DELAMINATION OF THE BOND INTERFACE BETWEEN FRP AND STEEL PLATE AND ITS STRUCTURAL HEALTH MONITORING

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ABSTRACT

In the present study the mechanical and delamination behavior of bond interface between FRP and steel plate has been investigated. Tension tests for eleven FRP reinforced steel strips and nine FRP-steel lap joints have been carried out. Analytical solutions for simple modelling considering bond interface shear stresses have been obtained and compared with experimental results. Fiber Bragg grating sensors have been installed in the bond interface for structural health monitoring. The fiber Bragg grating power spectra have shown to inform the initial occurrence of delamination. Alternative new estimation methods using the outputs of FBG sensors for the fracture of the bond interface have been proposed.

KEYWORDS

Delamination, Interface, Pultrusion, Fiber Bragg Grating Sensor.

INTRODUCTION

During last decade, the use of composite materials for strengthening and repair of existing structures has increased (e.g. Al-Emrani et al. 2005; Schnerch et al. 2005). Especially it would be interested in the reports in which steel structures have been strengthened or repaired using adhesively-bonded fiber laminates (Luke 2001; Miller et al. 2001). Also structural health and the damage identification should be assessed after various natural disasters. This kind of structural health monitoring requires an alternative long-time, high accuracy and stable sensor. The structural health monitoring using optical FBG (fiber Bragg grating) sensors has shown to give high accuracy strain data. The present authors have carried out various tests in which FBG sensors were installed and have shown that the optical power for FRP material decreases as the load increases, and its shape has two peaks after reaching some load levels (e.g. Yamada et al. 2006, 2007 and 2008). When this spectrum has two peaks, the strain responses have changed like two different FBG sensors due to the occurrences of small transverse cracks inside the FRP material under locally large stress concentration. Even for steel material, they have also shown that the shape have two peaks after reaching at yielding stress. In this study, FRP reinforced steel strips and FRP-steel lap joints have been subjected to tension loading. Simple analytical stress distribution considering bond interface shear stress has been obtained and compared with experimental results. FBG sensors have been installed in the bond interface for structural health monitoring. The FBG power spectra have shown to inform the initial occurrence of delamination load. Alternative new methods of structural health monitoring for the bond interface have been discussed.

FRP REINFORCED STEEL STRIPS

Experimental Method

Figure 1 shows a tensile test specimen for TD-series (double side reinforced steel plate) shown in Table 1. FRP plates having a length of 200 mm, a thickness of 4 mm and a width 25 mm were installed on a steel plate having a length 500 mm, a thickness of 12 mm and a width of 25 mm. The reinforcement was completed by bonding the pultruded FRP strips. The adhesion was produced by Fukui Fibertech Co. They...
consist of uni-directional roving layer (along the longitudinal direction) and UP (unsaturated polyester) resin. The fiber volume is 57% of the total volume and the measured average of Young’s modulus through coupon tensile tests is 45 GPa. The adopted epoxy adhesive for bonding steel and FRP was used and its length of the bonded FRP strips used was 200 mm. The TG-series in Table 1 mean the specimens for single side reinforced steel plate. The thickness of adhesive interface $t_a$ was not controlled but was seen a roughly around 0.4 mm for all the specimens through the measurements after testing.

Seven specimens in total eleven ones have FBG sensors at the bonded steel/FRP interface. For the precise variations of optical wavelength associated with the strain quantities of the steel and FRP in the interface, the sensor “FBG-F” and the sensor “FBG-S” were pasted at the FRP side and at the corresponding steel side, respectively. Both sensors whose centre points were a 15 mm distance from the edge of FRP reinforcement, were placed along longitudinal direction for obtaining tensile stains and the corresponding tensile stresses at this local point.

The FBG sensor consists of the clad and the core in which the simple elements called Bragg diffraction grating are photo-imprinted. In this experiment, the adopted sensors have 10 millimetres length and 20,000 gratings. When a broadband spectrum light comes in through the grating, the specific narrowband spectrum light reflects, and the reflection wave depends on the grating pitch, and called “Bragg wavelength”. The strain response arises due to the elongation of the sensor that corresponds to fractional change in grating pitch. The measured shift in Bragg wavelength is calibrated to the corresponding strain value, in this experiment, one nanometre wavelength is 833 micro-strains. The tensile tests for steel strips carried out by the authors have already showed that initially one peak type of waveshape mode is changed to be of two or three peaks just after yielding. The waveshape becomes the multi-peak type at the occurrences of fatigue yielding of steel because the yielding results from the shear localization of the multi crystal steel material, and in trinsically a accompanies the localization of plastic deflection, say, “Lunders band”. Indeed, the diameter of the crystal of normal steel is around from 10 to 60 micro-meters, therefore, the crystal size is the grating pitch multiplied by 20 to 120.

