FATIGUE LIFE EVALUATION OF BOLT MADE OF WOVEN FABRIC FRP

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Keywords: *GFRP, woven fabric, bolt, FEM, fatigue, reliability, SWT parameter*

Abstract

The bolt made of GFRP, which guarantees the properties such as sufficient electric insulation, is utilized as one of joints. It is important for the design of joint to check the stress distribution of bolt thread and to evaluate the fatigue characteristics.

The purpose of this study is to evaluate fatigue characteristics of GFRP bolt by an analysis considered with anisotropic properties of failure modes. In particular, the results of FEM analysis have been reflected the failure modes of fatigue tests. The stress distributions of bolt thread made by GFRP differ from them made by stainless steel. It is revealed that the difference generates the complex failure modes. We've also proposed a procedure of appreciation for fatigue test data with a scatter. As the confidence level with a probability of failure has been introduced, the S-N diagram for design can obtain even in case of small samples.

1 Introduction

The bolt made of glass fiber reinforced plastic (GFRP) guarantees the properties of anti-corrosion and sufficient electric insulation which are required as joint parts. Considering the effects of cyclic loading worked on the joint parts of structures, the long-term reliability is one of important items to maintain. Therefore, it is very important for a long-term property such as fatigue life to consider the evaluation of reliability.

Mechanical properties of material should be investigated to clarify the stress distribution in the case of damage occurring at the bolt thread root. To obtain the mechanical behaviors of the bolt, three-dimensional finite element analysis and scale of assessments of load calculated with theory based on mechanics of materials are assumed to be indispensable [1]. Some solutions for mechanical behaviors available for a bolt made of isotropic materials have been already published [1]. However, we don't have any paper concerned with the bolt made of GFRP. In addition, the bolt used in this study has been produced by GFRP with plane woven fabric structure. As GFRP bolt is an anisotropic material, the scale of assessments of load on the bolt thread and stress at bolt thread root are quite complicated.

It is necessary for the evaluation of mechanical properties of composite materials to obtain the relation between load and the strength in specific failure modes such as tensile or shear. For these reasons, it is necessary to evaluate the mechanical properties and the design of the bolt with considering these complexities. The purposes of this study are to establish the method of fatigue life evaluation of GFRP bolt based on the reliability and to make clear the characteristics by three-dimensional finite element analysis considered with anisotropy.

2 Experiment of GFRP bolt

2.1. GFRP bolt

2.2.1. Process of manufacturing bolt

GFRP has many advantages like the sufficient electric insulation, low heat conduction, and anti-corrosion. GFRP bolt employed in this study was made of E-glass cloth/epoxy.

The bolt was manufactured by lathe from GFRP plate which is laminated by the plane woven glass cloth with $\pm\theta$ to the axial direction as shown in Fig.1. In this paper, θ is 7° and the volume fraction of glass fiber is about 45%, receptively. It is expected that the bolt can perform good tensile strength and superior shear strength.
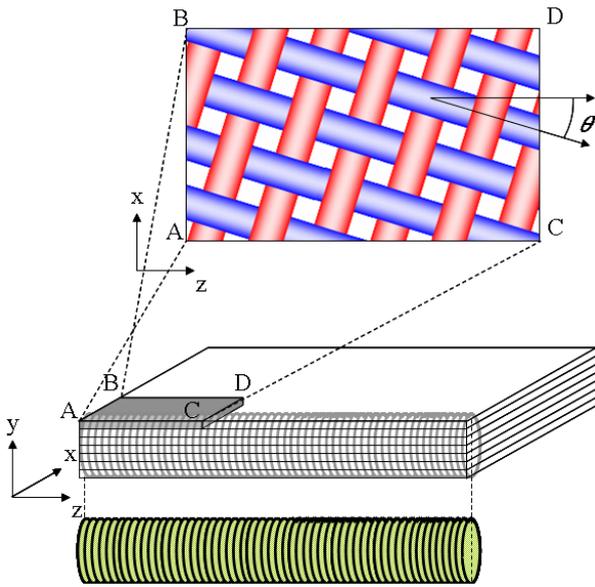
Fig.1. GFRP bolt made of off-axis E-glass cloth/epoxy laminates

