frequency bandwidth. In addition, the repeater extends ground, underground and in-building coverage.

In this research, the effectiveness of repeat antennas using ferrite-loaded glass-fabric/epoxy composites was investigated in terms of material properties, and structural analysis was carried out. The EM wave absorber over 10 dB attenuation at 2 GHz was fabricated by using conductive carbon black in Ni–Zn ferrite/epoxy composite, which showed higher permittivity. The EM wave absorber selected in the material design stage was laminated with glass-fabric/epoxy composite to measure mechanical properties in tensile and bending tests. The structural analysis of composite antenna package was conducted under wind pressure, and the results were compared with that made of aluminum.

2. Material Design of EM Wave Absorber

2.1. Preparation of Material

Ni–Zn ferrite was fabricated with nickel oxide (NiO, 97%, Daejung Chemicals and Metals Co. Ltd., Korea), zinc oxide (ZnO, 99%, Daejung Chemicals and Metals

Table 1.
Fabricating procedure and composition of Ni–Zn ferrite

Process	Conditions			Remarks
Material	NiO 20	ZnO 10	Fe_2O_3 70	Weight percent
Mixing	Acetone 100 g	Material 200 g	Ball 300 g	Zirconia ball (⌀3, 5, 10 mm)
Milling	24 h			Ball mill machine
Drying	12 h at room temperature			Fume hood
Calcining	2 h at 1200°C (rising rate: 5°C/min)			Furnace
Grinding	2 h			Grinder/Mortar
Screening	#400 (38 μm)			Sieve

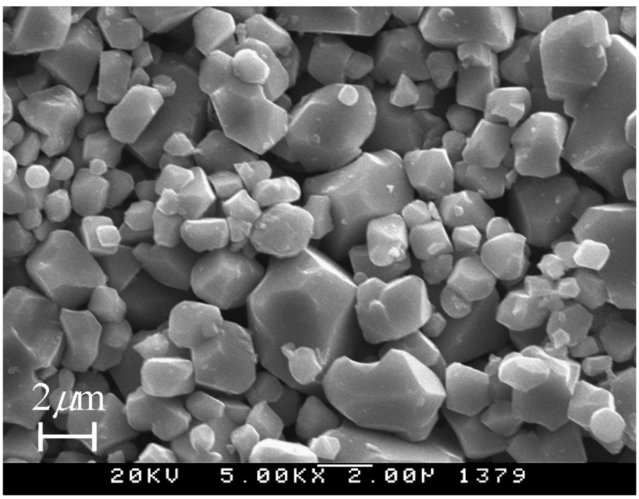

Figure 1. Morphology of Ni–Zn ferrite by SEM (×5000).

Co. Ltd., Korea) and iron (III) oxide (Fe_2O_3, 99%, Yakuri Pure Chemicals Co. Ltd., Japan). The composition of Ni–Zn ferrite and the fabrication process are shown in Table 1.

Nickel oxide and zinc oxide were mixed with iron (III) oxide, and milled over 24 h in a ball-mill machine. Dried composite was calcined at 1200°C for two hours in a furnace and then passed through #400 mesh sieve with 38 μm openings. The particle size of Ni–Zn ferrite was limited to 38 μm because EM wave absorbing characteristics and matching frequency depend on the particle size with similar attenuating ability [13]. The particles of the Ni–Zn ferrite composite are shown in Fig. 1.

