Application of photoelastic coating technique in tests of solid wooden beams reinforced with CFRP strips

T.P. NOWAK, L.J. JANKOWSKI, J. JASIEŃKO
Wrocław University of Technology, Wybrzeże Wyspianskiego 27, 50-370 Wrocław, Poland

The paper presents selected results of tests carried out on hundred year old joists strengthened with carbon fibre reinforced polymers (CFRP). Besides the conventional electric-resistance extensometers (ERSG), the photoelastic coating technique (PCT) was used to measure strains in the reinforced (bonded) cross sections. No such attempt to apply PCT has been described in the literature before. The technique requires further studies to verify agreement between its results and the ones obtained by conventional measuring techniques.

Keywords: timber structures, strengthening, CFRP, rehabilitation, photoelastic coating technique, four-point bending

1. Introduction

The preservation of historic wooden components covers not only their technical condition, but also the artistic and cultural value of the building as a whole, including its ornamental details (often in the form of original woodcarving and polychrome). According to the Venice Charter, any measures taken with regard to national heritage buildings are to preserve and reveal the historic and aesthetic value the building, respecting the ancient substance and elements constituting authentic documents of the past. It is, however, allowed to strengthen historic buildings using modern conservation, construction and engineering techniques, provided the principles of conservation doctrine are adhered to [1–6].

The advances made in materials technology have significantly contributed to the development of construction and conservation technologies. When high-strength epoxy resins were synthesized in the late 1960s, attempts were made to use them to strengthen building structures. Compositions based on synthetic resins can be used to reinforce structural cross sections, to reproduce cross-sectional geometry and to produce joints bonding the reinforcing element with the reinforced one. The use of resins and gluing is becoming a recognized way of conserving timber structures, except for surface protection [3, 7–8].

The load-bearing capacity of components subjected to bending is usually determined by the cross-sectional tension zone. Wood defects in the tension zone reduce the load-
bearing capacity of the component much more than wood defects in the compression zone. A possible way of strengthening is to use reinforcement in the form of, for example, steel bars and plates and FRP (Fibre Reinforced Polymers) rods and strips [9–13]. Epoxy adhesives are mainly used to bond the reinforcement with the wood [14]. Steel plates and FRP materials are also used to reinforce shearing zones [15–16].

FRP composite materials are increasingly often used to reinforce wooden elements, increasing their load-bearing capacity and stiffness and endowing them with a more uniform structure [17–20]. Moreover, the new materials can be used to strengthen historic components in poor technical condition. FRP composites are usually reinforced with carbon fibres (CFRP), glass fibres (GFRP) and aramid fibres (AFRP).

This paper presents selected results of experimental research aimed at applying CFRP strips to reinforce defective (biological corrosion, inclusions, slope of grain, cracks) wooden beams and restore their load-bearing capacity, with a special focus on a comparison of strains measured by electric-resistance strain gauges with the ones determined using the photoelastic coating technique.

2. Material and method

2.1. Material

Wooden (pine) joists from a hundred (ca) year old building were the subject of the investigations. Different ways of reinforcing the beams with CFRP strips, presented in [e.g. 11, 20–21], were applied. Series A beams were not reinforced and served as the reference. In total, 21 beams (including 18 one hundred year old ones; 7 types, 3 beams in a series), each 4000 mm long and 120×220 mm in cross section, were tested. Test results for the series F beams are presented.

The series F beams were reinforced in the maximum bending moment zone with 400–600 mm long CFRP strips in a horizontal arrangement. The weakening of the tension zone was simulated by a cut out hole 25 mm in diameter (Figure 1).

![Fig. 1. Reinforcement scheme for beams of series F [mm]](image)
Because of its consistency (making it easy to insert the reinforcement into the cross section), adhesive S&P Resin 55 (based on epoxy resin) for composite mats was used.

Table 1. Technical data of CFRP strip

<table>
<thead>
<tr>
<th>Kind of strip</th>
<th>Strip width/breadth $b$ [mm]</th>
<th>Strip thickness $t$ [mm]</th>
<th>Young’s modulus $E$ [GPa]</th>
<th>Tensile strength $f_t$ [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFK S&amp;P 150/2000</td>
<td>50</td>
<td>1.2</td>
<td>165</td>
<td>2800</td>
</tr>
</tbody>
</table>

2.2. Method

The beams were subjected to four-point bending (Figure 2) on a testing stand shown in Figure 3.

