Development of Reduction Technique of Thermal Stress
Induced in CFRP Bonded Steel Plates

Toshiyuki Ishikawa
Assistant Prof., Department of Urban Management, Kyoto University, Kyoto, Japan

Atsushi Hattori
Associate Prof., Department of Urban Management, Kyoto University, Kyoto, Japan

Hirotaka Kawano
Prof., Department of Urban Management, Kyoto University, Kyoto, Japan

Takashi Nagao
Researcher, Research & Development Center, Nippon Light Metal Co., Ltd., Shizuoka, Japan

Akira Kobayashi
General Manager, Composites Company, Nippon Steel Materials Co., Ltd., Tokyo, Japan

ABSTRACT

In CFRP bonded onto steel plates, thermal stress is induced in steel plate by temperature change, due to difference in coefficients of liner thermal expansion between steel and CFRP plates. In this study, reduction technique of the thermal stress in steel plate strengthened by CFRP plate, which is additional bonding of aluminum alloy plates, is proposed. Namely, the coefficient of liner thermal expansion of laminated plate consisted of CFRP and aluminum plates is designed as that of steel. In this study, to verify the effectiveness of proposed method, heat tests of CFRP and aluminum plates bonded onto steel plate were carried out. As a result, infinitesimal thermal stresses in steel plate with CFRP and aluminum alloy plates were measured while large thermal stress was measured in conventional CFRP bonded steel plate.

KEYWORD

CFRP plate, thermal stress, aluminum alloy plate, steel plate, heat test
1. INTRODUCTION

Recently, carbon fiber reinforced polymer, CFRP, plates have been used for the strengthening or rehabilitation of steel structures [1]-[3]. CFRP plate has an advantage of light weight compared to the conventional materials, such as steel or concrete. Additionally, the application of CFRP plate brings the rapid repair works. Therefore, many researchers have been studied about the application of CFRP plates on steel structures.

Table 1 shows a typical linear thermal expansion coefficient of steel and CFRP plate. As shown in this table, coefficients of liner thermal expansion of steel and CFRP plate are quite different. Therefore, in the steel structures strengthened or rehabilitated by bonding CFRP plates, thermal stresses are induced by temperature change [4]. Accordingly, thermal stresses are considered in the design of strengthening or rehabilitation of steel structures by bonding CFRP plate [5], [6].

In this study, to reduce the thermal stress induced in steel structures, additional bonding of aluminum alloy plates with CFRP plates is proposed. As listed in Table 1, coefficient of linear thermal expansion of aluminum alloy is almost twice as large that of steel. Namely, in the proposed method, by applying the aluminum alloy plate, the coefficient of linear thermal expansion of laminated plate consisted of CFRP and aluminum plates is designed as that of steel.

To verify the effectiveness of proposed method, heat tests of CFRP and aluminum plates bonded onto steel plates were carried out in this research.

2. DESIGN OF LAMINATED PLATE

Generally, the coefficient of linear thermal expansion of CFRP plates can be easily controlled by volume fraction of carbon fibers. If linear thermal expansion coefficient of CFRP plate is controlled as 11.7μ/°C, however, Young’s modulus of CFRP plate becomes almost same as that of matrix resin because of very low volume fraction of carbon fibers. Therefore, to reduce the thermal stress in steel structures strengthened by CFRP plates, the authors propose the additional bonding of aluminum plates, which has relatively higher coefficient of linear thermal expansion and Young’s modulus.