2.1.2. Failure mode

The typical example of broken bolts by fatigue test is shown in Fig.2. The failure modes of all of specimens show the similarity from a macroscopic standpoint. And, the damage has been occurred at the bolt thread root. However, microscopically, it is cleared that the fracture morphology at the bolt thread root paralleling to fiber bundle is different from the others which are not parallel to the fiber bundle by the observation with digital microscope. The parts of the bolt thread parallel to fiber bundle are broken by the delamination and the others are broken by the fiber breakage. The different failure modes are shown in Fig.3. I is considered that the mechanical characteristics of GFRP bolt can be strongly affected by the anisotropic characteristics of the inner structure.
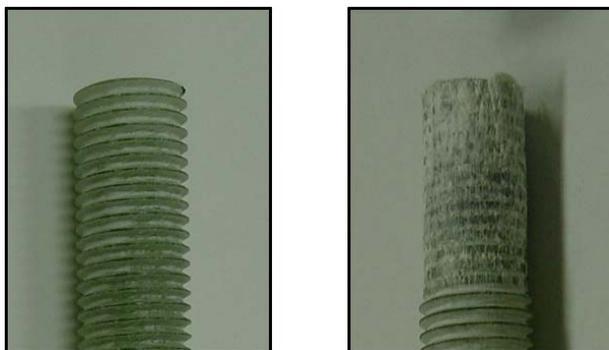
(a) Before test   (b) After test
Fig.2. Test specimen
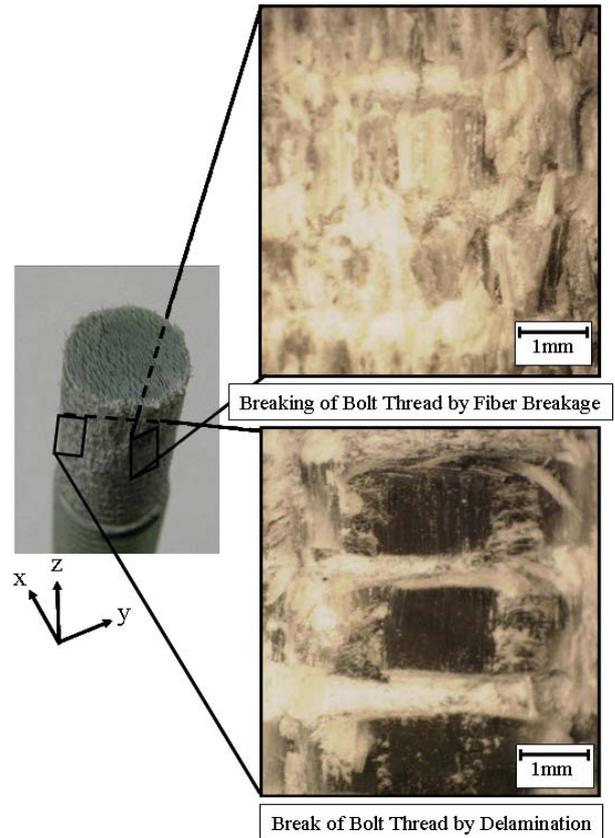
Fig.3. Difference of fracture morphology of bolt thread root after test

2.2. Tensile test

The experiment has been carried out under the condition as shown in Fig.4. The bolt is loaded through the stainless steel (SUS304) nuts with washers which are attached on the two sides of bolt. The washers does not touch the bolt directly because the washers have a hole larger than the diameter of bolt. The distance between nuts is 90 mm. The bolt and the nuts used are M16 refer to Japanese Industrial Standards (JIS [2]). An example of the experimental results is shown in Fig.5. The relation between the applied load and the displacement up to maximum load shows almost liner. The load is dropped dramatically after maximum load and then, some load is sustained up to the final failure.

