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The fatigue strength and life of a GFRP composite bogie frame for urban subway trains were evaluated in this study. The GEP224 glass fabric/epoxy was selected as the structural material of a composite bogie frame to save its weight. In order to obtain the fatigue characteristics of the GEP224 glass/epoxy composite material, the tension–compression fatigue test was done with three different stacking sequences of warp direction, fill direction, and warp/fill direction, respectively. A fatigue test was conducted with a stress ratio, R of 0.1 and -1, and up to endurance limit of 10^7 with frequency of 5 Hz. The fatigue strength of the GFRP composite bogie frame was evaluated on the basis of the S-N curve and Goodman diagrams obtained from GEP224 glass/epoxy composites according to the JIS E 4207 and UIC 515/615-4. The result shows that fatigue strength of the GFRP composite bogie has satisfied the design requirements. Also, the GFRP composite bogie frame had a good fatigue performance in comparison with conventional metal bogie frame, considering its weight.

Keywords: GFRP composite bogie frame; fatigue life and strength; tension–compression fatigue; Goodman diagram; S-N curve

1. Introduction

Railway vehicles known as green transportation have advantages such as higher energy efficiency and transportation capacity in comparison with other forms of ground transportations. The improvement of design technology for railway vehicles is helping to more strengthen these advantages. In addition, the railway vehicles can lead to improved speed, load capacity, and ride comfort through the weight saving of carbody structures.[1,2] The optimum design and material substitution technique are widely used to reduce the weight of railway vehicles. While the optimum design technique produces the limited lightweight effects, the replacement of materials would be expected to produce a considerable reduction in weight.[3] Composite materials are generally applied to forms of ground transportations for lightweight design because they have higher specific stiffness and strength compared to conventional vehicle materials such as steel and aluminum.[4,5] In particular, the glass fabric/epoxy composite

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material is strongly recommended for railway applications as lightweight materials due to low material cost, easy managing, and mass marketing.[6] The bogie of railway vehicle, which supports the weight of carbody and passengers, is a primary structure subjected to the repeated external loading between rail and wheel. In order to have enough strength and stiffness against the external loading, bogie frames were generally made of solid steel or welded structures based on metal materials, such as SM490A. The weight of the bogie makes up approximately 37% of the total vehicle weight. Thus, the weight reduction of the components composed of the bogie system must be an essential item for the lightweight design in company with carbody structure of the railway vehicle. For this reason, the use of a polymer-based composite material has been attempted for bogie frames. Shin and Hahn [7] have evaluated the structural integrity under ground environments of hybrid railway carriage made of composite materials. This study showed that the design requirements of hybrid railway carriage structures made of composite materials is satisfied. Ko and Shin [8] studied a numerical evaluation on crashworthiness and rollover characteristics of a low-floor bus vehicle made of sandwich composites. They have suggested that effective equivalent damage model for composite sandwich panel could reduce the time of calculation and modeling work without error between the real and effective models. Geuenich and Leo et al. [9] built the world's first bogie frame made of advanced glass fiber composite. It is found that the use of composite element for the frame of the bogies gives a weight reduction of approximately 25%, enabling minimization of power capacity, energy consumption, and wear. Maurin et al. [10] studied mechanical reliability of the side beam of the composite-based bogie frame. The FBG sensor was used as *in situ* transducers for mechanical reliability assessment. Also, a 1,600,000 cycles' fatigue test of composite bogie frame was conducted. In this study, it was found that the ultimate load of composite side beam before the first failure appears to be greater than 350 kN. Kim [11] has developed a GFRP composite bogie frame for replacing a conventional steel bogie with weight saving. The load test of bogie frame under the critical operating conditions having vertical and twisting loads was performed. This study showed that the bogie frame made of composite has satisfied design requirements under various load conditions.

The bogie of railway vehicles was serviced under the long-term external environments for approximately 30 years, and their service life was greatly affected by vibration and repeated external loads that may occur in operation. The fatigue failure of the bogie frame could occur in long-term service life.[12] In particular, the fatigue characteristics of composite materials used for the lightweight of bogie frame has critical factors to assure its service safety. Therefore, the fatigue performances of composite materials applied to the bogie frame should be verified prior to running on track.

In this study, the structural safety of a composite bogie frame for urban subway train was evaluated. The fatigue test of a GEP224 glass fiber/epoxy 4-hareness satin-woven composite material applied to the bogie frame was performed to obtain three S-N curves of warp [0°], fill [90°] and warp/fill [0°/90°] directions under tension–compression loading condition. The Goodman diagrams of a composite material were also obtained for three directions from fatigue test. Then, the fatigue strength of bogie frame was assessed according to the JIS E 4207 and UIC 615-4 standards.