The linear thermal expansion coefficient of CFRP and aluminum laminated plate, αv, can be calculated by the following equation.

\[ \alpha_v = \frac{\alpha_f E_f A_f + \alpha_a E_a A_a}{E_f A_f + E_a A_a} \]  \hspace{1cm} (1)

where,
\[ E_f : \text{Young’s modulus of CFRP plate}, \]
\[ E_a : \text{Young’s modulus of aluminum plate}, \]
\[ A_f : \text{cross sectional area of CFRP plate}, \]
\[ A_a : \text{cross sectional area of aluminum plate}, \]
\[ \alpha_f : \text{liner thermal expansion coefficient of CFRP plate}, \]
\[ \alpha_a : \text{liner thermal expansion coefficient of aluminum plate}. \]

By substituting the linear thermal expansion coefficient of steel, \( \alpha_s \), into \( \alpha_v \), \( E_a A_a / (E_f A_f) \) is given by

\[ \frac{E_a A_a}{E_f A_f} = \frac{\alpha_s - \alpha_f}{\alpha_a - \alpha_f} \]  \hspace{1cm} (2)

Accordingly, to design the linear thermal expansion coefficient of laminated plate as same as that of steel, the required stiffness of aluminum plate can be calculated by Eq.(2).

3. HEAT TEST

3.1 Test Specimens

Conventional CFRP bonded onto steel plate, Specimen-CC, is illustrated in Fig.1a. Two CFRP plates are bonded onto top and bottom surfaces of steel plate. CFRP plates of 1mm thickness and Young’s modulus of 140GPa are used for the specimen. The direction of the fibers in the CFRP plates is the same as the longitudinal direction of steel plate.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Coefficients of linear thermal expansion [μ/°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>11.5-12.0</td>
</tr>
<tr>
<td>CFRP plate</td>
<td>0-1.0</td>
</tr>
<tr>
<td>Aluminum alloy</td>
<td>21.0-24.0</td>
</tr>
</tbody>
</table>
In the specimen, stress reduction ratio, $\xi_0$, is 0.67. Therefore, when the axial load is applied, the stress in steel plate strengthened by CFRP plate becomes 0.67 times smaller than that without CFRP plates. $\xi_0$ can be calculated by the following equation.

$$\xi_0 = \frac{E_s A_s}{E_s A_s + 2E_f A_f} \quad (3)$$

where,

- $E_s$: Young’s modulus of steel,
- $A_s$: Cross sectional area of steel plate.

To design the laminated plate, $\alpha_s = 12\mu^\circ/\text{C}$, $\alpha_f = 1\mu^\circ/\text{C}$ and $\alpha_e = 23\mu^\circ/\text{C}$ are assumed in this study. By substituting these values to Eq.(2), $E_s A_s / (E_f A_f)$ becomes 1. Therefore, by replacing one CFRP plate in Specimen-CC to an aluminum plate with same tension stiffness, liner thermal expansion coefficient of laminated plate becomes the same as that of steel without change in stress reduction ratio.

Specimens-CA and AC with laminated plates are shown in Figs.1b and 1c, respectively. In Specimen-CA, the aluminum plates of 2mm thickness and Young’s modulus of 70GPa are adhered on the CFRP plates. In Specimen-AC, the aluminum plates of 2mm thickness are inserted between steel and CFRP plates.

In the Specimen-ACA, two aluminum plates of 1mm thickness and the CFRP plate of 1mm thickness are bonded onto steel plate, as illustrated in Fig.1d.

Additionally, for the compassion of behavior of thermal stress induced in steel plate, two aluminum plates bonded onto steel plate, Specimen-AA, is also prepared.

The surfaces of the steel plate were polished with the #100 sandpapers specified in JIS R611. All the
specimens were cured in the temperature of 20°C at least one week.

3.2 Materials
Measured profiles of specimens, which are width of steel, CFRP and aluminum plates, \( b_s \), \( b_f \) and \( b_a \) and thickness of adhesive, \( h \), are listed in Table 2. The material properties of coupon test results are also listed in Table 3. The steel plates used in this study are JIS SS400. CFRP plate is fabricated by pultrusion technique.

3.3 Test Procedure
Locations of strain gages are illustrated in Fig. 2. Heart tests were carried out using electric oven placed in temperature-controlled room of 20°C.