The load sustained shows several peaks. The number of peaks are same as number of threads which are broken up to final failure.

In this study, we've defined the tensile strength as the maximum load. Table1 shows the tensile strength. The standard deviation is 0.855.
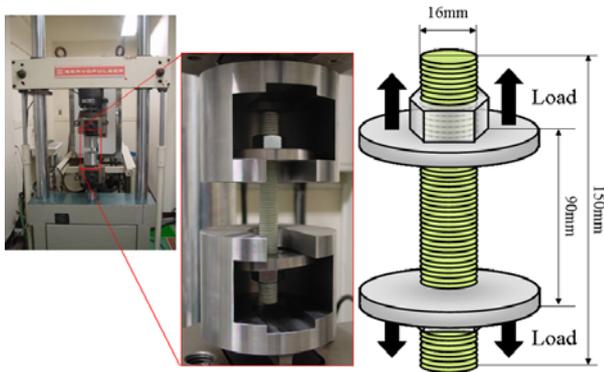
Fig.4. The experimental apparatus
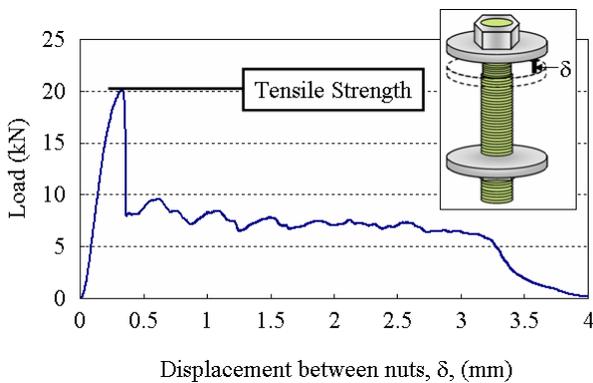
Fig.5. An example of tensile test result

Table1. Result of tensile tests

Number of Spesimens	Tensile Strength (kN)
1	20.14
2	19.02
3	20.77
4	18.85
5	18.85
6	19.81
Average	19.58

2.3. Fatigue test

Fatigue test is carried out the conditions under a constant repeated tensile load and the frequency of 1Hz. The testing conditions are shown in Table2.

The amplitude and mean level of applied load and number of cycles to failure are also shown in Table2. N_f represents the number of loading cycles to failure, R represents stress ratio, and P_{max} and P_a are maximum load and amplitude of load, respectively.

Table2. Result of fatigue test

Number of Spesimens	Pmax (kN)	Pa (kN)	R	Nf (cycles)	Data
1	9.0	4.5		24842	
2	9.0	4.5		14639	
3	9.0	4.5		30675	
4	10.0	5.0		12246	
5	10.0	5.0	0.00	10347	
6	10.0	5.0		3746	
7	10.0	5.0		5952	
8	11.0	5.5		7120	
9	12.0	6.0		2318	
10	16.0	8.0		362	
11	10.0	4.0		500000	Not failure
12	11.3	4.5		47650	
13	11.3	4.5		24191	
14	11.3	4.5		11710	
15	12.5	5.0		558	
16	12.5	5.0	0.20	4525	
17	12.5	5.0		3012	
18	13.8	5.5		454	
19	13.8	5.5		2987	
20	13.8	5.5		2240	
21	17.5	7.0		66	
22	14.0	3.5		1197302	Not failure
23	14.8	3.7	0.50	61558	
24	16.0	4.0		6326	
25	17.2	4.3		868	
26	12.0	2.0	0.67	1400000	Not failure
27	15.2	1.9		76648	
28	16.8	2.1	0.75	2765	
29	18.4	2.3		69	