2. GFRP composite bogie frame

2.1. Configuration of a composite bogie frame

The external shape of the composite bogie frame is similar to the conventional one as shown in Figure 1. It has two side beams and two crossbeams. The composite side beam is

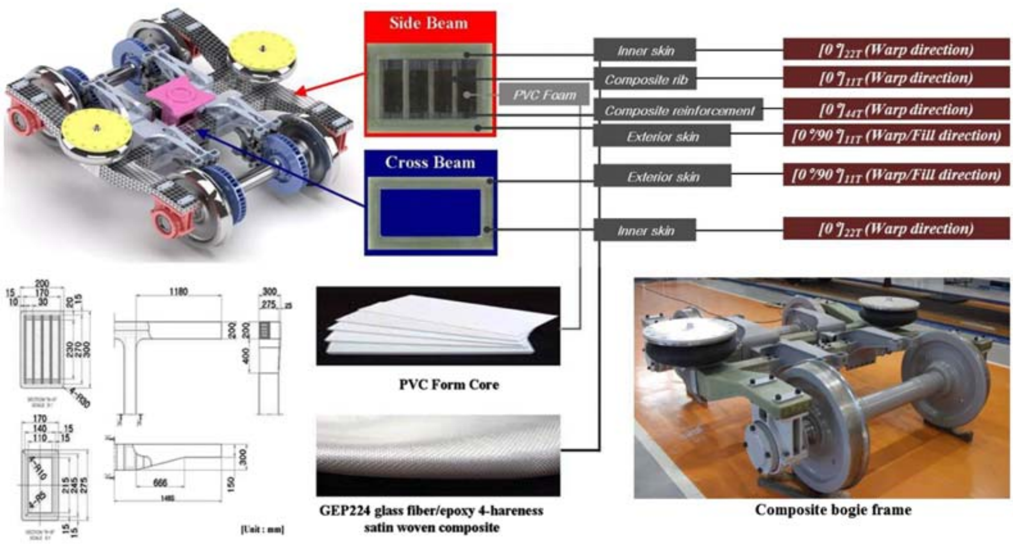


Figure 1. Configuration and design concept of a GFRP composite bogie frame.

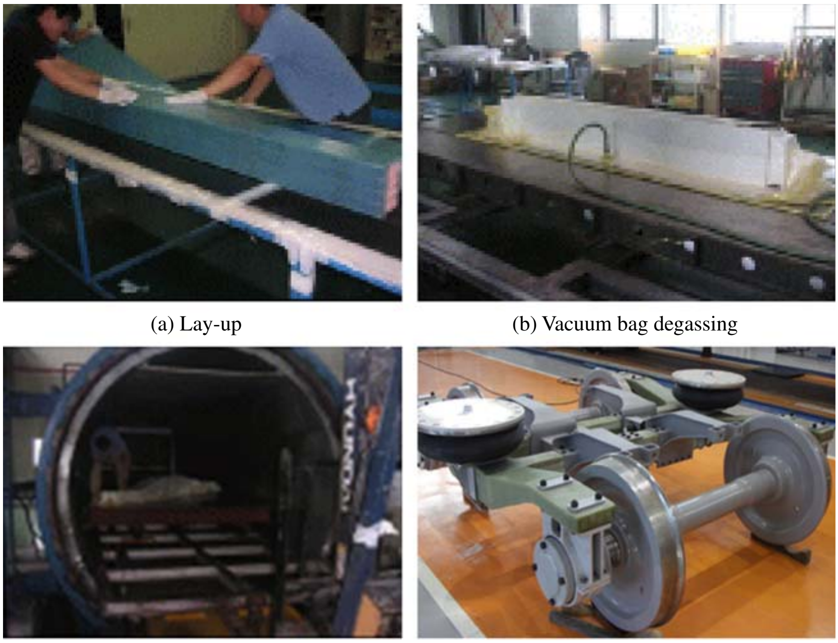
2970 mm long and 2170 mm wide. In order to meet the structural design requirements, the inside of the side beams of the proposed composite bogie frame was filled with the following structural parts; composite reinforcement, ribs, inner skin, exterior skin, and foam cores. In this study, the 4-harness satin fabric glass/epoxy prepregs (GEP224, SK Chem., Korea) were stacked up on the inner structural part form skin. Figure 3 shows the schematic representation of 4-harness satin-woven composite. The notation used this study to identify the layup of the 4-harness satin-woven composite is similar to the one used for unidirectional composite where all angles refer to the direction for the warp fiber.