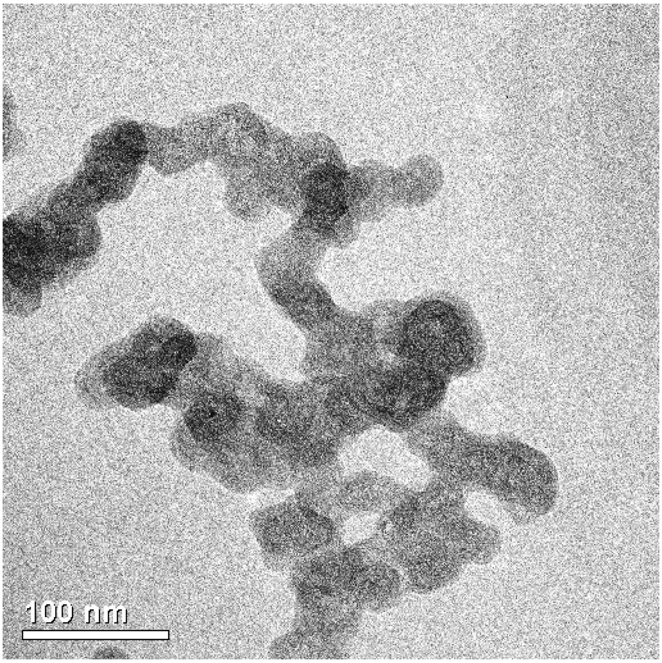

Figure 2. Morphology of Ketjen black by TEM.

Conductive carbon black (Ketjen black EC-300J, Mitsubishi Chemical Co. Ltd., Japan) was added to Ni–Zn ferrite to validate the effects of the conductive material. The image of Ketjen black is shown in Fig. 2 [14].

2.2. Fabrication of Specimen

Specimens were fabricated by the cement mixed method with Ni–Zn ferrite/epoxy and Ni–Zn ferrite/Ketjen black/epoxy [15]. Epoxy (YD-128, Kukdo Chemical Co. Ltd., Korea) as a bonding agent was used to shape those particles into specimens, and hardener (D-230, Kukdo Chemical Co. Ltd., Korea) was added to epoxy with 30 PHR (per hundred resin) ratio. The epoxy-mixed composite was compressed in Nylon mold, and cured for 2 h at 60°C. After curing, the composite was fabricated to the desired shape for the specimen, which was a hollow cylinder with an inner diameter of 3 mm (+0.05/−0) and of an outer diameter of 6.95 mm (+0.05/−0), by lathe work. The composition of specimen is presented in Table 2. Ketjen black was added to Ni–Zn ferrite/epoxy composite by volume fraction to maintain the same quantity of Ni–Zn ferrite in each specimen.

2.3. Measurement of Electromagnetic Properties

The specimens were inserted into the coaxial 7 mm air line, and vector values of S-parameters were obtained by a network analyzer (N5230A, Agilent Technologies, USA). The S-parameters were converted to complex permittivity and permeability by Nicolson–Ross–Weir algorithm [4]. The properties of specimens are illustrated

Table 2.
Composition of Ni–Zn ferrite composite (volume %)

Type	Ni–Zn ferrite	Epoxy	Ketjen black
NZF	40	60	–
NZF_c1	40	58.26	1.74
NZF_c2	40	56.52	3.48

