Failure evaluation of timber beams locally reinforced by CFRP strips using 3D digital image correlation system

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ABSTRACT: Presence of big knots significantly reduces the load bearing capacity of timber elements, in particular if they are loaded under tension or bending. In order to strengthen such elements a cost effective and less intervening technique of local reinforcement using CFRP strips has been evaluated recently. In this method a D-shape CFRP plate is placed in a groove cut at the location of the knot and glued to the timber element. Different failure modes can occur in the reinforced area such as deboning of the adhesive, shear failure in the timber, and tensile failure in the CFRP. In addition, conventional failure modes in timber beams including tensile and compressive failure parallel to the grain as well as tensile failure perpendicular to the grains should be considered. To evaluate the complex stress and strain distribution in the reinforced part of the beam a test program was set up. A series of four point bending tests was conducted on timber beams strengthened with the local reinforcement method at their mid-span. A modern 3D digital image correlation (DIC) system was used to measure the full-field displacement and strain fields of the CFRP strip as well as the reinforced timber beam. We captured the debonding between the CFRP strip and the timber element using the out-of-plane strains measured by the 3D DIC system. The results show an increase in the flexural stiffness of the timber beam when applying the reinforcement. The failure, however, is governed by premature deboning of the CFRP strip from the timber beam on one side and a shear failure in the timber beam on the other side that is followed by the sudden tensile failure perpendicular to the grains.

1 INTRODUCTION

Knots are remnants of branches that grow through the stem of a tree and appear in sawn timber elements. Knots reduce the efficient cross section of the beam by decreasing the volume of longitudinal fibers and distorting fibers around them, and cause stress concentrations. Hence, they are considered a natural defect in structural timber elements. Mechanical properties of the elements carrying knots are lower than those with clear wood, specifically when they are loaded under tension or bending (Bodig and Jayne Benjamin 1982). Existing residential and historical timber buildings have a lot of elements carrying critical knots that need to be taken care of (Nowak et al. 2013).

When studying timber beams in a macro scale, the presence of a knot can be simulated by a hole (Guindos and Guaita 2014). The worsening effect of holes, located in timber elements, depends on their size, shape and position. Increasing the size of the hole in the cross section of flexural beams, in particular in tensioned region, results in an intense decrease in their flexural stiffness and strength.

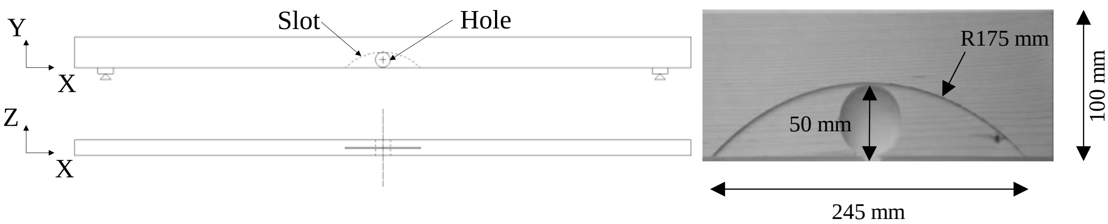
Burawska et al. (2015) suggested a local near surface mounted (NSM) reinforcement method using D-shape CFRP strips to recover the mechanical properties of timber beams with knots, which were represented by holes. Various failure modes are expected in timber beams reinforced with the suggested method such as debonding of the adhesive, shear failure in the timber, and tensile failure in the CFRP. In addition, conventional failure modes can occur in the timber beam including tensile and compressive failure parallel to the grain as well as tensile failure perpendicular to the grain as a secondary failure mode. In order to satisfy the goal of the reinforcement, local failure modes of the reinforcement should be minimized. Debonding of the CFRP is one of the premature failure modes that should be prevented in order to reach standard failure modes in the timber beam.

In this study, we aimed at evaluating the applicability of the suggested local D-shape reinforcement as a retrofitting technique to recover the mechanical properties of timber beams with knots. The failure modes were also explained in detail using a modern 3D digital image correlation measurement.