2.2. Manufacturing procedures of a composite bogie frame

The reinforcement, composite rib, inner skin, and exterior skin of bogie frame were laid up according to each stacking sequence using 4-harness satin fabric glass/epoxy prepregs (GEP224). The Airex® foam of Alcan Composites was inserted between the ribs to fill the space. Table 1 lists the material properties of the GEP224. In order to obtain bending stiffness and sustain the compressive force imposed on the longitudinal direction, the composite reinforcement and inner skin were laid up to warp $[0°]_n$ direction. To obtain high in-plain shear property, the exterior skin was laid up to warp/fill $[0°/90°]_n$ direction that intersect each layer. The composite bogie frame was curried using autoclave under 80 and 125 °C temperature cycles with a pressure of 6 bar. After the manufacturing of the inner structural part, the

Table 1. Tensile and compressive properties of a GEP224 glass fabric/epoxy composite.

GEP224 glass fabric/epoxy (stacking sequence)	Tensile		Compressive	
	Modulus (GPa)	Strength (MPa)	Modulus (GPa)	Strength (MPa)
Warp direction	34.42	636.06	34.05	565.58
Fill direction	13.19	106.98	13.83	217.12
Warp/fill direction	24.25	402.82	23.86	425.23



(a) Lay-up (b) Vacuum bag degassing

(c) Curing (d) GFRP composite bogie frame

Figure 2. The manufacturing procedures of GFRP composite bogie frame.

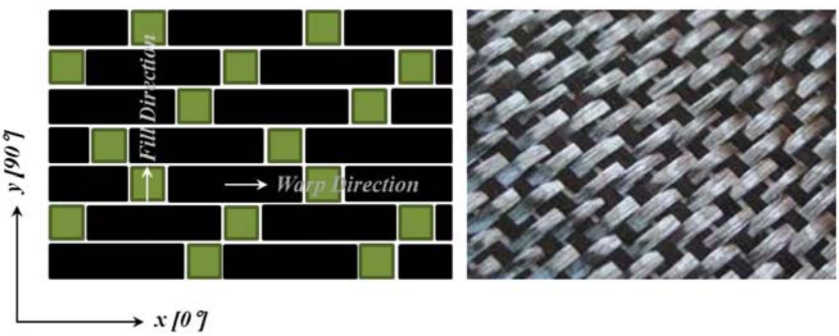


Figure 3. The schematic representation of 4-harness satin-woven composite.

two crossbeams and the two side beams were assembled by an adhesively bonded method using FM73 film. The final product weighed 145 kg. Figure 2 shows the manufacturing procedures of a GFRP bogie frame.

3. Evaluation of fatigue life for a composite material

3.1. Test method

In order to obtain the S-N curves, the fatigue test of the GEP224 glass fabric/epoxy composite applied to the bogie frame was performed for warp, fill and warp/fill directions under tension–compression load condition using dynamic test machine (MTS-810) according to the

ASTM D 3479.[13] A frequency of 5 Hz, at which the temperature rise in the test specimen can be almost ignored during the test, was selected,[14] and a stress ratio (R) of −1 was applied. The five specimens were used for each stress level. The endurance limit was selected as 10^7 cycles, which is common for the composite fatigue test. The mechanical properties of tensile and compressive failure strength were obtained for three directions according to ASTM D 3039 [15] and ASTM D 3410 [16] prior to the fatigue test. Table 1 shows the tensile and compressive properties of the GEP224 glass fabric/epoxy composite material.

The fatigue test of composite materials is generally conducted for two different types of tension–tension and tension–compression by reason of difference in between tensile and compressive properties. In this study, GEP224 glass fabric/epoxy composite was tested by tension–compression fatigue because tension and compression load was dominating due to vibration of the carbody and wheel-set during operation. The tension–compression fatigue of a composite material may be typified by difficulties in testing, such as buckling of specimens