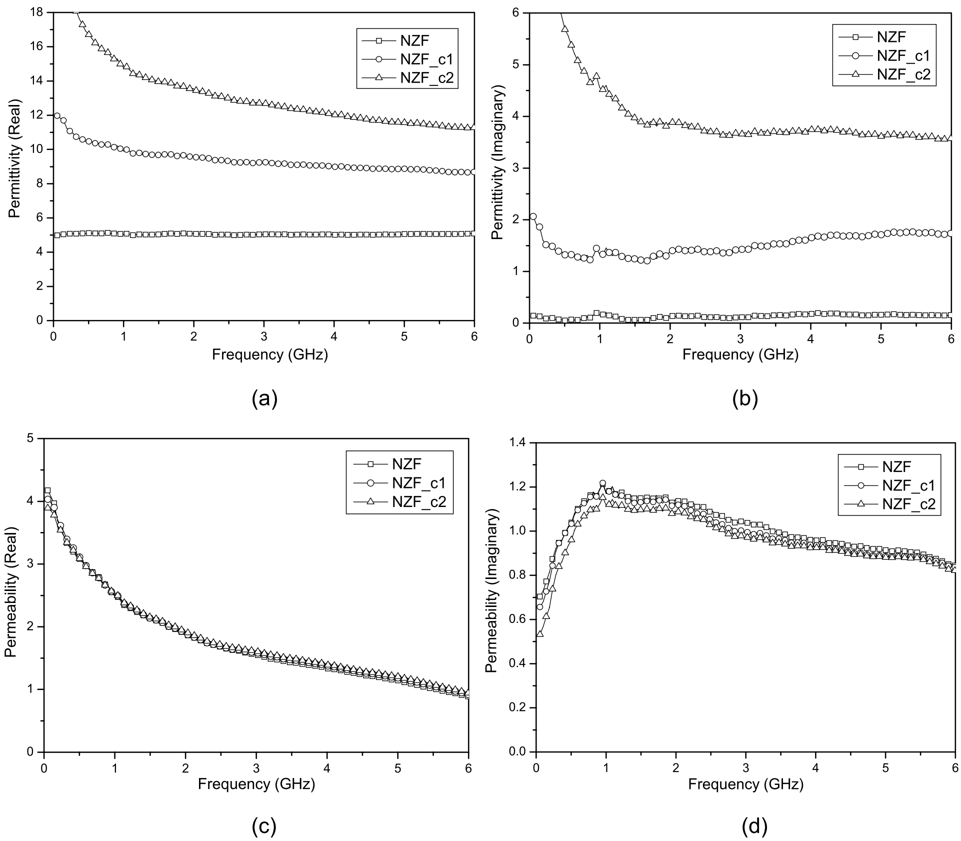

Figure 3. Material properties of Ni–Zn ferrite composites: (a) real part of permittivity; (b) imaginary part of permittivity; (c) real part of permeability; and (d) imaginary part of permeability (starting frequency is 0 GHz).

in Fig. 3. The specimens showed different values of complex permittivity, which increased with increasing content of Ketjen black, while showing similar values of complex permeability. The conductive material in the magnetic material affected the complex permittivity and increased the dielectric loss without an increase in magnetic loss.

The normalized input impedance of absorbing wall is given by complex permittivity, permeability, thickness, and frequency from the transmission line theory. Therefore, the reflection loss of specimens with material properties is given by the frequency and thickness in a single layer absorber. The equations used for this calculation are described in equations (1)–(3) [3, 4, 7]:

$$\Gamma = \frac{Z_{in} - Z_{out}}{Z_{in} + Z_{out}} = \frac{\overline{Z} - 1}{\overline{Z} + 1}, \tag{1}$$

$$\overline{Z} = \frac{Z_{in}}{Z_{out}} = \sqrt{\frac{\mu_r}{\varepsilon_r}} \tanh\left(j \frac{2\pi}{\lambda} \sqrt{\mu_r \cdot \varepsilon_r} \cdot t \right), \tag{2}$$

$$\text{reflection loss (dB)} = 10 \log |\Gamma|^2 = 20 \log \frac{|\overline{Z} - 1|}{|\overline{Z} + 1|}, \tag{3}$$

where λ is the wavelength of the incident plane wave in free space and j is the unit complex number. The reflection coefficient Γ was described in equation (1), and when $\Gamma = 0$ (where $\overline{Z} = 1$), perfect absorption occurred. The ratio of incident and reflected impedance on absorbing wall with reflector could be calculated by complex permittivity (ε_r), complex permeability (μ_r), and thickness (t). The reflection loss was also calculated by calculating the reflection coefficient.

Figure 4 shows the calculated results of reflection loss of specimens. NZF showed the matching frequency at 4.2 GHz in the case of a 6 mm thick specimen, and the matching frequency was changed by the thickness of the specimen. NZF_c1 showed the matching frequency at 2.9 GHz in the same thickness. The matching frequency and absorbing range were changed by thickness and the content of Ketjen black. The specimens which attenuate EM wave over 10 dB at 2 GHz were NZF_c1 (7 mm), NZF_c2 (6, 7 mm), therefore, NZF_c2 of 6 mm thickness was selected for the absorbing layer of the repeat antenna.

According to an additional experiment, ferrite-loaded glass-fabric and epoxy composite showed quite similar results as with glass-fabric and epoxy composite in reflection loss in Fig. 5, because the glass-fabric layer is made of glass-fabric and epoxy, which materials have very low dielectric loss and tangent loss. Surely, these materials have a certain value of permittivity below 10; however, they have a very low complex term, which can hardly affect the reflection loss.