![Fig. 2. Loading configuration and dimensions of tested beams in [mm]](image)

![Fig. 3. Beam F2 on testing stand](image)
Fork support, preventing loss of flexural stability (buckling), was used. Loading was applied by a servomotor made by VEB Verkzeugstoffprüfmaschine Leipzig and the force was measured by an ETP 7920-16 force gauge made by MOM Kalibergyár. The results were registered by a PC and a multichannel measuring system UPM 100 made by Hottinger Baldwin Messtechnik. The measuring equipment used in the tests was calibrated to 1% of the indication error in at least accuracy class 1.

During measurements the following were registered: the loading force (including the ultimate force) by the computer system, beam displacement in the middle cross section and on the supports by induction gauges W50 TS, strains in the wood by electric-resistance strain gauges RL 300/50 and strains in the strip by electric-resistance strain gauges RL 120/20. On the lateral surfaces of the beams (in the middle of their span) strain gauges were stuck on as shown in Figure 4. On the strips strain gauges were stuck on at every 50 mm along the whole length of each strip (Figure 5).

![Fig. 4. Arrangement of electric resistance strain gauges on lateral surface of beam $F$ [mm]](image1)

![Fig. 5. Arrangement of electric resistance strain gauges on strip in beam $F$ [mm]](image2)

Strains in the middle cross section of the tested beams were measured by electric-resistance strain gauges (ERSG) and on the opposite lateral surfaces by means of the photoelastic coating technique (PCT).

The photoelastic coatings were made of epoxy resin Epidian 5 with di-naphthalate addition, cold hardened with amino hardener Z-1 (100:12.5:10 parts by weight). The plate was 1.9 mm thick, 400 mm wide and 200 high. The coatings were glued to the lateral surfaces of the beams in the bending region, using an adhesive with an aluminium dust addition. A polariscope of V type (model 031 made by Vishay) and a digital camera were used to record images of (full- and half-order) isochromatic fringes.

Photoelastic measurements were performed using the field method. Full- and half-order ($N = 0, 1, 2...$ and $N = 0.5, 1.5, 2.5...$) isochromatic images were recorded. The information about the location of the particular isochromatic fringes in the analyzed cross section was used to determine the strain pattern. The accuracy of estimating the location of an isochromatic fringe of a given order was ± 0.1 of the isochromatic fringe order.
The surface of beam F2 prior to sticking on the photoelastic coating is shown in Figure 6. A knot, a hole, slots with bonded-in strips, natural cracks and the characteristic pattern of fibres around the knot are visible.

![Image of beam F2 surface](image)

Fig. 6. Surface of beam F2 before photoelastic coating was stuck on [21]

### 3. Results

Table 2 shows ultimate force values for beams of series A and F. The increase in load-bearing capacity for the series F beams relative to the series A beams (unreinforced reference beams) was calculated from formulae (1).

$$
\Delta F_u = \frac{F_{u,F} - F_{u,A}}{F_{u,A}} \cdot 100\%
$$

(1)

where $F_u$ is the mean ultimate force value for a particular beam series.

The increase in the load capacity of the tested elements reinforced with CFRP strips is significant since it amounted to 21% for the series F beams and to slightly above 79% for the series D beams [20–21]. The results for series F are very similar, which should be regarded as exceptional for full-size solid wooden cross sections (Table 2 and Figure 7).

<table>
<thead>
<tr>
<th>Beam</th>
<th>A1</th>
<th>A2</th>
<th>A3</th>
<th>F1</th>
<th>F2</th>
<th>F3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultimate force $F_u$ [kN]</td>
<td>27.02</td>
<td>30.69</td>
<td>35.01</td>
<td>37.59</td>
<td>36.49</td>
<td>38.08</td>
</tr>
<tr>
<td>Mean ultimate force $F_{u,av}$ [kN]</td>
<td>30.91</td>
<td>37.39</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Increase in load capacity $\Delta F_u$ [%]</td>
<td>–</td>
<td>21.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 7 shows static equilibrium paths and, for comparison, a trend line (determined by the least squares method) for the three tested reference beams. Limit deflection L/250 for floors and deflection L/167, i.e. increased by 50% for old (historic) building under repair are represented by vertical lines [22].
Fig. 7. Equilibrium paths for series F beams

Fig. 8. Normal stress in bottom strip in beam F2

Fig. 9. Tangential stress in bond for bottom strip in beam F2
Figure 8 shows the normal stress pattern in the bottom strip of beam F2 while the tangential stress in the adhesive-bonded joint is shown in Figure 9. For the series F beams the maximum stress in the bottom strip was 363 MPa (strain in beam F1 was registered at a force of 37.2 kN immediately before the beam failed). The degree of strip cross section use was less than 13%. The tensile strength of the strip is 2800 MPa (Table 1).