First, test specimens were hungered about 2 hours in the electric oven with opening the door. After the strain measurement at 20°C, door was closed and the temperature in oven was turned up to 40°C. The strains of specimens were measured again after keeping the temperature in oven at 40°C about 2 hours. Measured temperatures at start and end of heat test, \( T_s \) and \( T_e \), are also listed in Table 2.

To confirm the coefficient of liner thermal expansion of materials used as well as to calculate the thermal stresses, strains of free expansion in each material under the temperature change were also measured.

4. TEST RESULTS

4.1 Calculation of Thermal Stress
Thermal stress in steel plate, \( \sigma_s \), was calculated by

\[
\sigma_s = E_s(\varepsilon_{sm} - \varepsilon_{sf}) \tag{4}
\]

where,
\( \varepsilon_{sm} \) : measured strains of steel plate with CFRP and/or aluminum plates,
\( \varepsilon_{sf} \) : measured strains of free expansion of steel plate.

In the same way, thermal stresses in CFRP and aluminum plates, \( \sigma_f \) and \( \sigma_a \), were calculated.

4.2 Thermal stress in steel plates
Thermal stress distributions of all specimens are shown in Fig.3. In these figures, horizontal axis, \( x \), shows the distance from center of the specimens, as shown in Fig.1. In Fig. 3, analytical thermal stress distributions proposed in reference paper [7] were also drawing. Calculation procedure of analytical thermal stress in reference [7] is briefly explained in appendix.
In Specimen-CC, compression thermal stress is induced in steel plate. On the other hand, tensile thermal stress is observed in Specimen-AA. As generally known, thermal stress is induced in composite structures by using the materials with different thermal expansion coefficients. Furthermore, thermal stresses in steel plate near the CFRP or aluminum plates ends are smaller than that in the center of the specimen because of the stress transfer lag, shear lag, by adhesive layers between steel and CFRP or aluminum plates. In the analytical method, shear lag effect of all adhesive layers is considered. Therefore, analytical values and test results show the same tendency.

Generally, thermal stress induced in steel plate strengthened or repaired by CFRP plates, $\sigma_{sT}$, is calculated by

$$\sigma_{sT} = -(1 - \xi)E_s(\alpha_s - \alpha_f)(T_e - T_i) \quad (5)$$

Thermal stress of Specimen-AA is also calculated by substituting $E_s$, $A_s$ and $\alpha_s$ instead of $E_f$, $A_f$ and $\alpha_f$ of Eq.(5).

Thermal stresses of Specimens-CC and AA given by Eq.(5), $\sigma_{sT}$, are illustrated in Figs. 3a and 3b as solid lines. As can be seen from these figures, measured thermal stresses in steel plate at the center of the specimens are on the thermal stress of $\sigma_{sT}$. 
In Specimens-CA, AC and ACA as, shown in Figs.3c to 3e, thermal stresses induced in steel plates are quite small compared with the Specimens-CC and AA. Especially, thermal stress of Specimen-ACA is almost zero along the longitudinal direction of steel plate. Accordingly, the thermal stress induced in steel plate can be widely reduced by additional bonding of aluminum plates.

Thermal stresses in steel plate at the center of specimens with laminated plate can be estimated by

\[ \sigma_{st} = -E_s \left\{ (1 - \xi)(\alpha_s - \alpha_f) + \frac{J}{1 + J}(\alpha_f - \alpha_a) \right\}(T_s - T_1) \]  

(6)

where,

\[ \xi = \frac{E_s A_s}{E_s A_s + 2(E_f A_f + E_a A_a)} \]  

(7)

\[ J = \frac{2E_s A_s}{E_s A_s + 2E_f A_f} \]  

(8)

In Specimen-ACA, cross sectional area of aluminum plate, \( A_a \), is the total area of aluminum plates. The thermal stress, \( \sigma_{st} \), given by Eq.(6) for Specimens-CA, AC and ACA were approximately zero.