3. Structural Analysis

3.1. Fabrication of Specimen

The specimens for tensile and bending tests were fabricated in a laminated structure with an absorbing layer and a glass-fabric/epoxy layer as shown in Fig. 6. The composition of NZF_c2 was used to fabricate the absorbing layer with a 6 mm thickness which was selected through the process of material design. The epoxy-mixed composite was compressed at 1 MPa in mold and cured for one hour at 60°C. After curing, the glass-fabric with epoxy was compressed on both sides of the

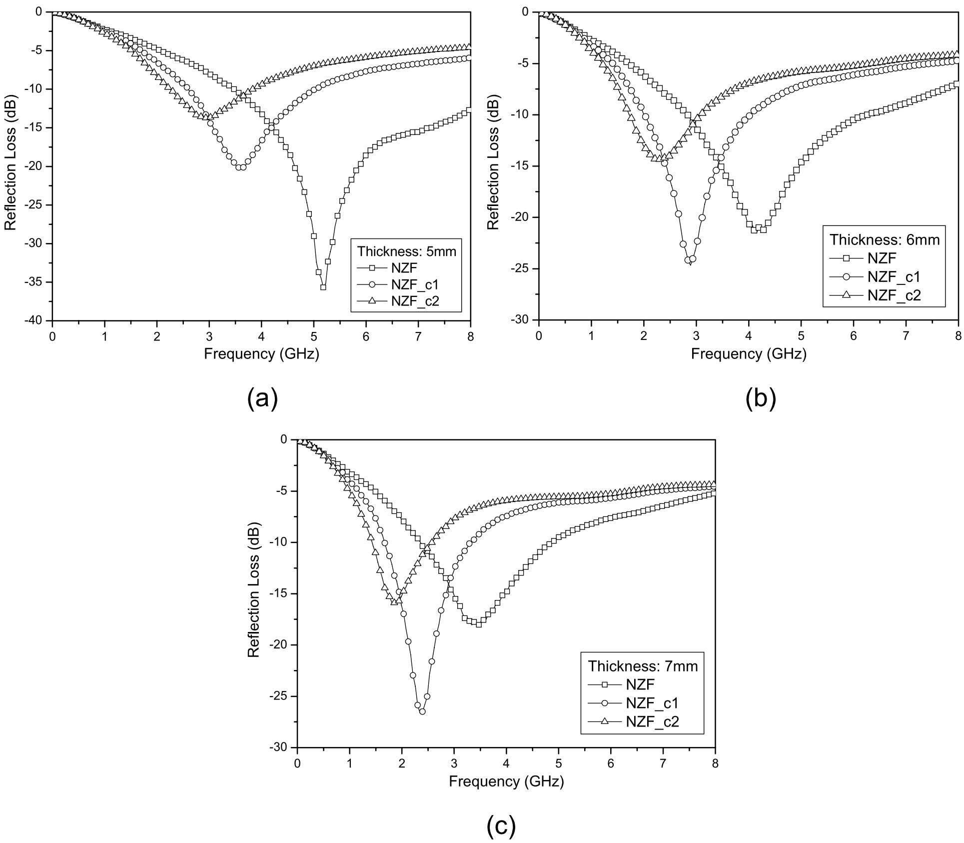

Figure 4. Reflection loss calculated by material properties: (a) 5 mm thick; (b) 6 mm thick; and (c) 7 mm thick specimens (starting frequency is 0 GHz).

absorbing layer. Total thickness became 9 mm (+0.2/−0.2) and four plies of glass-fabric were used in each side. The composites of glass-fabric/epoxy with absorbing layers were cured for two hours at 60°C.

3.2. Tensile and Bending Test

Tensile and bending tests were carried out to evaluate mechanical properties. The tensile test was conducted at room temperature using ASTM D638-02a with a dynamic material testing machine (8801, Instron, USA). The constant crosshead speed was 0.05 mm/s. Three specimens were tested and Poisson's ratios were obtained with a strain gauge. Figure 7 shows specimens after tensile tests, and the results are presented in Table 3. Each tensile modulus has a large deviation, and the combined effect of the multi-materials in the three-layer specimen might cause this deviation.