### Stress Analysis

Using strain data by conventional electric strain gauges, ESG7, ESG8 and ESG9, the axial steel stress distribution of No. TD78F at initially loaded 60kN level are plotted by square dots in Figure 2. In this figure, heavy curves show theoretical distributions for the axial force of steel $S_s$ and the shear of the epoxy adhesive interface $\tau$. For obtaining the theoretical results the following fundamental differential equation for $S_s$ on account for the coordinate $x$ from the center of the specimen shown in Figure 2 are adopted,

$$\frac{d^2S_s}{d\xi^2} - \lambda^2S_s = \frac{P_G}{2E_f t_f t_a}$$

(1)

where $\lambda = \sqrt{\frac{G_a t_f}{E_a t_a} \left( \frac{2}{E_a t_a} + \frac{1}{E_f t_f} \right)}$, $G_a = \frac{E_a}{2(1 + \nu_a)}$, $\xi = \frac{x}{l}$. Also $E_s$, $E_a$ and $E_f$ are the Young’s modulus of steel, adhesive and FRP, respectively, $t_s$, $t_a$ and $t_f$ are the thickness of steel, adhesive and FRP, respectively;

### Table 1. FRP reinforced steel strip specimens.

<table>
<thead>
<tr>
<th>No.</th>
<th>Memo</th>
</tr>
</thead>
<tbody>
<tr>
<td>TG61N</td>
<td>single without FBG</td>
</tr>
<tr>
<td>TG62F</td>
<td>single with FBG</td>
</tr>
<tr>
<td>TG63F</td>
<td>single with FBG</td>
</tr>
<tr>
<td>TD71N</td>
<td>double without FBG</td>
</tr>
<tr>
<td>TD72N</td>
<td>double without FBG</td>
</tr>
<tr>
<td>TD73N</td>
<td>double without FBG</td>
</tr>
<tr>
<td>TD74F</td>
<td>double with FBG</td>
</tr>
<tr>
<td>TD75F</td>
<td>double with FBG</td>
</tr>
<tr>
<td>TD76F</td>
<td>double with FBG</td>
</tr>
<tr>
<td>TD77F</td>
<td>double with FBG</td>
</tr>
<tr>
<td>TD78F</td>
<td>double with FBG</td>
</tr>
</tbody>
</table>

Figure 1. Double side reinforced steel plate specimen for TD-series (in mm).
and \( \nu_a \) is the Poison’s ratio of adhesive. The half length of FRP reinforcement length \( l \) is in this study adopted as 100mm, and then the solution of Eq.1 is obtained using as follows

\[
\sigma_s = \frac{2S_s}{bt_s} = \frac{P}{bt_s} \left( \frac{2}{2+k} \right) \left( k + \frac{\cosh \lambda \xi}{\cosh \lambda} \right) \quad \text{(axial stress of steel in \(-l < x < l\))} \tag{2}
\]

\[
\sigma_f = \frac{S_f}{bt_f} = \frac{P}{2bt_f} \left( \frac{2}{2+k} \right) \left( 1 - \frac{\cosh \lambda \xi}{\cosh \lambda} \right) \quad \text{(axial stress of FRP)} \tag{3}
\]

\[
\tau = \frac{P}{2lb} \frac{\lambda}{2+k} \frac{1}{\cosh \lambda} \sinh \lambda \frac{\xi}{\cosh \lambda} \quad \text{(shear stress of adhesive)} \tag{4}
\]

where \( b \) is the width and \( k = E_a t_a / (E_f t_f) \). In this paper, \( E_s = 205\text{GPa}, \ E_a = 2.7\text{GPa}, \ E_f = 45\text{GPa}, \ t_a = 0.4\text{mm} \) and \( \nu_a = 0.36 \) are used.

![Figure 2. Stress distribution at \( P = 60\text{kN} \) (TD78F).](image)

![Figure 3. Load versus strain curves(TD77F).](image)

![Figure 4. Delamination detail.](image)

![Figure 5. Examples of waveshape measurement outputs.](image)

![Figure 6. Load versus \( \Delta \varepsilon \) relations (TD77F).](image)
Results and Discussions

Figures 3, 4, 5 and 6 show an example of No.TD77F for double side reinforcement. Figure 3 is the load versus strain curves, in which ESG-F are the average of ESG-F1, ESG-F2, ESG-F3 and ESG-F4 data in Figure 1. The vertical axis $P_{op}$ in Figure 5 is normalized by the maximum power of input optic source. First cracks were seen in the edge portion near the installation points of electric strain gauges, ESG-F3 and ESG-F4 over the 60kN load levels. But Figure 5 obtained from the output data of FBG-F shows that the waveshape at a 54.7kN load level changed completely different from that at initial unloaded state. This waveshape change suggests the sign of the delamination failure of the interface.