3 Evaluation

It is important for the design of joint to evaluate fatigue properties of GFRP bolt. .
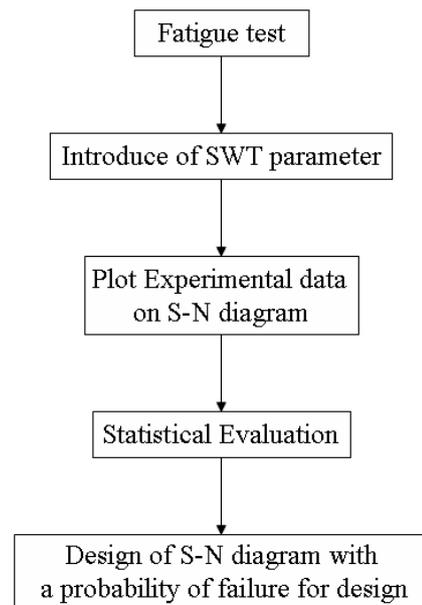
Fig.6. Flow chart of a procedure of statistical evaluation

As the mechanical properties of GFRP bolt has a dispersion, we have to adopt a statically evaluation to obtain the design standard. The procedure is shown in Fig.6.

3.1. SWT parameter

The S-N diagram is used to evaluate the results of fatigue test conducted in the condition under the constant stress ratio or the constant mean stress. In order to treat the fatigue properties in various stress conditions, huge number of test specimens and a lot of time will be required because it is needed to get S-N diagram with various stress conditions. In this paper, fatigue properties are evaluated by Smith-Watson-Topper (SWT) parameter, which can treat the test data with different stress ratio. SWT parameter is shown in Eq. (1).

$$\sigma_S = \sqrt{\sigma_{max} \sigma_a} \qquad (1)$$

where σ_S, σ_{max}, and σ_a represent SWT parameter, maximum stress, and stress amplitude, respectively.

SWT parameter has been published by Smith K. N. et al. in 1970 [3].

We have applied SWT parameter to the experimental data shown in Table2. In stead of Eq. (1), SWT parameter "P_s" is calculated by Eq. (2).

$$P_S = \sqrt{P_{max} P_a} \qquad (2)$$

where, P_{max} and P_a are maximum and amplitude of load, respectively. Fig.7 shows the S-N diagram with SWT parameter.

From Fig.7, it is recognized that SWT parameter can be applied to GFRP bolt.
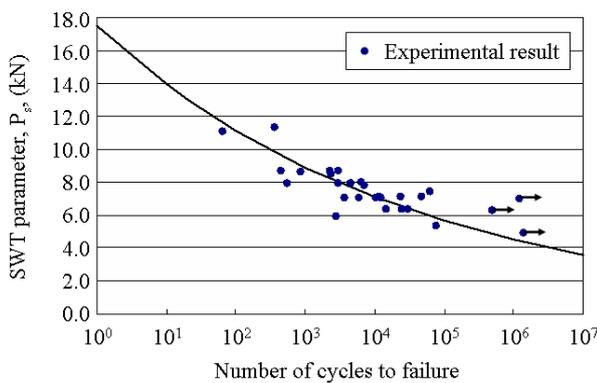
Fig.7. S-N diagram by use of SWT parameter

3.2. Reliability approach

As the initial failure is generated a local region, the fatigue life will be affected by the micro-structure such as the inhomogeneity of material and the defects like void. Therefore, the fatigue life will show a scatter.

A design standard is decided by safety factor. According to ASME sec. III, the safety factors are 1/2 for stress and 1/20 for life, respectively, and it can be recognized that ASME does not consider of scatters. To conduct fatigue design based on reliability engineering, it is necessary to disclose the distribution characteristic of fatigue strength and life.

It is expected that the S-N diagram may obtain from small number of samples if the confidence level is introduced. Two methods are utilized to obtain S-N diagram with small number of specimens. One is the parameters of fatigue strength distribution. The other is a fatigue design standard based on reliability engineering.