Three-point bending tests were performed at room temperature using ASTM D790-03 and a universal testing machine (LR50K-Plus, Lloyd Instruments Ltd.,

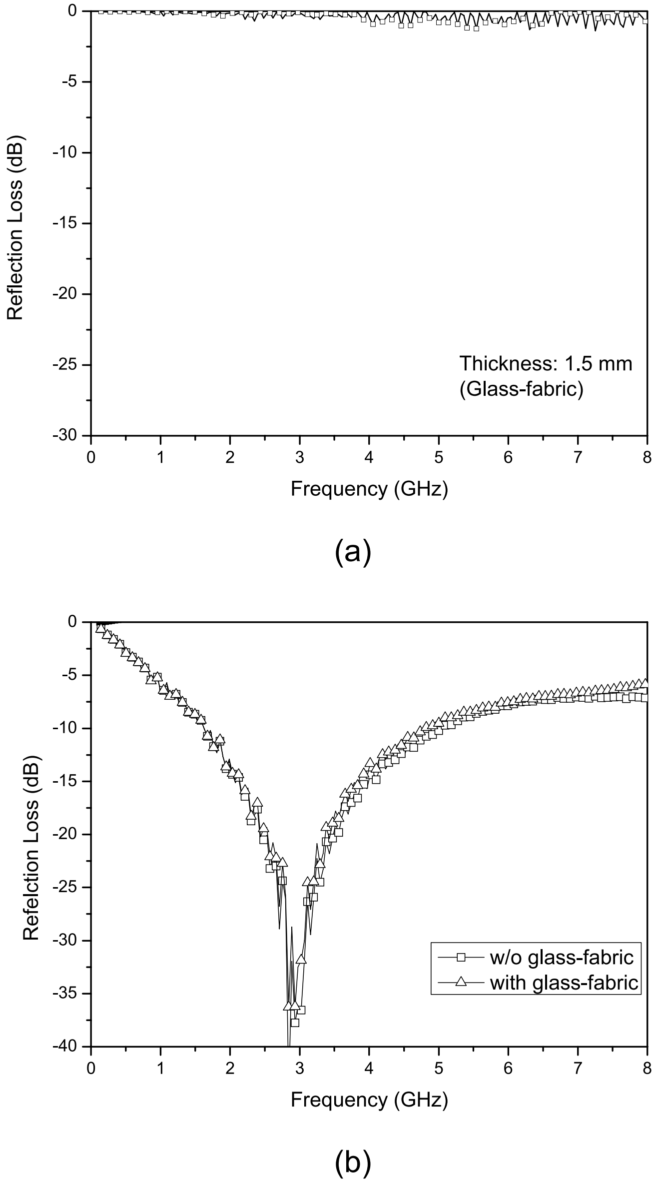

Figure 5. Reflection loss calculated by material properties (starting frequency is 0 GHz): (a) glass-fabric; (b) compare specimens (with glass-fabric and epoxy composite).

UK). The results of the bending tests are presented in Table 4. Bending strength and modulus were more uniform and higher than those from tensile tests. The result might be obtained from the more uniform material properties in the glass-fabric than those in the absorbing layer because the outer layers, glass-fabric, dominate the properties for bending.

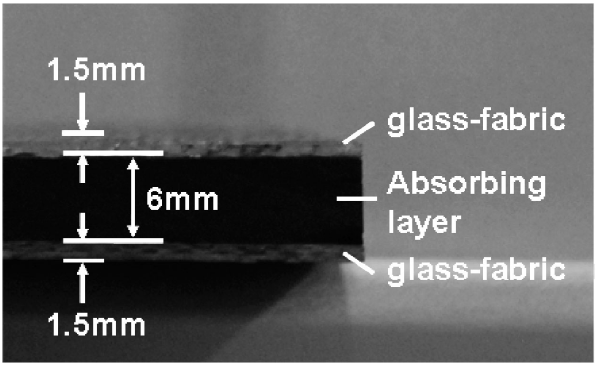

Figure 6. Cross-section photograph of specimen.

