NONLINEAR STRESS ANALYSIS FOR STEEL PLATE BONDING CFRP SHEET UNDER UNIAXIAL TENSILE LOADING

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1. INTRODUCTION

CFRP in sheet form is usually applied to repair and strengthen steel structures which have reduced load-carrying capacity due to natural hazards, corrosion damages, and fatigue damage. In particular, to maximize the effectiveness of the repair and reinforcement method using CFRP sheets, and to prevent peeling of CFRP layers under large deformations such as buckling, the polyurea putty with a low elastic modulus (54.7 MPa) and high elongation (300%-500%) is usually inserted between the steel members and the CFRP sheet. Therefore, it is clear that the maximum strength of the steel members repaired or reinforced is often determined by the peeling failure of the interface between the structure and the CFRP sheet. For this reason, in order to perform the most effective repair and reinforcement, it is necessary to grasp the peeling mechanism of CFRP sheet and the mechanical behavior of the adhesion layer inserted between the steel member and CFRP sheet. However, some studies proposed linear theoretical analysis to determine the peeling strength of CFRP sheet by calculating the principal stress on the adhesion layer, and there is no study in which nonlinear analysis has been mentioned. Therefore, this study establishes a nonlinear theoretical analysis method considering the nonlinear material condition of steel, adhesion layer, and CFRP sheet; for steel plate bonding a layer of the CFRP sheet under uniaxial tensile loading.

2. PROPOSED CALCULATION EQUATION

As the first premise for nonlinear theoretical analysis method, this study used the steel plate (see **Fig. 1**) bonding only one layer of CFRP sheet under uniaxial tensile loading, to determine the peeling mechanism of the CFRP sheet and the mechanical behavior of the adhesion layer inserted between the steel member and CFRP sheet. Moreover, this study has referred to the calculation process of the linear analysis of Prof. KAMIHARAKO[1].

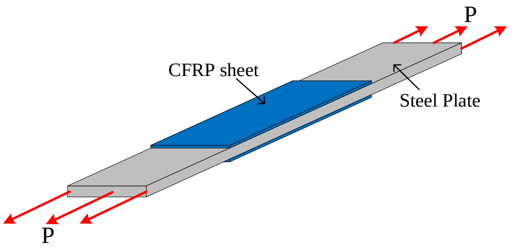


Fig. 1 Analytical object (Steel plate bonding a layer of CFRP).

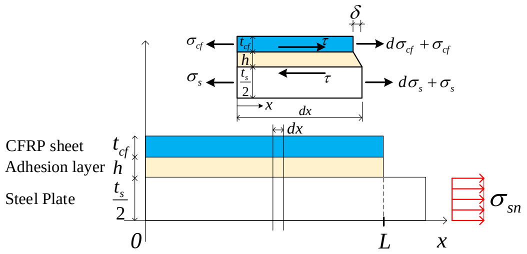
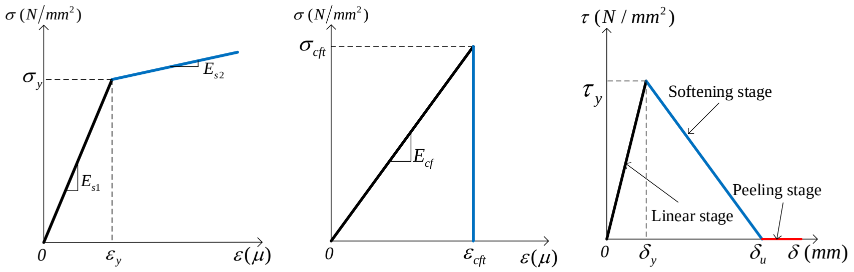


Fig. 2 Modeling (1/4 model).



(a) Steel (σ-ε) (b) CFRP sheet (σ-ε) (c) Adhesion layer

Fig. 3 Constitutive models of materials.

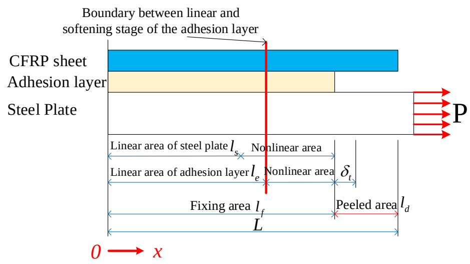


Fig. 4 The peeling mechanism of CFRP sheet

2.1 Differential equation

The calculated model is described as a quarter model (see **Fig. 2**) of the CFRP-sheet-bonded steel plate; and considered the nonlinear material condition of steel, CFRP sheet, and the adhesion layer as shown in **Fig. 3**. Here, as a bonding constitution rule of CFRP, it is generally assumed that the material model of the adhesion layer is considered by the relationship between shear stress and relative displacement, as shown in **Fig. 3c**. Additionally, the elastic modulus of the adhesion layer is smaller by two orders of magnitude than that of steel and CFRP sheet, so the stress of the adhesion layer is assumed only shear stress, and steel plate and CFRP sheet is assumed only tensile stress.