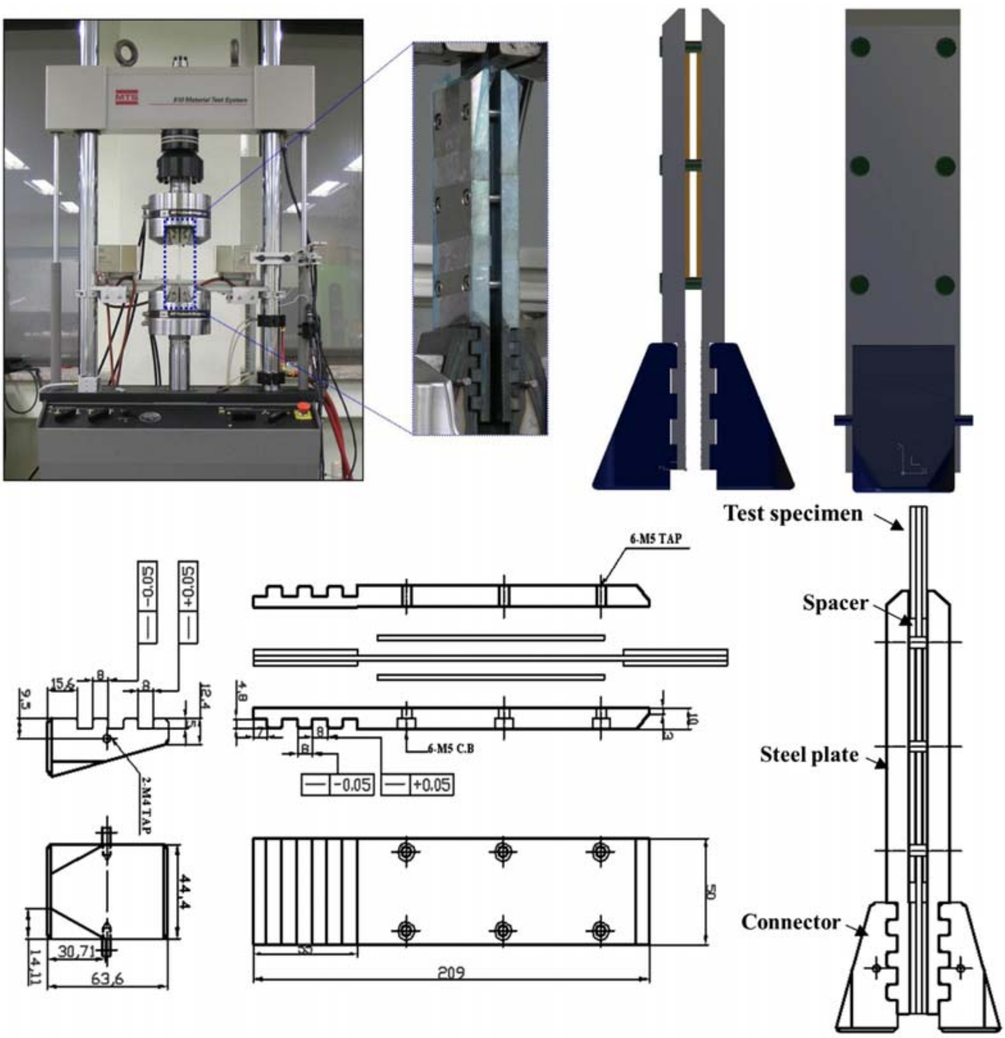


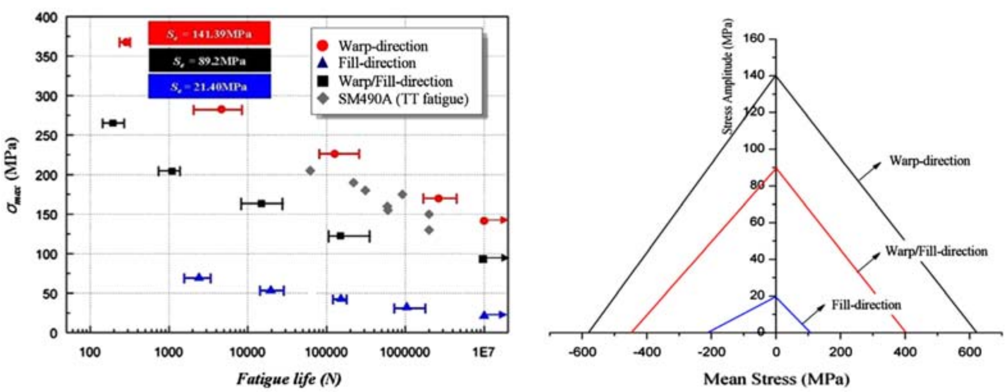
Figure 4. Fatigue test instrument and the modified antibuckling jig.

and lack of control of the stress state. Also, the delamination and crack tip opening can occur even in a compression region. For this reason, the composite shows shorter fatigue life in tension–compression test than in tension–tension test. And, the additional buckling caused by compression load makes it difficult to evaluate fatigue life. Curtis [17] suggested the anti-buckling jig to prevent the buckling during the compressive loading. In this study, the modified antibuckling guide was introduced and designed to evaluate the tension–compression test of composite laminate. The antibuckling jig suggested by Curtis was composed of side steel plate, spacer, connector, and the bottom of steel plate. The modified antibuckling jig used in this study has a grip part of bottom steel plate manufactured by knurling to hold a specimen. The connector was designed to transfer fatigue load according to slot cutting. However, the friction force would occur by contact between jig and specimen under compressive load. Therefore, Teflon film was used to prevent the fraction force between jig and specimen during the fatigue test. Also, the support pins were added to maintain a distance between steel plate and specimen for the minimum fraction force.[18] Figure 4 shows the modified antibuckling jig and dynamic test machine for fatigue test.

