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Fusion Energy Division

FACE COMPRESSION YIELD STRENGTH OF THE COPPER-INCONEL COMPOSITE SPECIMEN

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ABSTRACT

A new equation for the face compression yield strength of copper-Inconel composite material has been derived. Elastic-plastic finite element analyses were also made for composite specimens with various aspect ratios to examine the edge effect of the specimen. According to the results of both the new equation and the analyses, the face compression yield strength of the composite should be decreased by about 25% from the value obtained with Becker's equation.

1. INTRODUCTION

The face compression yield strength of the copper-Inconel composite material used for Compact Ignition Tokamak (CIT) coil design was previously determined by using Becker's equation,¹ which was derived with the hypothesis that copper and Inconel yield simultaneously. In general, however, because the yield stress of Inconel is much higher than that of copper, Inconel does not yield simultaneously with copper. Thus, a new equation for face compression yield strength has been derived which accounts for the yielding of the copper while the Inconel remains in the elastic condition.

Although these equations are derived only for infinite-aspect-ratio specimens (i.e., the width of the specimen is much larger than the thickness), actual CIT coils have finite width. The edge effect of the composite^{1,2} is also an important consideration in determining the face compression yield strength. The elastic-plastic finite element method is used to examine the edge effect.

The face compression yield strength of the composite material based on the newly derived equation and the elastic-plastic finite element analysis is discussed.

2. NEW EQUATION FOR FACE COMPRESSION YIELD STRENGTH

2.1 BASIC RELATIONS OF COMPOSITE MATERIAL

For the composite material made of copper (c) and reinforcement (r) shown in Fig. 1, the stress intensity (or Tresca stress) σ_{Tresca} is written as

$$\sigma_{\text{Tresca},c} = \sigma_{f,c} - \sigma_{i,c} \quad \text{in copper,} \quad (1)$$

$$\sigma_{\text{Tresca},r} = \sigma_{f,r} - \sigma_{i,r} \quad \text{in reinforcement,} \quad (2)$$

where σ_f and σ_i are face compression stress and in-plane stress, respectively.

Equilibrium of in-plane force leads to the equation

$$\alpha \sigma_{i,c} + (1 - \alpha) \sigma_{i,r} = 0, \quad (3)$$

where α is the thickness ratio of copper.

Fig. 1. Composite material under face compression stress.

It is assumed here that the copper is in the plastic condition whereas the reinforcement is in the elastic condition. From the stress-strain relation for an elastic body,

$$\epsilon_{i,c}^{(e)} = \frac{\sigma_{i,c}}{E_c} - \frac{\nu_c \sigma_{i,c}}{E_c} - \frac{\nu_c \sigma_{f,c}}{E_c} \quad \text{in copper,} \quad (4)$$

$$\epsilon_{i,r} = \frac{\sigma_{i,r}}{E_r} - \frac{\nu_r \sigma_{i,r}}{E_r} - \frac{\nu_r \sigma_{f,r}}{E_r} \quad \text{in reinforcement,} \quad (5)$$

where $\epsilon_i^{(e)}$, E , and ν are in-plane elastic strain, Young's modulus, and the Poisson ratio, respectively.

The total strain in copper is expressed by the simple summation of elastic strain and plastic strain $\epsilon^{(p)}$:

$$\epsilon_{i,c} = \epsilon_{i,c}^{(e)} + \epsilon_{i,c}^{(p)}. \quad (6)$$

Incompressibility of elastic strain in copper yields

$$\epsilon_{f,c}^{(p)} + 2\epsilon_{i,c}^{(p)} = 0 . \quad (7)$$

For face compression of the composite material, the following relations hold:

$$\sigma_{f,c} = \sigma_{f,r} (= \sigma_f) , \quad (8)$$

$$\epsilon_{i,c} = \epsilon_{i,r} (= \epsilon_i) , \quad (9)$$

$$\alpha\epsilon_{f,c}^{(p)} = \epsilon_{f,comp}^{(p)} , \quad (10)$$

where $\epsilon_{f,comp}^{(p)}$ is face compression plastic strain in the composite.

2.2 THE PROBLEM WITH BECKER'S EQUATION

It was hypothesized¹ that face compression yielding would occur in an infinite composite when both materials yield simultaneously, which is expressed as

$$\sigma_{Tresca,c} = \sigma_c^{(y)} , \quad (11)$$

$$\sigma_{Tresca,r} = \sigma_r^{(y)} , \quad (12)$$

where $\sigma^{(y)}$ is yield stress. These equations may be rewritten by substituting Eqs. (1), (2), and (8) as

$$\sigma_f - \sigma_{i,c} = \sigma_c^{(y)} , \quad (13)$$

$$\sigma_f - \sigma_{i,r} = \sigma_r^{(y)} . \quad (14)$$

From Eqs. (3), (13), and (14), the face compression yield strength of the composite is given by

$$\sigma_f^{(y)} = \alpha\sigma_c^{(y)} + (1 - \alpha)\sigma_r^{(y)} . \quad (15)$$

This derivation process is schematically expressed by Fig. 2.