The strains in the central cross sections of the tested beams were calculated on the basis of the recorded photoelastic images, from this basic relation [23–24]:

\[
(\varepsilon_1 - \varepsilon_2) = N \cdot f_\varepsilon, \tag{2}
\]

where:
- \(\varepsilon_1, \varepsilon_2\) – the principal strains [\(\text{[-]}\)],
- \(N\) – the fringe order [\(\text{[-]}\)].

\[
f_\varepsilon = \frac{\lambda}{2t_c \cdot K}, \tag{3}
\]

where:
- \(\lambda\) – the wavelength of the white light used during recording [m],
- \(t_c\) – the thickness of the photoelastic coating [m],
- \(K\) – an optical strain coefficient [\(\text{[-]}\)].

Strain isochromatic order \(f_\varepsilon = 1.501 \times 10^{-3}\) was adopted for the calculations.

Figures 10–23 show exemplary images of full-order isochromatic fringes and strain \(\varepsilon(h)\) distributions for different loading levels (beam F2).
Fig. 12. Isochromatic fringes – beam F2 ($F = 15.1$ kN)

Fig. 13. Strain in wood in bent section – beam F2 ($F = 15.1$ kN)

Fig. 14. Isochromatic fringes – beam F2 ($F = 20.1$ kN)

Fig. 15. Strain in wood in bent section – beam F2 ($F = 20.1$ kN)

Fig. 16. Isochromatic fringes – beam F2 ($F = 25$ kN)

Fig. 17. Strain in wood in bent section – beam F2 ($F = 25$ kN)
Application of photoelastic coating technique in tests of solid wooden beams reinforced.

Fig. 18. Isochromatic fringes (with marked analyzed section) – beam F2 ($F = 30 \text{ kN}$)

Fig. 19. Strain in wood in bent section – beam F2 ($F = 30 \text{ kN}$)

Fig. 20. Isochromatic fringes – beam F2 ($F = 34.5 \text{ kN}$)

Fig. 21. Strain in wood in bent section – beam F2 ($F = 34.5 \text{ kN}$)

Fig. 22. Isochromatic fringes – beam F2 ($F = 36.4 \text{ kN}$)

Fig. 23. Strain in wood in bent section – beam F2 ($F = 36.4 \text{ kN}$)
An analysis of the isochromatic fringe images and strain $\varepsilon(h)$ distributions in beam F2 (Figures 10–19) showed that:

- the distribution of strain $\varepsilon(h)$ in the analyzed cross section is nonlinear and its disturbances increase with the load and are closely connected with the structure of the investigated surface,
- the sign of strain $\varepsilon(h)$ changes at a distance of ca 95 mm from the lower edge of the beam and this point shifts only slightly as the load increases,
- the effect of the hole on strain distribution in the tensioned zone is clearly visible, whereas the knot located at the level of the beam’s theoretical neutral axis generates a lower strain gradient,
- changes in the $\varepsilon(h)$ value in the extreme fibres of the tensioned zone indicate the influence of the bottom strip: initially $\varepsilon(h)$ increases and from the load of 25.0 kN decreases, which is probably connected with the interference of strain fields generated by the hole located above, the influence of the strip and the bending of the beam; after the ultimate force value (36.49 kN) was reached, the strip came unstuck from the wood.

Thanks to the use of the photoelastic coating the state of strain in the investigated area of the beam could be qualitatively and quantitatively assessed for the whole loading range. The comparison of the strain values (calculated on the basis of the images of isochromatic fringes) for the loads of 34.5 kN (Figure 20) and 36.4 kN (Figure 22) indicates that when the load of 34.5 kN was exceeded, the beam entered the stage of failure. This is corroborated by the disproportionately large increase in strain relative to the increase in force, the nonlinearity of the deflection-force function and the characteristic patterns of isochromatic fringes around the tips of the cracks propagating during this stage of loading. For example, Figure 24 shows a pattern of isochromatic fringes indicating that the loading of the crack’s edges corresponds to mode I with a small percentage of mode II. Although cracking was not closely analyzed here, one should note that the obtained information (images of isochromatic fringes) makes such analysis possible.