The differential equations obtained from the balance equations of force and the material models is shown as follows.

In case of $0 \le \delta \le \delta_y$

$$\frac{d^2\delta(x)}{dx^2} - \left(\frac{2}{E_{s1}t_s} + \frac{1}{E_{cf}t_{cf}}\right)\frac{\tau_y}{\delta_y}\delta(x) = 0 \;\; if \left(\varepsilon_s \le \varepsilon_y\right) \tag{1a}$$

$$\frac{d^2\delta(x)}{dx^2} - \left(\frac{2}{E_{s2}t_s} + \frac{1}{E_{cf}t_{cf}}\right)\frac{\tau_y}{\delta_y}\delta(x) = 0 \;\; if \left(\varepsilon_s > \varepsilon_y\right) \tag{1b}$$

In case of $\delta_y < \delta \le \delta_u$

$$\frac{d^2\delta(x)}{dx^2} - \left(\frac{2}{E_{s1}t_s} + \frac{1}{E_{cf}t_{cf}}\right)\frac{\tau_y}{\delta_u - \delta_y}\left(\delta_u - \delta(x)\right) = 0 \;\; if \left(\varepsilon_s \le \varepsilon_y\right) \tag{2a}$$

$$\frac{d^2\delta(x)}{dx^2} - \left(\frac{2}{E_{s2}t_s} + \frac{1}{E_{cf}t_{cf}}\right)\frac{\tau_y}{\delta_u - \delta_y}\left(\delta_u - \delta(x)\right) = 0 \;\; if \left(\varepsilon_s > \varepsilon_y\right) \tag{2b}$$

Keywords: Nonlinear analysis, Steel plate, CFRP sheet, FEM, Repair.
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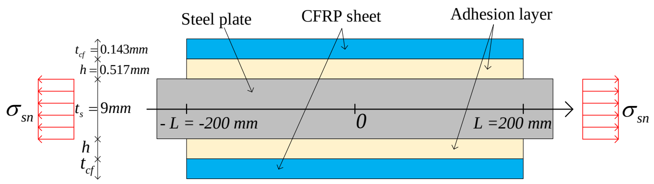
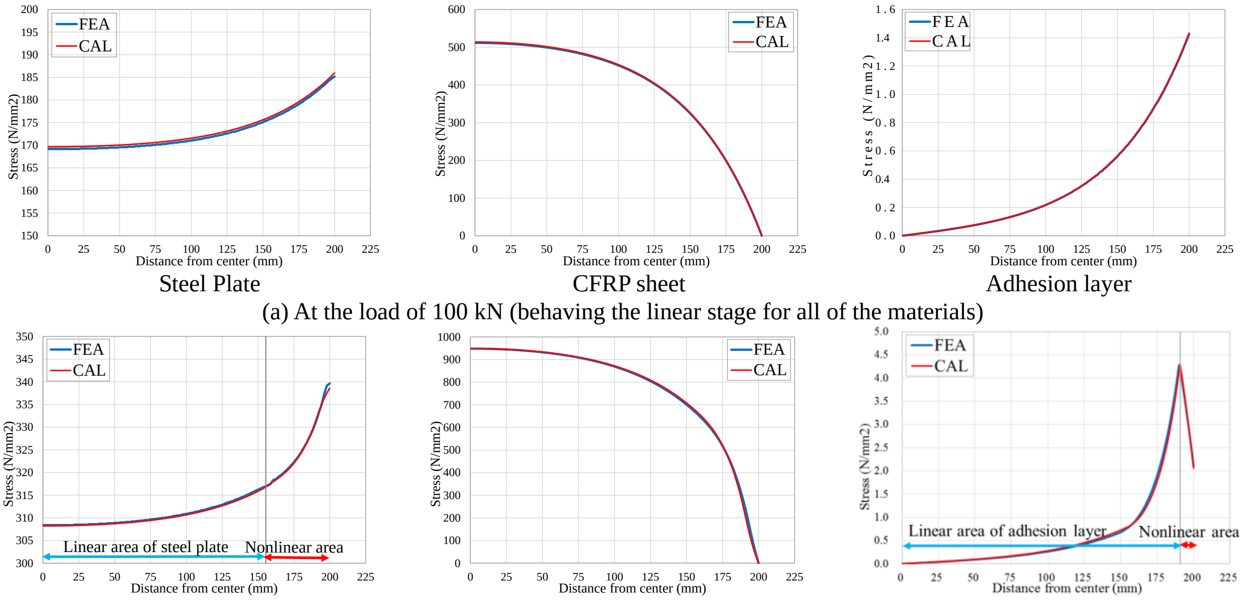


Fig. 5 The model of Example.