3.2. *Fatigue test results*

The GEP224 glass fabric/epoxy composite applied to the bogie frame was composed of the crossing of the fiber bundles, which runs in the warp direction and fill directions, at every four times. It gives different fatigue characteristics according to fiber directions. Accordingly, the fatigue test should be conducted for warp direction, fill direction, and warp/fill direction of a composite material. For the tension–compression fatigue test, five different stress levels were selected between 20 and 65% of the tensile and compressive strengths of each direction.

Figure 5(a) shows the S-N curve of the GEP224 glass fabric/epoxy and SM490A steel for maximum stress. In order to compare the fatigue characteristics between metallic material and composites applied to bogie frame, the SM490A steel material has also been considered for fatigue test. The fatigue strength of the composite at endurance limit of 10^7 was 141 MPa in the warp direction, 21 MPa in the fill direction, and 89 MPa in the warp/fill direction. The fatigue strength of SM490A was 155 MPa for nonwelded part and 110 MPa for the welded part with grinding.[19] It was found that fatigue characteristics and life of the glass fabric/epoxy composite in warp direction were better than those of the welded parts of SM490A.



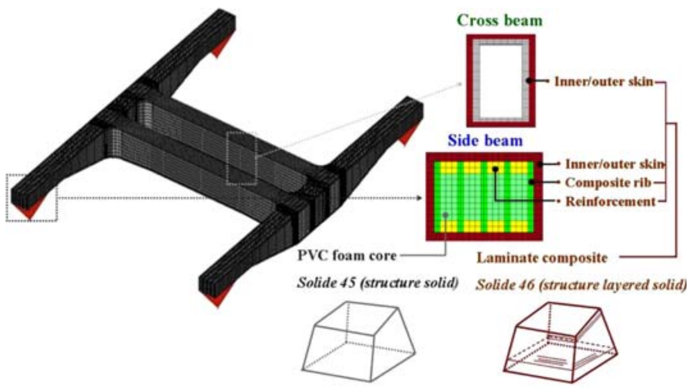
(a) S-N curve (b) Goodman diagram

Figure 5. The fatigue test results of GEP224 glass fiber/epoxy 4-harness satin-woven laminate composite.

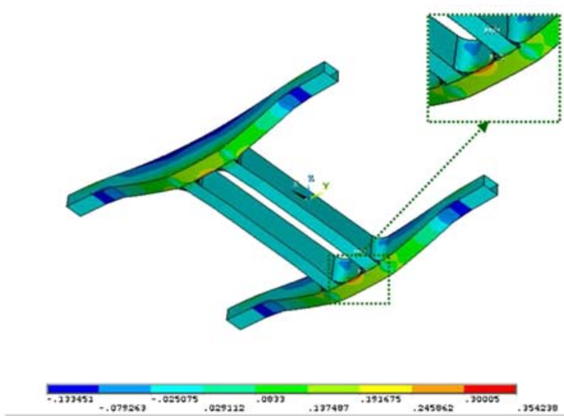
Therefore, the GEP224 glass fabric/epoxy laminate composite has many advantages of application in bogie frames due to good fatigue performance and weight savings. Figure 5(b) shows the Goodman diagram of the composite material in each fiber direction.

4. Evaluation of fatigue strength for a composite bogie frame

In general, a bogie frame is designed in accordance with regulations such as KS R 9210,[20] JIS E 4207/4208,[21], and UIC 515/615-4 [22] in Korea. However, in order to be internationally recognized for product, the evaluation of fatigue strength for railway bogie frames has been made mainly under the load conditions specified by JIS E 4207 and UIC 615-4. The present study has evaluated the fatigue strength in accordance with JIS E 4207 and UIC 615-4 for comparison with existing metallic railway bogie frames. According to the JIS E 4207, a static structural analysis was conducted based on vertical, lateral, twisting, and breaking loads. Based on these stress results, the fatigue stress by a combined load was subsequently derived. In UIC 615-4, the fatigue strength is evaluated depending on main in-service loads caused by operation of vehicles. In case of an anisotropic laminate composite bogie frame, the fatigue strength should be evaluated using stress results calculated in each fiber direction.



(a) Finite element model



(b) The contour of Tsai-Wu failure index

Figure 6. The FE model and Tasi–Wu failure index for a composite bogie frame.

4.1. Structural integrity of a GFRP composite bogie frame

To evaluate the fatigue strength of the composite bogie frame, a static structural analysis was firstly conducted under various load conditions. On the basis of results of static structural analysis, the fatigue stress by a combined load was subsequently derived.

Figure 6(a) shows the finite element (FE) model used for structural integrity analysis of the bogie frame. The static analysis of the composite bogie frame was done using Ansys v11.0, a FE analysis program. The 3D layered solid element(solid 46) was used for the reinforcement, ribs, and inner and outer skins and 3D solid element(solid 45) was used for the PVC foam core. The number of nodes and elements for the FE model was 144,515 and 158,176, respectively.