2 MATERIAL AND METHODS

A series of spruce beams with grade C24 according to EN 338 was prepared for the typical four point bending test. Sound timber beams were cut in a length of 2000 mm, height of 100 mm, and width of 50 mm. In order to represent the knots, sound beams were weakened by drilling a hole with a diameter of 50 mm at the bottom part of the mid-length of timber beams, see Figure 1a. The local reinforcement was done on every weakened beam in the following main steps. First, the beam was turned upside down and a slot was cut on its bottom side at the location of the hole. A D-shape CFRP strip, a CFRP lamella of type S&P 150/2000, with a thickness of 1.4 mm and a height of 50 mm was placed in the slot. Finally, the perimeter of the hole was sealed and a fluid epoxy resin-based adhesive, S&P 55, was injected into the slot between the CFRP and the timber beam. It must be noted that before their placement, the CFRP strips were sanded by a rough sand paper and cleaned thoroughly of dust and grease using industrial acetone. Furthermore, the slot in the beams was cleaned by mean of compressed air to remove any loose tissue remained after cutting. Figure 1b shows the dimension of the hole and slot in which the D-shape CFRP strip was placed.

To investigate the recovering of stiffness and strength by the local reinforcement method, the sound beam was loaded up to 40% of its nominal characteristic flexural strength. The same beam was then weakened and tested up to the same load level. The weakened beam was finally reinforced and loaded up to failure.



(a) (b)

Figure 1. (a) Position of knot and slot at the mid-length of the beam and (b) size and shape of slot for inserting reinforcement strip.

The complete load history was imposed under displacement control with a displacement rate of 0.03 mm/s applied by both loading plates. Strain gauges were used to measure the distribution of longitudinal strain at the height of the CFRP as shown in Figure 2. Total force was measured by the load cell of the compression machine and the total deflection by a LVDT, which was installed at the mid-span of the beam.

Using conventional measurement techniques, LVDTs and strain gauges provide us with valuable data at specific points. However, they are not capable of measuring a large field of displacement. In order to investigate the failure modes and capture the full-field displacement and strain, 3D digital image correlation (DIC) system can be used. This technique has been used in a broad range of scientific fields and more recently in civil engineering. Sadeghi Marzaleh et al. (2013) used the 3D DIC system in order to capture the full-field in-plane displacement and the failure modes in masonry walls.

In this study, the commercial package of GOM Company, ARAMIS, was used as the 3D DIC system. This system encompasses two 4-mega pixel cameras with 20 mm lenses. The set-up of the system is shown in Figure 3. A stochastic pattern was applied on the front and bottom faces of the beam as well as the CFRP strip that allows comparing the two stereo photos of a specimen in a deformed state with those of the initial state. With such setup the accuracy of the measurement is estimated to be around 0.1 pixel. In the current project, the side length of the measurement window, 250 mm, is mapped into 2000 pixels that corresponds to pixel size of 0.125 mm and a resolution of about 0.01 mm.

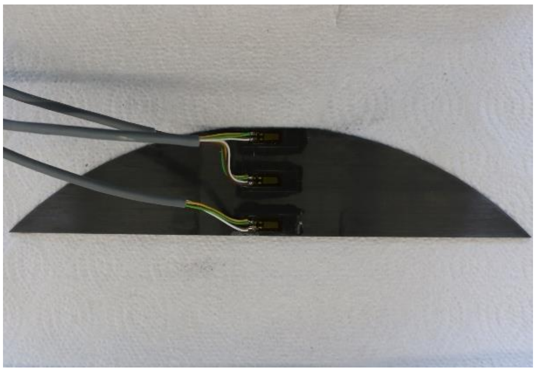


Figure 2. Strain gauges configuration.