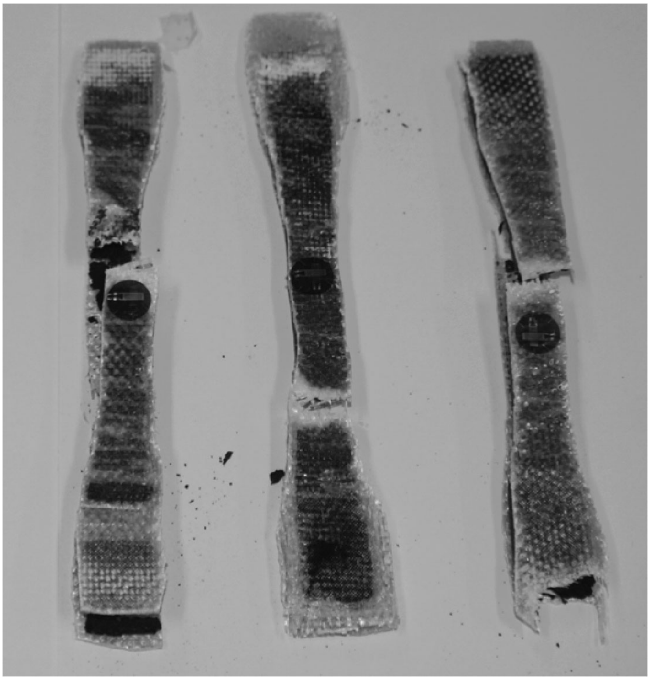

Figure 7. Specimens after tensile test.

Table 3.
Result of tensile test

No.	Tensile strength (MPa)	Poisson's ratio	Tensile modulus (GPa)
1	78.25	0.18	12.00
2	73.14	0.23	10.50
3	79.50	0.16	5.10
Average	76.96	0.19	9.20

Table 4.
Result of three-point bending test

No.	Max. load (N)	Flexural strength (MPa)	Elastic modulus (GPa)
1	386.44	109.78	14.83
2	389.12	142.17	21.62
3	440.79	153.91	18.98
4	430.91	147.71	17.07
5	433.05	139.88	16.51
Average	416.06	138.69	17.80

3.3. Finite Element Method (FEM)

A structural analysis of the repeat antenna was conducted by FEM to test for its integrity under wind pressure, especially in response to wind. The overall size of a repeat antenna is 484 mm in length, 400 mm in width, and 10 mm in depth. The wind pressure was estimated in accordance with JIS B 8830 (ISO 4320: Wind load assessment) as shown in equation (4):

$$F = C \cdot q \cdot A, \tag{4}$$

where F: wind force (N), C: force coefficient, q: wind pressure (N/m^2), A: load area (m^2).

Here, the force coefficient is 1.2 when the aspect ratio of pressured section is below 5. The wind pressure varies with altitude from the ground, and satisfies equation (5) in a typhoon condition (55 m/s).

$$q = 980\sqrt[4]{h}\ (\text{N/m}^2), \tag{5}$$

where h: altitude from the ground (m^2).

In the calculated result, the repeat antenna received a wind force of 1077 N at 500 m height in typhoon condition (55 m/s) as shown in Fig. 8. Boundary conditions were kept limited, and it was assumed that the antenna was completely fixed to the part of joint illustrated as in Fig. 9.

ANSYS was used for the analysis, and SOLID187 (3-D 10-Node Tetrahedral Structural Solid) was used for element. The properties used in the analysis are shown in Table 5 [16] and Table 6.

The results of the structural analysis are presented in Table 7 and Fig. 10.

To compare aluminum and composite packages under the same conditions, an analysis of an aluminum antenna with a 9 mm thickness in 50 m height was additionally conducted, and it showed a maximum displacement of 0.054 mm and the maximum von-Mises stress of 10.22 MPa. For the other side, the analysis result of the composite antenna was a maximum displacement of 0.42 mm and the maximum von-Mises stress of 11.68 MPa. The composite antenna had higher dis-

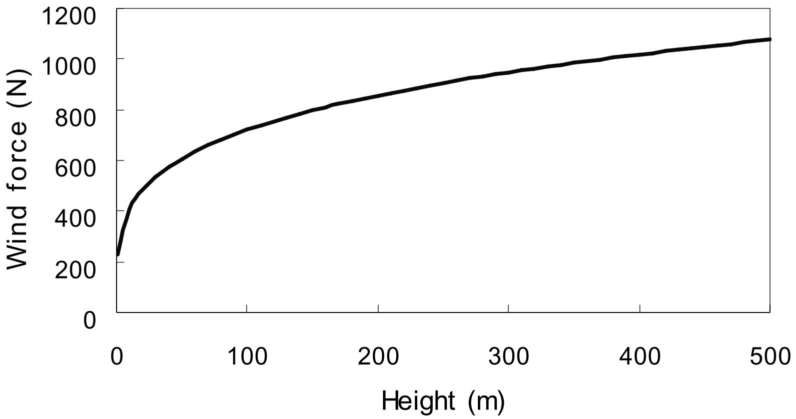

Figure 8. Wind force graph depending on altitude in typhoon condition.