The static analysis of the bogie frame was based on both of JIS E 4207 and UCI E 615-4. In the analysis, vertical, lateral, and twisting loads generated during operation of a bogie frame were considered. Table 2 shows load cases used for the structural analysis of the bogie frame. Empty weight, passenger load, and full weight were used to obtain the load condition.

The Tsai–Wu failure criterion was used for failure evaluation of composite bogie frame. From the static structural analysis results, the maximum value of Tsai–Wu failure index was 0.38. Therefore, the composite bogie frame satisfied the design requirements. Figure 6(b) shows the results of the Tsai–Wu failure index of composite bogie frame. Figure 7 shows the orthogonal directional stress results of a bogie frame under twisting load condition. The maximum stress of a bogie frame on the warp direction was 129.3 MPa. And, the fill direction stress was 82.3 MPa. The orthogonal directional stress of a bogie frame under twisting load was lower than directional failure strength of GEP224. Table 3 lists the orthogonal directional stress results of a bogie frame under every load condition.

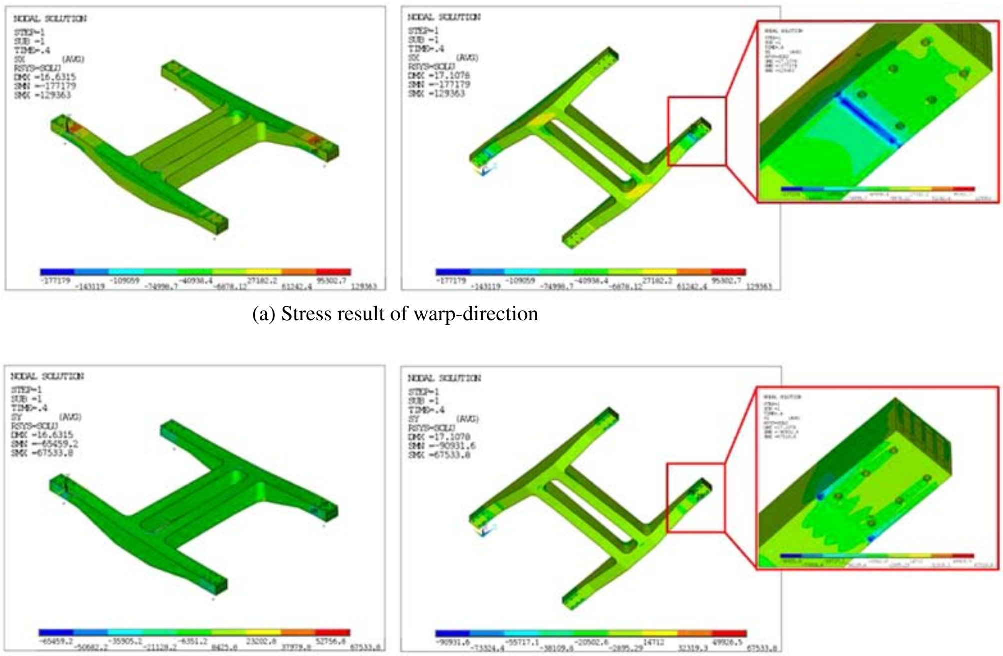
Table 2. Load cases for a GFRP bogie frame.

Load case	Vertical load		Twisting		Lateral load	
JIS E 4207	$F_{V1.3}$	$F_{V1.0}$	F_{T1}	F_{T2}	F_{A1}	F_{A2}
1	178,542 N					
2		137,340 N				
3		137,340 N	−15 mm	−15 mm		
4		137,340 N			93,195 N	
5		137,340 N				93,195 N

$F_{V1.3}$: Vertical load under 1.3 g
$F_{V1.0}$: Vertical load under 1.0 g
$F_{T1,\ T2}$: Displacement for bogie frame under twisting load case
$F_{A1,\ A2}$: Lateral load for bogie frame on reft or right side frame

UIC 515/615–4	F_{Z1}, F_{Z2}	F_{Z1}, F_{Z2}	G	F_Y
	Exceptional load	Main in-service load		
1	202,324 N			
2		155,593 N	$10^0/_{00}$	
3		155,593 N	$10^0/_{00}$	
4		155,593 N		94,075 N
5		155,593 N		−94,075 N

$F_{Z1,\ Z2}$: Vertical load under exceptional and main in-service load case
G: Track twisting under main in-service load case
F_Y: Lateral load for bogie frame on left or right side frame
$^0/_{00}$: Permill