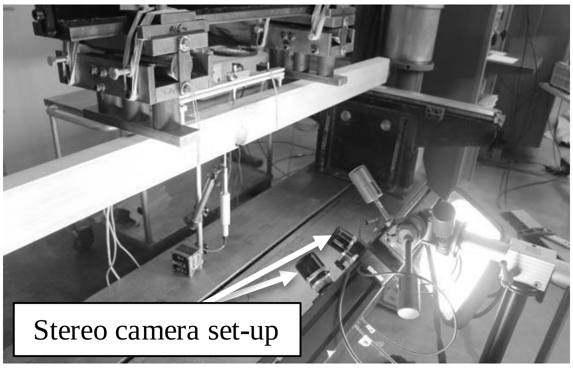
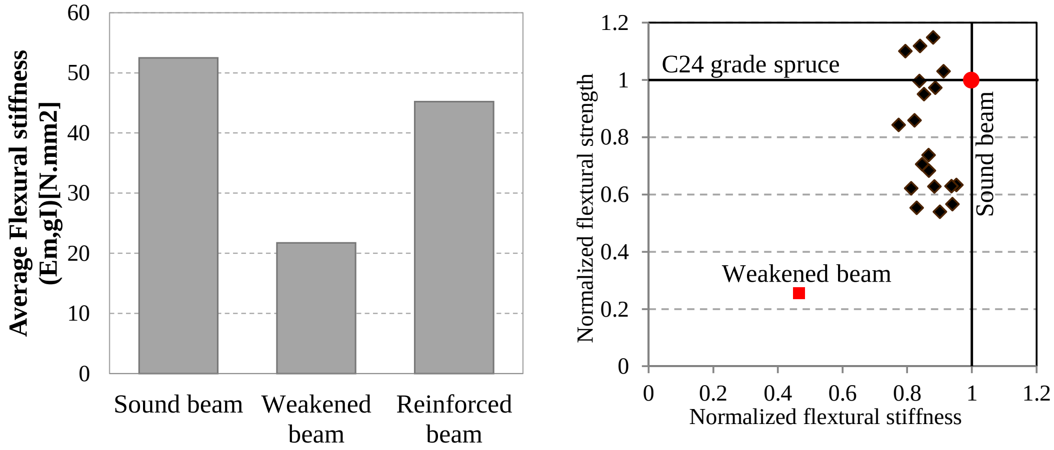


Figure 3. 3D image correlation system installation.

3 TEST RESULTS

3.1 Flexural stiffness and strength

As mentioned in the previous section, beams are produced of spruce with grade C24. Flexural strength for this grade is 24 MPa (DIN EN 338:2010-02). The average flexural stiffness of the weakened beams was about 41% of their sound counterparts (Figure 4a). Reinforcing the weakened beams with the suggested method increased the flexural stiffness significantly by about two fold (Figure 4a). The flexural strength of the reinforced beams also increased compared to the weakened beams (Figure 4b). However, there was a high scatter in the results, which is because the flexural strength of the reinforced beams is highly dependent on the failure mode. When a premature failure occurs at the local reinforcement, the increase in the flexural strength remains limited.



(a) (b)

Figure 4. Test results regarding (a) the average flexural stiffness and (b) the flexural strength and stiffness normalized to the sound C24 grade spruce beam.

3.2 *Failure modes*

There was a direction relationship between the applied vertical displacement and the machine force (Figure 5a). During the increase in the applied displacement, some noise was heard due to the cracking between the reinforcement and the timber beam. The load level, at which the noise was heard, was different for various experiments. However, no drop was observed in the load-deflection curve due to the suspected failure and the total force kept increasing. By increasing the applied displacement, finally the load bearing of the beam dropped expressively with a loud noise, see Figure 5a. This was attributed to the shear failure at the connection between the CFRP and timber beam, and the horizontal crack as a result of failure in timber perpendicular to grain. In the horizontal crack one side of the CFRP strip was completely disconnected from the timber beam (Figure 5b).

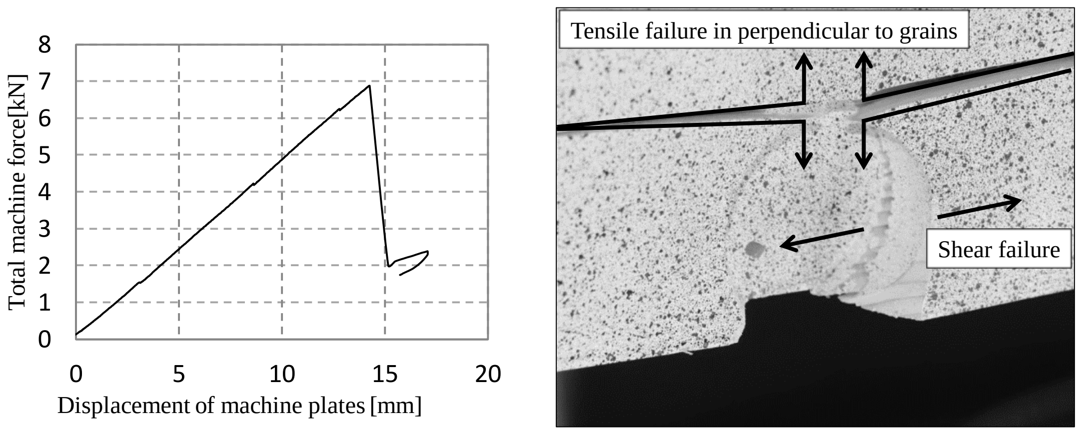
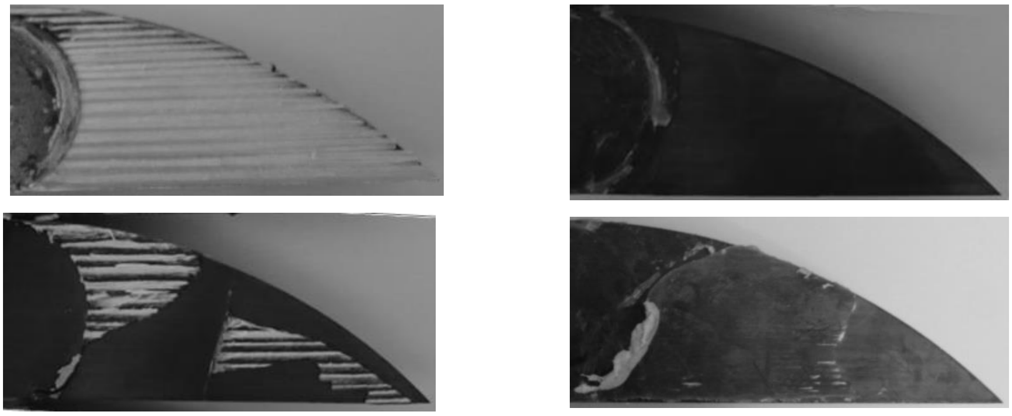