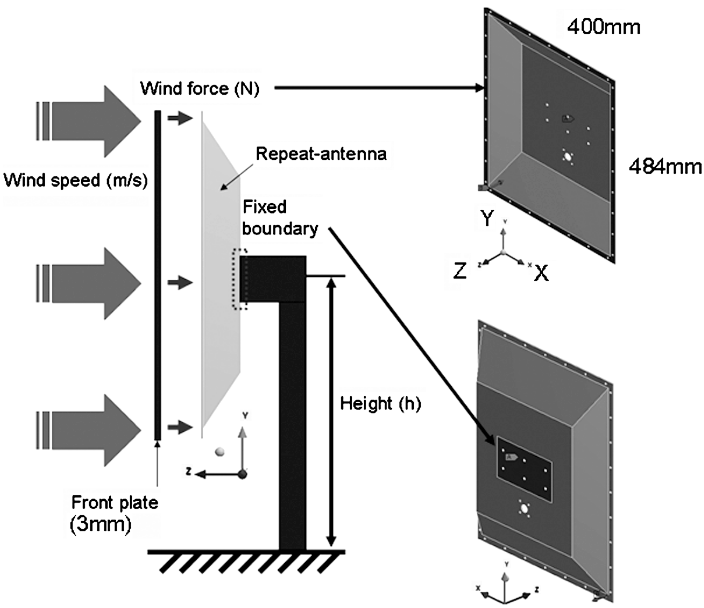

Figure 9. Schematic diagram of repeat antenna for structural analysis.

Table 5.
Properties of Al6061-T6 [16]

Density (kg/mm^3)	Elastic modulus (GPa)	Poisson's ratio	Shear modulus (GPa)
2.70e–6	68.90	0.33	26.00

Table 6.
Properties of ferrite-loaded glass-fabric/epoxy composites

Direction	Density (kg/mm^3)	Elastic modulus (GPa)	Poisson's ratio	Shear modulus (GPa)
X or XY	2.82e–6	9.20	0.199	3.84
Y or YZ	2.82e–6	9.20	0.385	3.32
Z or XZ	2.82e–6	17.80	0.385	6.43

Table 7.
Results of structural analysis

Material	Thickness (mm)	Altitude (m)	Max. displacement (mm)	von-Mises stress (MPa)
A16061-T6	3	50	0.78	68.80
	9	50	0.05	10.22
Composite	9	50	0.40	11.53
	9	200	0.57	16.31
	9	500	0.72	20.51

placement and stress than the aluminum antenna, but those values do not affect the antenna's ability or structural safety.

An analysis of the composite antenna was done against the wind pressure of a typhoon when installed at 500 m altitude. From the results, we were able to conclude that the composite antenna was safe enough because its maximum von-Mises stress (21.5 MPa) was lower than tensile strength (77.0 MPa) and bending strength (138.7 MPa).

4. Conclusions

An EM wave absorbing layer for the repeat antenna which attenuates EM wave over 10 dB at 2 GHz was designed and fabricated. The composition and fabrication procedures of the EM wave absorbing material were presented with the measurement method. These experimental procedures revealed that the thickness of the layer and the amount of the conductive material were parameters of material design that were crucial for selecting suitable conditions of the absorber because they increased the dielectric loss and changed the matching frequency of Ni–Zn ferrite/epoxy absorber. Tensile and bending tests were conducted to obtain mechanical properties for structural analyses, and the results showed high strength and modulus. Structural analyses were conducted under maximum wind pressures. The repeat-antenna system with ferrite-loaded glass-fabric/epoxy composites was strong enough to be installed outdoors.