In general, this hypothesis is not satisfied, because the yield stress of the reinforcement material is about four times as large as that of the copper for CIT coils. The reinforcement is elastic even if the copper yields. Thus, a different expression for face compression yield strength is needed.

BECKER'S EQUATION

Fig. 2. Derivation of Becker's equation.

2.3 DERIVATION OF NEW EQUATION

It is assumed that only the copper yields when face compression plastic strain in the composite reaches -0.2% . This is expressed as

$$\sigma_{\text{Tresca},c} = \sigma_c^{(y)}, \quad (16)$$

$$\epsilon_{f,\text{comp}}^{(p)} = -0.002. \quad (17)$$

Equations (3) and (13) also hold under this assumption. It is also assumed that Poisson ratios for copper and reinforcement are equal; that is,

$$\nu_c = \nu_r (= \nu). \quad (18)$$

With substitution of Eqs. (8), (9), and (18), Eq. (4) may be written as

$$\frac{\nu}{E_c} \sigma_f - \frac{1-\nu}{E_c} \sigma_{i,c} + \epsilon_{i,c}^{(p)} = 0, \quad (19)$$

and Eq. (5) may be written as

$$\frac{\nu}{E_r} \sigma_f - \frac{1-\nu}{E_r} \sigma_{i,r} + \epsilon_i = 0. \quad (20)$$

From Eqs. (3), (6), (7), (10), (13), (19), and (20), the face compression yield strength of the composite is obtained as

$$\sigma_f^{(y)} = \frac{\frac{\epsilon_{f, \text{comp}}^{(y)}}{2\alpha} - (1-\nu) \left(\frac{1}{E_r} \frac{\alpha}{1-\alpha} + \frac{1}{E_c} \right) \sigma_c^{(y)}}{\frac{1}{E_r} \left[\nu + (1-\nu) \frac{\alpha}{1+\alpha} \right] + \frac{1}{E_c} (1-2\nu)}. \quad (21)$$

This derivation process is shown schematically in Fig. 3.

Fig. 8. Derivation of Horie's equation.

2.4 COMPARISON OF BECKER'S EQUATION WITH HORIE'S EQUATION

In Becker's equation, it is assumed that not only copper but also the reinforcement yields when yielding of the composite occurs. For the equation introduced here (referred to subsequently as "Horie's equation"), it is assumed that only the copper yields when the plastic strain of the composite reaches -0.2% . The plastic strain of -0.2% is consistent with most of the tests used for determining the yield stress. The present equation is derived by using stress-strain relations for both the

copper and the reinforcement, definition of the total strain of the copper, the incompressibility relation of the plastic strain of the copper, and the mixture rule of face compression plastic strains rather than by using the Tresca yield condition in the reinforcement.

Figure 4 shows the difference between the two equations as a function of α . Material properties used here are:

$$\begin{aligned} E_c &= 135 \text{ GPa} & \sigma_c^{(y)} &= 308 \text{ MPa} \\ E_r &= 200 \text{ GPa} & \sigma_r^{(y)} &= 1218 \text{ MPa} \\ \nu &= 0.3 & \epsilon_{f,comp}^{(p)} &= -0.002 \end{aligned}$$

According to this figure, there are two intersection points, which correspond to α values of 0.278 and 1. At $\alpha = 1$, the specimen is made of solid copper. At $\alpha = 0.278$, the Tresca stress in the reinforcement is the same value as the yield stress of the

Fig. 4. Comparison between Becker's equation and Horie's equation.

reinforcement. Becker's equation should be applied only for α values less than 0.278, and Horie's equation should be applied for α values larger than 0.278.

Since the actual α value for the baseline CIT coils is about 0.5, Horie's equation will more accurately predict the value of the face compression yield strength. For $\alpha = 0.51$, the face compression yield strength is 577 MPa by Horie's equation, whereas it is 754 MPa by Becker's equation. According to the elastic-plastic finite element analysis for the same case with an infinite-aspect-ratio specimen (described in the next section), the value is 571 MPa. Horie's equation and the finite element analysis give a value about 25% smaller than that given by Becker's equation.

3. EDGE EFFECTS FOR VARIOUS ASPECT RATIOS

3.1 ANALYSIS METHOD

The aspect ratio of composite material specimens affects the face compression yield strength because of the nonuniform expansion of the edges.¹ The elastic-plastic finite element method is used to analyze the finite-aspect-ratio effect.

The MSC/NASTRAN code is used for the analysis, with three-dimensional, eight-node, isoparametric elements, von Mises yield criterion, associated flow rule, and BFGS quasi Newton-Raphson method.³

A plot of stress vs strain for each of the incremental load steps is constructed. The face compression yield stress is determined from the intersection point of the calculated face compression stress-strain curve and a 0.2% strain offset line, which has the same gradient as the elastic part of the curve.