3.2.1. Normalized stress

A normalized stress shown in Fig.8 has been introduced by Zako et al. in order to obtain the probability of failure for small test data [4]. The normalized stress means the stress value that is normalized to fatigue strength at the number of cycles to failure N'. This means what the fatigue strength distribution is same as the distribution at an arbitrary number of cycles.
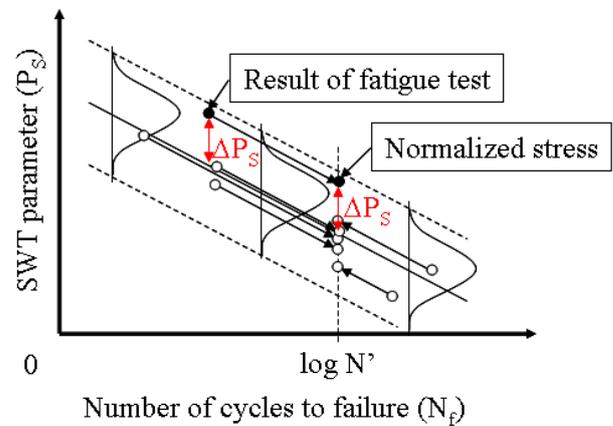
Fig.8. Scheme of normalized stress

3.2.2. Estimation of parameters of fatigue strength distribution

When the probability distribution is applied to data with scatter, the method of estimation of parameters with probability paper is utilized [5]. It is necessary to calculate the central value of cumulative probability to each data in the method of estimation of parameters with probability paper. Median Rank Method is applied to ranking [6].

The probability distributions considered with fatigue strength distribution are normal, log-normal,

and Wibull distribution [7]. The most correlated distribution to scatter of data in these distributions is selected.

Johnson method is applied to consider the break data in fatigue test [8].

3.2.3. Determination of fatigue design standard

In the traditional procedure to get the S-N diagram for design, a constant safety factor is applied. It is necessary for the experimental data with scatter to determine a design standard based on the reliability engineering. The procedure of determination of design standard with fatigue strength distribution has been proposed.

The fatigue strength with arbitrary failure probabilities can be calculated by the fatigue strength distribution obtained from the experimental results.

It is recognized that the proposed method, which is considered the probability of failure and the confidence level, is the applicable one to determine the S-N diagram for design.

Fig.9 shows the relation between the fatigue strength with probability of failure and the confidence level. The number of specimens will affect the probability of failure and the confidence level. Therefore, the S-N diagram which is obtained by these procedures is very reasonable and usuful.
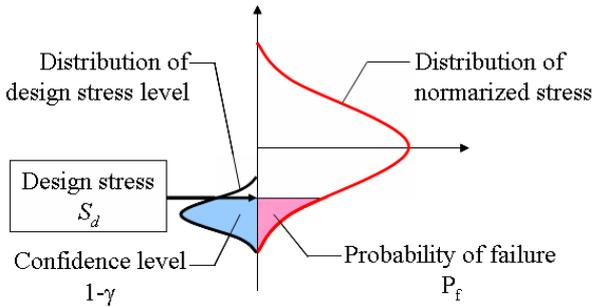
Fig.9. Scheme of design stress
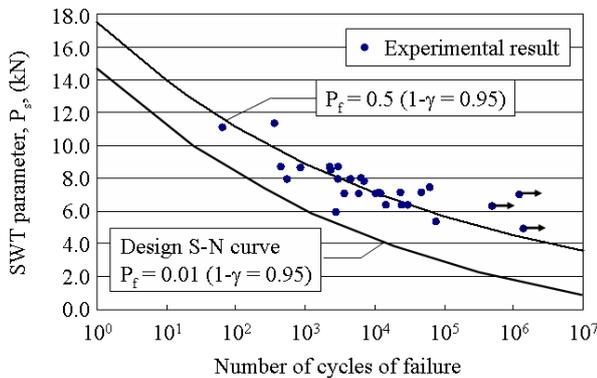
Fig.10. Design S-N diagram based on reliability engineering

Fig.10 shows the S-N diagrams when the probability of failure P_f are 0.5 and 0.01, and the confidence level is 0.95, respectively.