(a) Stress result of warp-direction

(b) Stress result of fill-direction

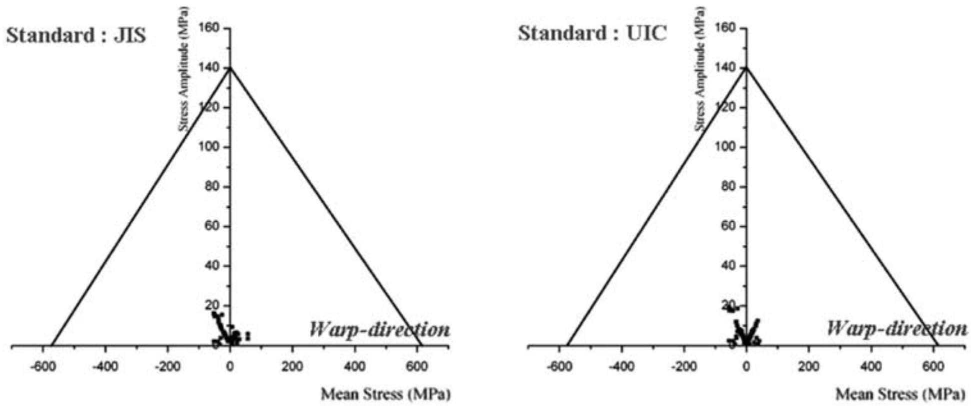
Figure 7. The results of orthogonal directional stress of a bogie frame under twisting load condition.

Table 3. Structural analysis results of GFRP bogie frame.

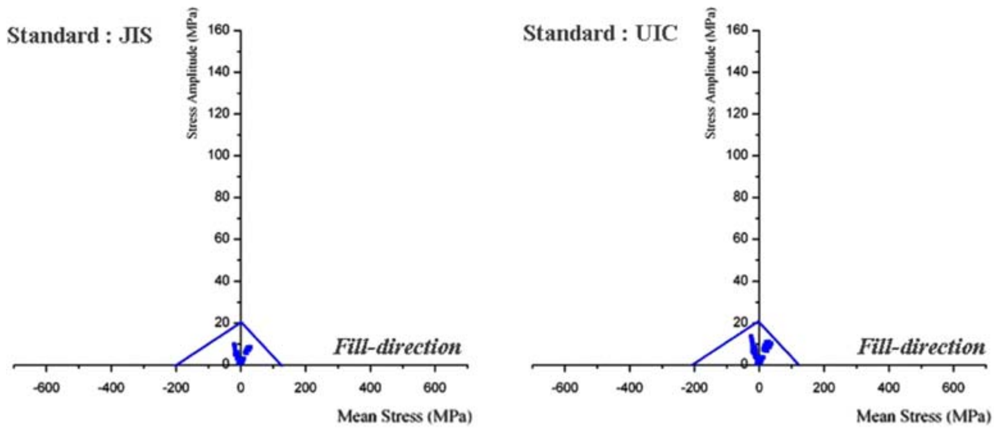
	JIS E 4027			UIC 515/615-4		
	Maximum orthogonal stress (MPa)		Tsai-Wu index value	Maximum orthogonal stress (MPa)		Tsai-Wu index value
	Warp direction [0°]	Fill direction [90°]		Warp direction [0°]	Fill direction [90°]	
Load case 1 (vertical)	58.1	33.7	0.32	67.5	39.2	0.34
Load case 2 (twisting)	129.3	67.5	0.35	137.2	82.3	0.38
Load case 3 (twisting)	129.3	67.5	0.35	137.2	82.3	0.38
Load case 4 (lateral load)	49.1	26.7	0.31	54.3	31.2	0.31
Load case 5 (lateral load)	49.1	26.7	0.31	54.3	32.1	0.31

4.2. Fatigue strength of GFRP composite bogie frames

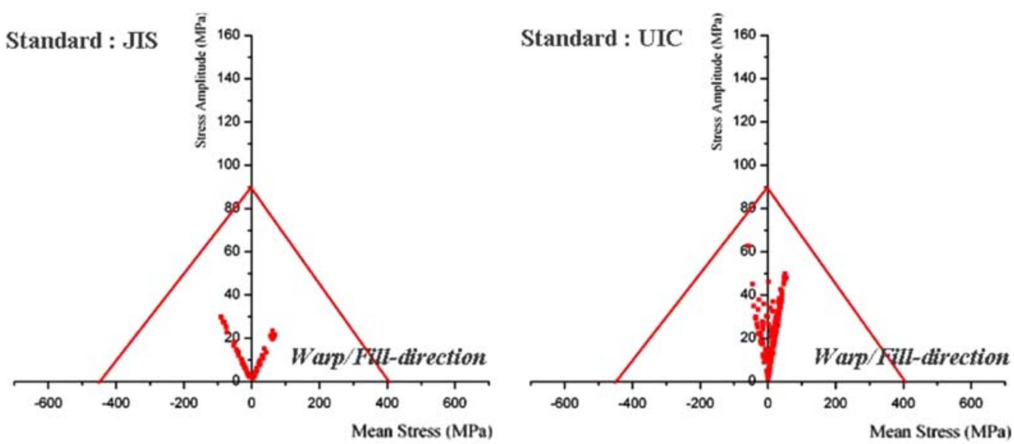
Based on the stress results obtained from static analysis, the mean stress and stress amplitude were drawn, and then applied to Goodman diagram of each-direction, and accordingly fatigue strength was evaluated by Equation (1). The stress value of static analysis result was used for evaluation of fatigue life and strength of a GFRP bogie frame. The stress results of nodes located at the point of maximum stress value were presented in the form of mean stress and stress amplitude in accordance with Equations (2) and (3).