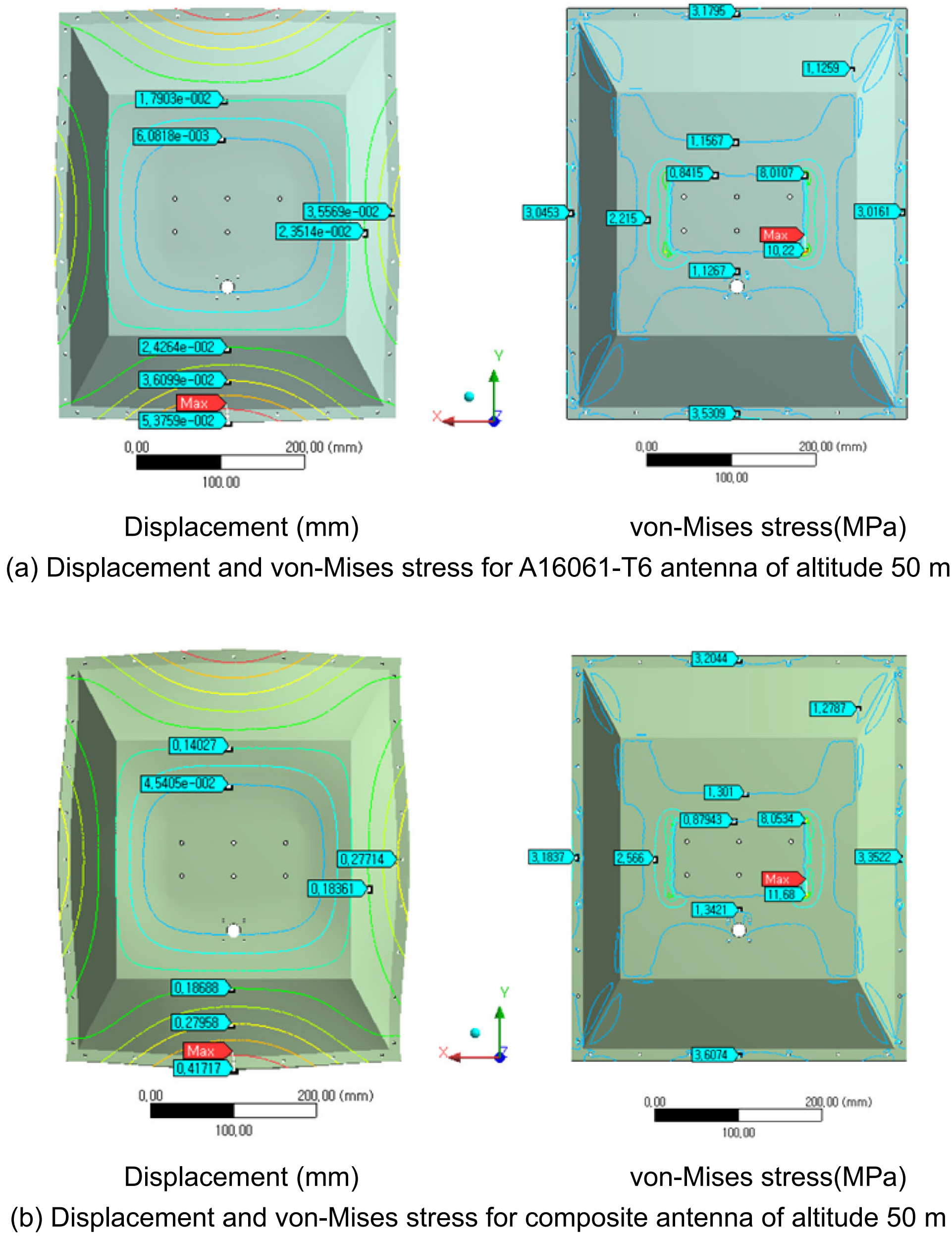

Figure 10. The result of analysis: (a) thickness 9 mm, altitude 50 m, A16061-T6; (b) thickness 9 mm, altitude 50 m, composite. This figure is published in color online, see http://www.brill.nl/acm

In order to ensure the effectiveness of ferrite-loaded glass-fabric/epoxy composites, further experiments such as temperature and humidity test for environmental test are necessary. For the material design, various conductive materials such as carbon nanotubes and carbon nanofibers should be considered to further reduce the weight of the repeat antenna.

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