4.3 Thermal stress in CFRP and aluminum plates

Distributions of thermal stress on the surface of CFRP or aluminum plate are also plotted in Fig.3.

In Specimens-CC and AA, tensile and compression thermal stresses are respectively induced in CFRP and aluminum plates. They are equilibrated to the thermal stress in steel plates. Therefore, the measured thermal stress at the center of specimens are almost the same as that calculated by the following equations.

\[ \sigma_f = -\frac{A_s}{2A_f}\sigma_{st} \]  

(9)

\[ \sigma_a = -\frac{A_a}{2A_a}\sigma_{st} \]  

(10)

In Specimens-CA, AC and ACA, as shown in Figs. 3c to 3e, thermal stresses in CFRP and aluminum plates are respectively larger than that in Specimens-CC and AA. This is because the difference of linear thermal expansion coefficients between CFRP and aluminum plates is bigger than that between steel and CFRP plate or steel and aluminum plate. Therefore, the thermal stresses of CFRP and aluminum plates, \( \sigma_f \) and \( \sigma_a \), given by the following equations, must be considered to the design of CFRP and aluminum plates.

\[ \sigma_f = E_f \left\{ \xi(\alpha_s - \alpha_f) - \frac{J}{1 + J}(\alpha_f - \alpha_a) \right\}(T_s - T_1) \]  

\[ \sigma_a = E_a \left\{ \xi(\alpha_s - \alpha_f) + \frac{1}{1 + J}(\alpha_f - \alpha_a) \right\}(T_s - T_1) \]  

(11)

(12)

5. CONCLUSIONS

In this study, to reduce the thermal stress induced in steel structures strengthened by CFRP plate, additional bonding of aluminum alloy plates was proposed. Furthermore, heat tests of CFRP and aluminum alloy plates bonded onto steel plate were carried out. Main conclusions are as follows;

(1) A reduction technique of thermal stress induced in steel plate with CFRP plate, which is additional bonding of aluminum alloy plates, was developed.

(2) The required stiffness of aluminum alloy plates to reduce the thermal stress in steel plate with laminated plates can be designed by Eq.(2).

(3) The proposed method can significantly reduce the thermal stress in steel plate compared with conventional CFRP bonded steel plate.

(4) Design thermal stresses induced in CFRP and aluminum alloy plates can be estimated by Eqs.(11) and (12), respectively.

ACKNOWLEDGEMENT

The authors acknowledge Mr. T. Furutani of Kyoto University who contributed to the heat tests.

APPENDIX

Analysis method of thermal stresses in steel, CFRP, aluminum plates and adhesive layers has been proposed in reference [7]. In the proposed analysis method, stress in steel plate multilayered reinforcing plates, as shown in Fig.A1, can be calculated by following equation.

\[ \sigma(x) = D(e(x) - e_f) \]  

(A1)

where,
Fig. A1 steel plate multilayered reinforcing plates

\[ D = \begin{bmatrix} E_i & 0 & \ldots & 0 \\ G_{ei} & E_i & \ddots & \vdots \\ \vdots & \ddots & \ddots & 0 \\ G_{ei} & \ldots & 0 & E_i \end{bmatrix} \]  
(A2)

\[ \sigma(x) = \left[ \sigma_s(x), \sigma_t(x), \tau_t(x), \ldots, \sigma_s(x), \tau_t(x) \right]^T \]  
(A3)

\[ \varepsilon(x) = \left[ \varepsilon_s(x), \varepsilon_t(x), \gamma_t(x), \ldots, \varepsilon_s(x), \gamma_t(x) \right]^T \]  
(A4)

\[ e_x = \begin{bmatrix} \varepsilon_{x1} & \varepsilon_{x2} & \ldots & \varepsilon_{xN} \end{bmatrix} \]  
(A5)

\[ \varepsilon_{x1} = \varepsilon_{x1}^{T_e} \]  
(A6)

\[ \varepsilon_{x2} = \varepsilon_{x2}^{T_e} \]  
(A7)