4 Discussion

4.1. FE modeling of bolt and nut

Three-dimensional finite element model of bolt and nut are employed to reveal the stress distribution. Fig.11 shows a 3-D FEM model. To imitate real shapes of bolt and nut thread, the number total elements is 65536 and the smallest size of element is 0.125mm. The analysis has been performed under the condition of uniformity displacement loading on the bottom face of nut. Through the real nut is hexagon shape, the analysis has been performed with circular nut which has the same surface area with hexagon nut due to simplify.
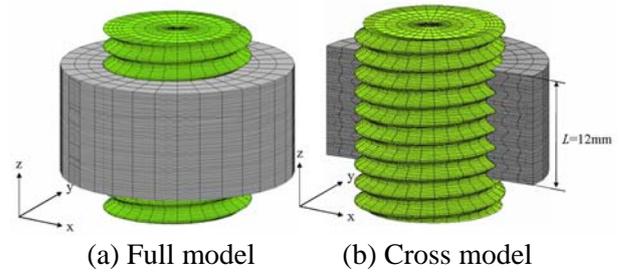
(a) Full model   (b) Cross model
Fig.10. 3-D model of bolt and nut

4.2. Verification of analysis model

To verify the finite element model, the analysis result has been compared with the theory for isotropic material [1]. Mechanical properties of bolt and nut are shown in Table3. The axial force is calculated by Eq. (3).

$$\frac{F}{F_b} = \frac{\sinh \lambda z}{\sinh \lambda L} \qquad (3)$$

where, F represents axial force worked on cross-section of bolt (z coordinate value:z) when z coordinate value of bottom face of nut is shifted into original point, F_b represents tensile load worked on shank of bolt, L represents nut length, and λ represents in Eq. (4).

$$\lambda = \sqrt{\frac{\frac{1}{A_b E_b} + \frac{1}{A_n E_n}}{\left(\frac{k_b}{E_b} + \frac{k_n}{E_n}\right) \tan \beta}} \qquad (4)$$

where A, E, and k represents cross-section area orthogonal to axial, Young's modulus and stiffness, respectively. The subscript of b and n represent bolt and nut. β represents the lead angle. The numerical results are shown in Fig.12. As the friction and

stress concentration are not considered, the difference of both results has been recognized. However, it has been found that the mechanical behavior can be simulated by FEM model and the scale of assessments of axial force at bottom face of nut turned out to be the largest which shows the same trend with the results of FEM analysis and Eq. (3).

Table3. Mechanical properties of stainless steel

E (Young's modulus) (MPa)	1.97×10^5
G (shear modulus) (MPa)	7.37×10^4
ν (Poisson's ratio)	0.34
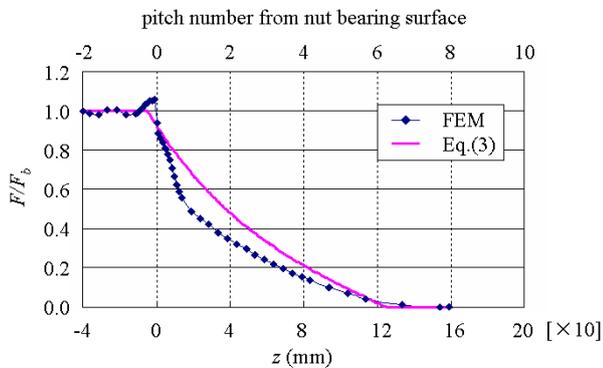
Fig.11. Distribution of bolt-axial force ratio

4.3. Mechanical properties of GFRP bolt

Woven fabric composites have the complicated internal structure due to complex architecture of fiber bundles. The most difficult point is to make a FE mesh model which can be presented the internal structure accurately. To avoid the difficulty, the geometric unit model of woven structure is generated, and the equivalent mechanical properties are calculated.