3.2 ANALYSIS MODEL

A typical mesh subdivision of the composite material specimen tested for face compression yield strength is shown in Fig. 5. Because of the geometric symmetry of the specimen, with a fine mesh located near the edge, one-eighth of the test specimen is modeled.

Roller boundary conditions are applied on the symmetry surfaces. Uniform displacement boundary conditions and face compression loading are also applied

ELASTIC-PLASTIC COPPER-INCONEL SPECIMEN ANALYSIS
 3-D END EFFECT OF SPECIMEN WITH MULTIPOINT
 CONSTRAINTS, $R = 7.8$, FIXED
 UNDEFORMED SHAPE

Fig. 5. Typical mesh subdivision of one-eighth of the composite.

on the reinforcement surface. For the analysis of the specimen with an infinite aspect ratio, a uniform displacement boundary condition is also applied on the edge surfaces.

The stress-strain curve for the copper is approximated by four straight lines from the experimental results by Becker,¹ and the reinforcement is treated as elastic. These data are summarized in Table 1.

Table 1. Material properties for the analysis

Stress-strain relation of copper		
Stress (MPa)	Strain (%)	Tangent modulus (GPa)
0	0	—
175	0.13	134
225	0.2	71
275	0.35	33.3
300	1	3.8
Young's modulus of Inconel		
200 GPa		
Poisson ratio		
0.3		

3.3 ANALYSIS RESULTS

The face compression stress-strain curves obtained for aspect ratios $R = 1.0$, 2.5, 7.8, 20, 30, and ∞ are shown in Fig. 6. Face compression yield strengths for various aspect ratios, together with Becker's experimental results,⁴ are summarized in Fig. 7. This figure shows that finite element and experimental results have good agreement when the aspect ratio is smaller than 5 and that the agreement becomes poorer as the aspect ratio increases. Also, the face compression yield curve obtained by using the finite element model approaches Horie's equation as the aspect ratio becomes infinite.

Fig. 6. Face compression stress-strain curves for various aspect ratios (R) for a square specimen with uniform displacement load and $\alpha = 0.51$.

Fig. 7. Face compression yield strength of composite.

Table 2 summarizes the finite element model results for the finite-aspect-ratio composite. Results agree very well with Horie's equation when the face compression plastic strain of the composite reaches -0.2% . The equivalent stress of the reinforcement is much lower than its yield stress. When the equivalent stress of the reinforcement reaches its yield stress, the equivalent plastic strain of the copper is very high (0.69%), and the results agree very well with Becker's equation.

3.4 DISCUSSION

To examine the discrepancy between the finite element model and the experimental results for aspect ratios ranging from 5 to 8, an elastic-plastic finite element analysis with fixed boundary condition on the loading surface was performed. Results are shown in Fig. 7 as a dashed line. These results demonstrate that the experimental results agree better with finite element results with a fixed condition

Table 2. Result of elastic-plastic finite element analysis of the composite with $R = \infty$

	σ_f (MPa)	σ_r^{eq} (MPa)	ϵ_i (%)	$\epsilon_c^{eq(p)}$ (%)
When face compression plastic strain of composite reaches -0.2%				
Horie's equation	-577.3	857.7	0.1847	
Finite element model	-571.6	869.8	0.1900	
(Difference)	(0.990)	(1.014)	(1.029)	
When equivalent stress of reinforcement reaches its yield stress				
Becker's equation	-753.9	1218		—
Finite element model	-747.7	1218		0.6871
(Difference)	(0.992)	(—)		(—)

than with a roller condition. The actual condition of CIT coils is the roller condition because a turn is not constrained by the adjacent turns. Since a stack of specimens is used in Becker's experiment to avoid constraining the specimen, the roller condition seems to be simulated in the tests if the stack is tall enough. Thus, the reason for the difference has yet to be clarified.

According to the face compression yield strength curve in Fig. 7, the edge effect for the CIT toroidal field coil is very small since the aspect ratio is as large as 21. Considering the difficulty of the experiments for specimens with a large aspect ratio, the analytical equation for infinite aspect ratio may be applied to large-aspect-ratio coils with a proper correction factor such as 0.9.

When the aspect ratio is infinite, the finite element results agree well with Horie's equation because the copper thickness ratio, which is 0.51, is larger than 0.278, as mentioned in Sect. 2.

According to Fig. 6, it is observed that face compression yield strength determined by 0.2% plastic strain is near the flat part of the stress-strain curve when the aspect ratio is small and near the elastic part when the aspect ratio is large. The

reason is that the von Mises stress in copper is much larger for smaller aspect ratio specimens.

4. CONCLUSIONS

A new equation for the face compression yield strength of the composite is proposed for copper thickness ratios from 0.278 to 1.

As for the edge effect of the composite, the new equation, together with the proper correction factor (such as 0.9), is useful for aspect ratios larger than 15. Therefore, this equation can be used to evaluate the baseline toroidal field coil.

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