Figure 6 shows an example of the results of delamination occurrence estimation, $P_{sep}$. The horizontal axis in Figure 6 is $\Delta \varepsilon$ which is the difference of FBG-S strain with FBG-F strain. By using the least square method for the used of the two straight lines, $P_1 = a\Delta \varepsilon$ and $P_2 = b\Delta \varepsilon + c$, the coefficients $a$, $b$ and $c$ are obtained from the measured data. Then the cross-point of these two lines is now defined as the initial delamination load, $P_{sep}$, related with the measured data of some delamination failure. Including other specimen data, it is shown that the results from the present identification method for the initial occurrence of delamination load using the least square method for bilinear modelling with the FBG output data of the interface are around half of maximum load $P_{max}$ (full delamination load). And it was also confirmed by the re-check of FBG waveshape measurement data that they are consistent with the loads of the power spectrum shape change except for No.TG62F in which the delamination area were far from the FBG installation place.

LAP JOINT BETWEEN GFRP PLATES AND A STEEL GUSSET

Experimental Method

Figure 7 shows the tensile test specimens, JD-series shown in Table 2. Two FRP plates having a length of 280 mm, a thickness of 4 mm and a width of 50 mm were doubly lapped on a steel gusset plate having a length 300 mm, a thickness of 19 mm and a width of 50 mm. In the present experiments, the thickness of adhesive interface $t_a$ was controlled using the installation of 0.4mm diameter steel balls for JD04-series, 0.8mm ones for JD08-series or 1.2mm ones for JD12-series.

For three specimens in total nine ones, a FBG sensor whose diameter is around 0.2mm was installed in the layer of the adhesive interface. But the direction was adopted to be along the transverse direction of axial force shown in the A-A’ section diagram of Figure 7.

Stress Analysis

The axial stress data of steel at a 22.8kN load are plotted by square dots for No.JD08N in Figure 8. In the figure, heavy curves and are theoretical distributions for the axial stress of steel $\sigma_x$ and the shear of the epoxy adhesive interface $\tau$. Since the coordinate $x$ from the center of 80 mm lapped length shown in Figure 8 is adopted, then $l$ in Eq.1 is 40 mm in the present specimens. From the similar way to reinforced strips, the theoretical solution of Eq.1 are obtained as follows.
\[ \sigma_s = \frac{2S_s}{bt_s} = \frac{P}{bt_s} \left( \frac{\sinh \lambda \xi}{2 \sinh \lambda} + \frac{2 - k}{2 \cosh \lambda} + \frac{k}{2 + k} \right) \] (axial stress of steel in \(-l < x < l\)) (5)

\[ \sigma_f = \frac{S_f}{bt_f} = \frac{P}{2bt_f} \left( \frac{\sinh \lambda \xi}{2 \sinh \lambda} - \frac{2 - k}{2 \cosh \lambda} + \frac{2}{2 + k} \right) \] (axial stress of FRP) (6)

\[ \tau = \frac{P}{4bl} \lambda \left( \frac{\sinh \lambda \xi}{\sinh \lambda} \right) \left( \frac{2 - k}{2 + k} \right) \cosh \lambda \] (shear stress of adhesive) (7)

\[ \sigma_s (N/mm^2) \]

\[ \tau (N/mm^2) \]

Figure 8. Stress distribution at \( P = 22.8kN \) (JD08N).

Figure 9. Load versus strain curves.

Figure 10. Examples of waveshape measurement outputs.

Figure 11. Load versus \( \Delta F \) relations.

Figure 12. Delamination collapse views of two interfaces for JD12F.

Results and Discussions

Figures 9, 10 and 11 show the results of No.JD04F, JD08F and JD12F. In Figure 9 the load versus strain curves obtained by the wavelength measurement of FBG-A installed in the interface suggests the nonlinearity over
80kN load level. The maximum loads were 124.5kN for JD04F, 131.3kN for JD08F and 95.2kN for JD12F and gave the high maximum average shear stress even for JD12F in which $t_{\text{avg}}$ was 23.8N/mm$^2$. In Figure 10, the value of $F_{\text{op}}$ is normalized by the maximum power of input optic source and the shapes of (c1), (c2) and (c3) have a multi-peak types or spindle types. They suggest the non-uniform strain distribution of the sensor installation position. The peak value of $F_{\text{op}}$ spectra decreases as the load increases. Finally just before the maximum loads it was very low. Figure 11 shows the variations of $\Delta F$ which is defined as the current $F_{\text{op}}$ minus that at the initial pre-loading state ($P=0$). Some loading levels marked triangles may show the delamination occurrence due to micro-fracture in the adhesive interface. Figure 12 is example photos showing delamination behaviors at the interfaces. All in the test specimens the steel face sides have shown to have the bond layer and FRP skin and it means that the final delamination occurred in the FRP laminate.

**CONCLUSIONS**

In this paper, tension tests for eleven FRP reinforced steel strips and nine FRP-steel lap joints have been carried out. Analytical solutions for simple modelling considering bond interface shear stresses have been obtained and compared with experimental results. Fiber Bragg grating sensors have been installed in the bond interface for structural hearth monitoring. The fiber Bragg grating power spectra have shown to inform the initial occurrence of delamination. Alternative new estimation methods using the outputs of FBG sensors for the fracture of the bond interface have been proposed. The present successes suggest the usefulness of the application of FBG sensing to various FRP-steel hybrid structures in the future.

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**REFERENCES**