![Fig. 24. Characteristic pattern of isochromatic fringes at crack’s tip](image-url)
In order to quantitatively compare the strain measuring techniques, the relative difference $\Delta \varepsilon$ between the strains measured by strain gauges and the ones determined using the photoelastic coating technique was calculated for the points corresponding to the extreme strain gauges (Figure 4). The results for different load levels are compared in Table 3. The values of $\Delta \varepsilon$ were calculated from the formula:

$$\Delta \varepsilon = \left| \frac{\varepsilon_g - \varepsilon_p}{\varepsilon_g} \right| \cdot 100\%,$$  \hspace{1cm} (4)

where:

$\varepsilon_g$ – strain in the timber, obtained from electrical-resistance strain gauge (ERSG) measurements,

$\varepsilon_p$ – strain in the timber, obtained from photoelastic measurements (PCT).

Table 3. Comparison of strains in cross section of wood, determined by ERSG measurements and PCT measurements, for different load levels

<table>
<thead>
<tr>
<th>Force $F$ [kN]</th>
<th>Height of beam $h$ [mm]</th>
<th>Strain (ERSG) $\varepsilon_g$ [\mu m/mm]</th>
<th>Strain (PCT) $\varepsilon_p$ [\mu m/mm]</th>
<th>Relative differences in strain $\Delta \varepsilon$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.1</td>
<td>5</td>
<td>759</td>
<td>1037</td>
<td>36.6</td>
</tr>
<tr>
<td></td>
<td>210</td>
<td>-667</td>
<td>-942</td>
<td>41.2</td>
</tr>
<tr>
<td>15.1</td>
<td>5</td>
<td>1187</td>
<td>1477</td>
<td>24.4</td>
</tr>
<tr>
<td></td>
<td>210</td>
<td>-1018</td>
<td>-1013</td>
<td>1.5</td>
</tr>
<tr>
<td>20.1</td>
<td>5</td>
<td>1636</td>
<td>1724</td>
<td>5.4</td>
</tr>
<tr>
<td></td>
<td>210</td>
<td>-1353</td>
<td>-1326</td>
<td>2.0</td>
</tr>
<tr>
<td>25.0</td>
<td>5</td>
<td>2081</td>
<td>2114</td>
<td>1.6</td>
</tr>
<tr>
<td></td>
<td>210</td>
<td>-1663</td>
<td>-1395</td>
<td>16.1</td>
</tr>
<tr>
<td>30.0</td>
<td>5</td>
<td>2571</td>
<td>2640</td>
<td>2.7</td>
</tr>
<tr>
<td></td>
<td>210</td>
<td>-1954</td>
<td>-1580</td>
<td>19.1</td>
</tr>
<tr>
<td>34.5</td>
<td>5</td>
<td>3035</td>
<td>2537</td>
<td>16.4</td>
</tr>
<tr>
<td>36.4</td>
<td>5</td>
<td>3250</td>
<td>3171</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Fig. 25. Failure mode of beam F2
The mode of failure of beam F2 is shown in Figure 25. In none of the tested models the CFRP strip was found to fail. In most cases the beam failed along wood fibres, but not at the glue-wood boundary.

4. Conclusions

The investigations [21–22] have shown that the photoelastic coating reproduces well the structure of wood, including its cracks, defects, nail marks and connector (wooden plugs, screws, nails, etc.) holes.

When a photoelastic coating was stuck on, strain diagram disturbances caused by tangential stresses could be observed in the discontinuities (notches) in the cross section. Electric-resistance extensometry alone does not offer such possibilities since the measurements have a quasi-pointwise character, whereas the photoelastic coating supplies information from the whole surface.

The differences between the strain values measured by the strain gauges and the ones determined using the photoelastic method (Table 3) should be ascribed to structural differences (in wood fibre patterns, concentration of fibres, structural cracks and inclusions) between the two opposite lateral sides of the beams. It is impossible to produce a 120×220 mm (the tested beam cross section) wooden beam which would have an ideally parallel pattern of fibres on both sides.

To sum up, thanks to the use of the photoelastic coating the interaction between the reinforcing elements and the reinforced structure could be assessed more precisely. Therefore, this technique can be recommended for measuring strains in the components of timber structures. The observed differences between the strains measured by electric-resistance strain gauges and the ones determined by means of the photoelastic coating should not be considered as discriminating any of the measuring techniques.

It should be noted that the photoelastic coating became unstuck only at an advanced stage of failure. The results presented in [21] showed that the propagation of cracks in the wood (accompanying its failure) was reproduced in the characteristic image of isochromatic fringes observed in the coating and the cracking of the coating proceeded in the same direction as the failure in the wood. This opens up possibilities of observing the dynamics of the phenomena connected with limit states in timber structures.

References

Application of photoelastic coating technique in tests of solid wooden beams reinforced... 65


Zastosowanie metody elastooptycznej w badaniach drewnianych belek wzmocnionych taśmami CFRP