The geometric unit model has been made by WiseTex computer code [9]. The mechanical properties of glass fiber and epoxy are calculated according to literature data [10]. The shape parameters such as diameter of a filament and number of filaments are measured by the observation of digital microscope and the architecture of woven id measured by X-ray computed tomography. The geometric unit model is shown in Fig.12. The mechanical properties have been calculated by the homogenization method. The mechanical properties of woven fabric are shown in Table4, and the mechanical properties of the laminated plate of E-glass cloth [+7/-7] are shown in Table5.
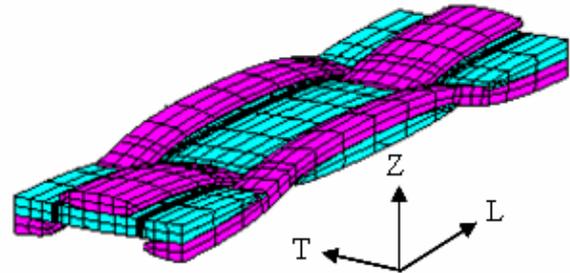
Fig.12. The geometric unit model of woven fabric

Table4. Mechanical properties of woven fabric

E_L(MPa)	E_T(MPa)	E_Z(MPa)
1.087×10^4	1.324×10^4	5.581×10^3
G_{TZ}(MPa)	G_{ZL}(MPa)	G_{LT}(MPa)
1.756×10^3	1.736×10^3	2.506×10^3
ν_{TZ}	ν_{ZL}	ν_{LT}
0.4017	0.2122	0.1387

Table5. Mechanical Properties of laminate sheet

E_L(MPa)	E_T(MPa)	E_Z(MPa)
1.144×10^4	1.385×10^4	5.814×10^3
G_{TZ}(MPa)	G_{ZL}(MPa)	G_{LT}(MPa)
1.762×10^3	1.734×10^3	2.770×10^3
ν_{TZ}	ν_{ZL}	ν_{LT}
0.3885	0.2031	0.1510

4.4. Analysis of GFRP bolt

The analysis is performed by uniformity displacement (0.1mm) on the bottom face of nut as same as the experiment.

Since the bolts have been broken at the bolt thread by shear, the axial stress and axial shear stress in vertical radial direction will be influenced the bolt failure strongly. The distribution of axial and shear stresses are shown in Fig.s 14 and 15, respectively. As shown in Fig.s 14 and 15, the high stress is provided with bolt thread root.

The axial and shear stresses at bolt thread root calculated along axial direction are shown in Fig.s 16 and 17, respectively. Due to compare analysis result with the bolt of stainless steels, the numerical results have been normalized by the applied load. From these results, two knowledge have been drew out. One is the axial and shear stresses of the bolt thread root. The stress of GFRP bolt at the nearest