Table. 1 Properties of the materials

Steel (SS400)			CFRP sheet			Adhesion layer		
E_{s1}	$2x10^5$	MPa	E_{cf}	$6.4x10^5$	MPa	τ_y	4.3	MPa
E_{s2}	$2x10^3$	MPa	σ_{cft}	2430	MPa	δ_y	0.15	mm
σ_y	317	MPa	b	60	mm	δ_u	0.34	mm
b	60	mm				b	60	mm



Steel Plate CFRP sheet Adhesion layer

(a) At the load of 100 kN (behaving the linear stage for all of the materials)

Steel Plate CFRP sheet Adhesion layer

(b) At the load of 182.9 kN (behaving the nonlinear stage for the steel plate and the adhesion layer)

Fig. 6 Comparison of stress distribution between FEA and CAL.

2.2 Calculation process

The calculation process in this study is conducted by gradually increasing the relative displacement of δ_t at the fixing section top of the CFRP sheet, as shown in **Fig. 4**. Based on the level of this relative displacement and the material model of the adhesion layer, the calculating program is classified into the three stages; including the completely linear stage, softening stage, and peeling stage of the adhesion layer. The stress value on the steel plate, the CFRP layer, and the adhesion layer obtained by solving the differential conditions (1) and (2), along with the corresponding boundary conditions. Additionally, at each step of the calculation process, the calculating program will be stopped if the stress on the CFRP layer is greater than the tensile strength of the CFRP sheet.

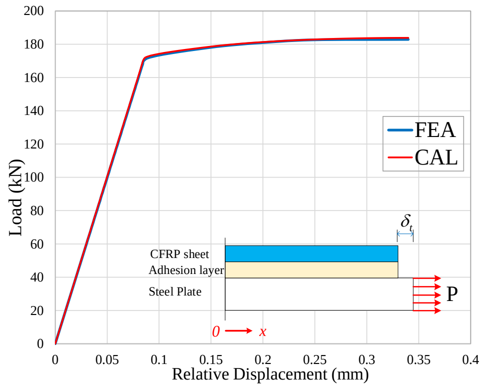


Fig. 7 Load - Relative displacement

2.3 Example and discussion

In the example, the calculated model and the properties of the materials are shown in **Fig. 5** and **Table 1**, respectively. As a base metal, SS400 steel was used. By using the proposed method of the nonlinear theoretical analysis; the stress, strain of the steel plate, the CFRP sheet and the adhesion layer on the model of example were obtained. Furthermore, in order to confirm the accuracy of the proposed method, 2D FEM nonlinear analysis was also implemented. In this 2D FEA model, the adhesion layer was simulated by using the interface element (CL12I element in DIANA analysis software). **Fig. 6** described the results of the proposed method and the FEM analysis, at the load of 100 kN, and 182.9 kN; and **Fig. 7** shows the relationship between the load and the relative displacement. The comparison of the CAL and FEA results shown in **Fig. 6** and **Fig. 7** indicates consistent agreement between the two results. Moreover, the mechanical behavior of the adhesion layer could be evaluated accurately by using the proposed theoretical analysis. Additionally, the peeling strength of the CFRP sheet in the proposed method is determined when the shear stress of the adhesion layer at the fixing section top of the CFRP sheet reaches the value of zero. In this example, the peeling load of the CFRP sheet is 183.825 kN.

3. CONCLUSION

In this study, for the steel member bonding a layer of CFRP sheet in uniaxial-tensile-stress condition, it was possible to accurately evaluate the peeling strength and the mechanical behavior of the adhesion layer, by developing the nonlinear theoretical analysis. In further research, it will be necessary to develop the nonlinear analysis method for the steel plate with multilayered CFRP sheet under uniaxial loading and bending.

REFERENCE

Kamiharako, A., Shimomura, T., Maruyama, K., Nishida, H.: Analysis of Bond and Debonding Behavior of Continuous Fiber Sheet Bonded on Concrete, Journal of JSCE, No. 634/V-45, pp. 197-208, 1999.11 (in Japanese).