(a) Reinforcement and inner skin for warp-direction



(b) Reinforcement and inner skin for fill-direction



(c) Exterior skin for warp/fill-direction

Figure 8. The results of fatigue life and strength for components of a composite bogie frame.

$$\frac{\sigma_a}{S_e} + \frac{\sigma_m}{S_u} = 1 \tag{1}$$

$$\sigma_m = \frac{(\sigma_{max} + \sigma_{min})}{2} \tag{2}$$

$$\sigma_a = \frac{(\sigma_{max} - \sigma_{min})}{2} \tag{3}$$

where S_e is the endurance limit of a material. S_u is the ultimatum stress of material. σ_a is the amplitude stress. σ_m is the mean stress. Figure 6 shows the fatigue life and strength of the composite bogie frame according to JIS and UIC regulations. Generally, for a metallic bogie frame made of an isotropic material such as steel, the Goodman diagram based on the fatigue limit is presented with only a single diagram. However, in the case of a composite bogie frame with orthotropic property, the Goodman diagram is drawn depending on each direction. Therefore, the fatigue strength of a composite bogie frame should be evaluated for each stacking sequence applied to its components.

The reinforcement core material inside beam was stacked with a single direction and inner skin of the crossbeam has laid up in warp direction and fill direction. The exterior skin of a bogie frame has been stacked with warp/fill direction.

From the results of evaluation of the fatigue strength for the composite bogie frame shown in Figure 8, the highest level of mean stress and stress amplitude was found in the exterior skin with a stacking sequence of warp/fill direction, while the lowest level of mean stress and stress amplitude was found in the interior skin of the crossbeam and reinforcement core materials with a unidirectional stacking sequence. Also, it was found that all mean stress and stress amplitude in the bogie frame were lower than the fatigue limit of the Goodman diagram of each composite direction. This means that the bogie frame made of the glass fiber/epoxy 4-harness satin laminate composite has a life cycle of over 10^7, which is the endurance limit. Therefore, the result showed that the GFRP composite bogie frame had a good fatigue performance over the conventional metal bogie frame, considering its weight.

5. Conclusion

In this study, the fatigue characteristics and life of the GEP224 glass fiber/epoxy 4-harness satin-woven composite applied to a bogie frame were evaluated by the tension–compression fatigue test. Also, the Goodman diagrams for each direction were obtained. Then, the evaluation of fatigue strength of a composite bogie frame was performed according to JIS E 4207 and UIC 515/615-4. The conclusions of this paper are as follows:

(1) The fatigue test of a GEP224 glass fabric/epoxy composite was conducted for tension–compression load with a stress ratio, R of 0.1 and -1, and an endurance limit up to 10^7 with frequency of 5 Hz. The modified antibuckling jig was introduced and designed to prevent the buckling during the compressive loading. The Goodman diagrams for each direction of GEP224 glass fabric/epoxy was obtained form S-N curves. It was found that the GEP224 glass fabric/epoxy composite material has many advantages of application in bogie frames due to good fatigue life and weight savings in comparison with the conventional metal materials.

(2) In order to evaluate structural integrity of GFRP composite bogie frame, the static analysis was performed by JIS and UIC regulations. The failure evaluation of the composite bogie frame was conducted using Tsai–Wu failure criterion. In the result of the structural integrity analysis, the composite bogie frame has satisfied the design requirements.

(3) The fatigue strength of bogie frame was evaluated using Goodman diagrams for each direction of a composite material. The results showed that the composite bogie frame has satisfied the requirements of JIS and UIC, and had a good performance in comparison with that of conventional metal bogie frame based on SM490A, considering its weight. In addition, it could reduce the weigh by over 60% and provide fatigue safety equivalent to the conventional metal bogie frame. Based on these results, it would be possible to achieve a lightweight composite bogie frame designed to maximize the weight saving effect of railway vehicles in company with the application in carbody structures of a composite material.

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