to bottom of surface of nut is smaller than the stress of bolt of stainless steels, because the modulus of elasticity of GFRP is smaller than stainless steels. The other is the distribution of axial and shear stresses at bolt thread root. The stress is decreased along axial direction with swung periodically. However, the stress of the bolt of stainless steels is decreased flatly. The stress at the bolt thread in parallel with fiber bundle is larger than the stress at the bolt thread to the direction of laminate on, for reason that the former stiffness is smaller than the latter one. In addition, GFRP-1 and GFRP-2 shown in Fig.s 16 and 17 mean the numerical results for the bolt thread in parallel with fiber bundle and for the bolt thread at the rotation of a quarter. Therefore, the nut position of GFRP2 has been rotated quarter-turn from GFRP-1 position. As shown in Fig.s 16 and 17, the numerical results have been differed each other by the difference of nut position. It is cleared that the effect of anisotropic mechanical properties on the distribution of stress generates the different finite mode.
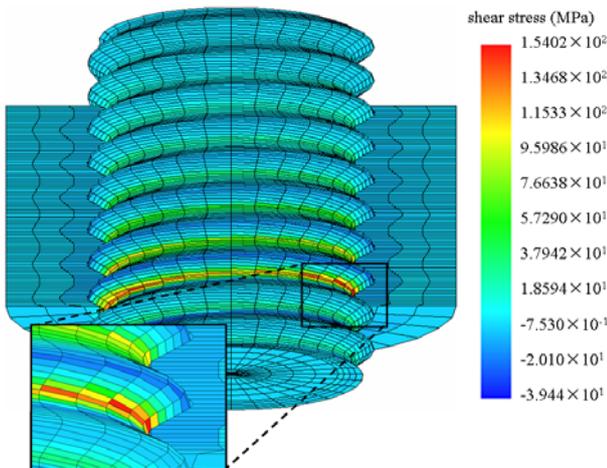
Fig.14. Distribution of shear stress of bolt thread
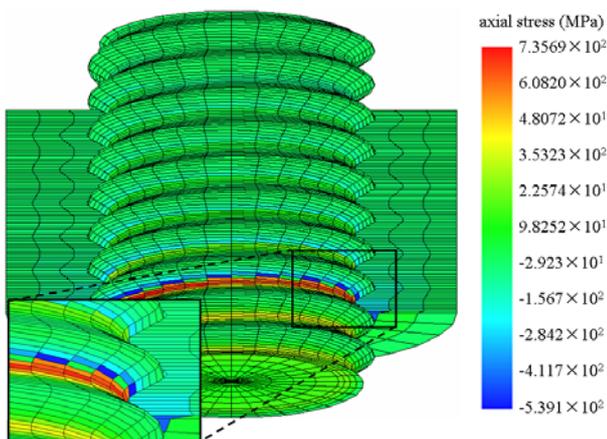
Fig.15. Distribution of axial stress of bolt thread
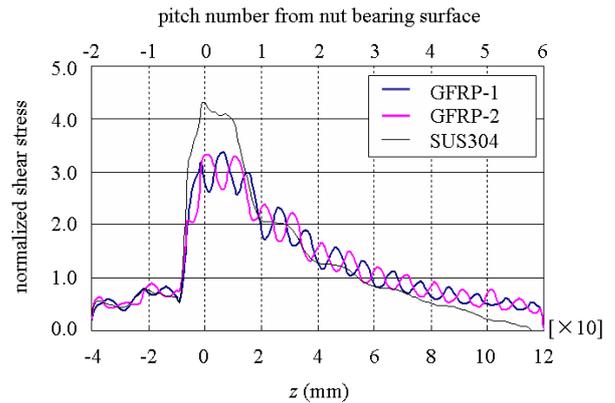
Fig.16. Distribution of shear stress of bolt thread root
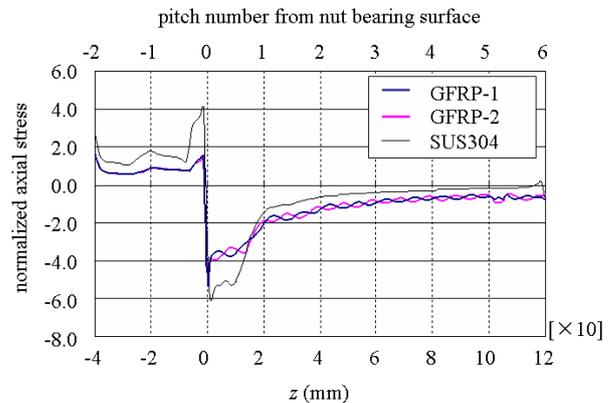
Fig.17. Distribution of axial stress of bolt thread root

5 Conclusions

In this paper, the fatigue tests of GFRP bolt and three-dimensional finite element analysis have been described.

The fatigue tests of GFRP bolt has been conducted. It has been recognized that fracture surface of bolt thread paralleled to fiber bundles have been different from the others. The former has been broken by delamination and the later has been broken by fiber breaking. We has introduced SWT parameter and confidence level in order to treat the data with different stress ratio and with scatter. It is recognized that the proposed method can obtain the S-N diagram even if it is small sample data. I

FEM analysis of GFRP bolt considered with anisotropy has been carried out. From the numerical results, it's demonstrated that the stress distribution of GFRP bolt thread is decreased along axial direction with swung periodically, which is different from the stress distribution of isotropic materials. It is also revealed that the difference of stress distribution generates the difference of failure mode.

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