where,

- \( E_i \): Young’s modulus of the \( i \)th reinforcing plate,
- \( G_{ei} \): shearing modulus of the \( i \)th adhesive layer,
- \( \sigma_s(x) \): stress in steel plate at \( x \),
- \( \sigma_t(x) \): stress in the \( i \)th reinforcing plate at \( x \),
- \( \tau_t(x) \): shear stress in the \( i \)th adhesive layer at \( x \),
- \( \varepsilon_s(x) \): strain in steel plate at \( x \),
- \( \varepsilon_t(x) \): strain in the \( i \)th reinforcing plate at \( x \),
- \( \gamma_t(x) \): shear strain in the \( i \)th adhesive layer at \( x \),
- \( \alpha_i \): linear thermal expansion coefficient of the \( i \)th reinforcing plate,
- \( i \): integers from 0 to \( N \),
- \( N \): number of reinforcing plates or adhesive layers.

\( \varepsilon(x) \) is given by solving the next differential equation [8].

\[ \frac{d\varepsilon(x)}{dx} = A\varepsilon(x) \]  
(A8)

where,

\[ A = \begin{bmatrix} 0 & 0 & \frac{2G_{ei}}{E_i t_e} \frac{h_i}{h_t} \\ 0 & 0 & -\frac{G_{ei}}{E_i t_t} \\ \frac{1}{h_i} & \frac{1}{h_t} & 0 \end{bmatrix} \]  
\((N = 1)\)  
(A9-1)

\[ A = \begin{bmatrix} 0 & 0 & \frac{G_{ei}}{E_i t_e} \frac{h_i}{h_t} \\ 0 & \ddots & \vdots \\ \frac{1}{h_i} & \ldots & 0 \end{bmatrix} \]  
\((N \geq 2)\)  
(A9-2)

\( t_i \): thickness of the \( i \)th reinforcing plate,
\( b_i \): width of the \( i \)th reinforcing plates,
\( b_j \leq b_{i+1} \leq b_i \),
\( h_i \): thickness of the \( i \)th adhesive layer.

General solution of \( \varepsilon(x) \) is given by

\[ \varepsilon(x) = Y(x)C \]  
(A10)

where,

\[ C = \begin{bmatrix} C_1 & \cdots & C_N \end{bmatrix} \]  
(A11)

\[ Y(x) = \text{Te}^{A(x)T}^{-1} \]  
(A12)
\[
\begin{bmatrix}
\epsilon_{1x} & \cdots & 0 \\
0 & \ddots & \epsilon_{ix}
\end{bmatrix}
\]
(A13)

\[
\begin{bmatrix}
\epsilon_{1x} & \cdots & 0 \\
0 & \ddots & \epsilon_{ix}
\end{bmatrix}
\]
(T_{(2i+1)x_{(2i+1)}}) = [v_1 \ldots v_j]
(A14)

\lambda_j : j \text{th eigenvalue of matrix } A,

\nu_j : j \text{th eigenvalue vector of matrix } A,

C_j : j \text{th unknown coefficient},

j : integer from 1 to 2i + 1.

Unknown coefficient vector, C, is given by boundary conditions and continuous conditions of strains. In this study, C is calculated by the following equation under the conditions of 
\[\varepsilon_x(l) = \sigma_{\text{sw}}/E_x, \quad \varepsilon_y(l) = 0 \quad \text{and} \quad \gamma_y(0) = 0.\]

\[
C = B^{-1}(e_0 + e_f)
\]
(A15)

where, 
\[
e_0 = \left(\frac{\sigma_{\text{sw}}}{E_x} 0 \cdots 0\right)^T
\]
(A16)

B_{(2i+1)x_{(2i+1)}} : matrix with first and 2i rows of matrix Y(l) and 2i + 1 row of matrix Y(0),

l : half length of reinforcing plates,

\sigma_{\text{sw}} : applied stress.

REFERENCES