Figure 5. (a) Load-deflection diagram of a locally reinforced beam and (b) the pronounced failures resulting the drop.

The reinforced section of the timber beam was cut and studied after the test. Figure 6 shows various failures observed at the reinforcement. The failures are classified in two groups: (1) the failure occurs in timber fibers, (2) the failure occurs at the interface between the adherent, i.e.

timber or CFRP strip, and the adhesive. When the failure occurred in the timber fibers, a higher flexural strength was observed in the locally reinforced beams.



(a) (b)

Figure 6. Failure in the (a) timber fibers and (b) interface between the timber and adhesive.

The results of 3D DIC measurement was used to evaluate this failure modes in detail. In order to verify the measurement of ARAMIS, a comparison was made between the value of strain in the longitudinal direction measured by strain gauges and the 3D DIC system. Figure 7 shows the distribution of horizontal strain through the height of the beam for one of the specimens. As shown in the figure, the image measurement gives an accurate result in terms of strain in the longitudinal direction of the beam. Therefore, the image correlation results formed a reliable basis for studying the failure in the interface that occurred in the out-of-plane direction.

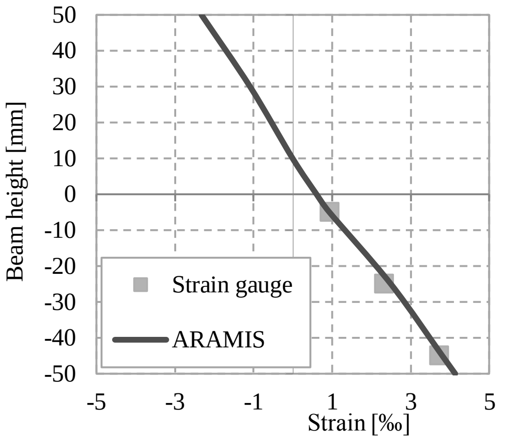


Figure 7. Distribution of horizontal strain through height of the beam.

4 DISCUSSION

In this section, the procedure of failure in locally reinforced timber beams using D-shape CFRP strips is explained and the effectiveness of the method is discussed regarding the failure mode.

To investigate the failure perpendicular to the beam plane, i.e. out-of-plane direction, the bottom surface of the beam was considered. Two strain gauges were placed on the bottom surface using the image correlation results, see Figure 8. They captured the relative deformation of the reinforcement and the timber beam that could be formed as a result of various failures such as deboning of the adhesive and shear failure in the timber.

Figure 8 shows the direction of major strain on the bottom surface of the timber beam too. As seen in the figure, far from the CFRP strip, a field of tensile strain parallel to the CFRP strip is generated in the bottom surface of the timber beam due to applied bending moment. Close to the CFRP strip, however, the tensile strain field becomes oriented and a tension is applied to the CFRP strip in the out-of-plane direction. Therefore, in addition to the in-plane tensile strain applied to the CFRP strip due to bending, the reinforcement is under a combination of shear stress and out-of-plane tensile stress.

The step by step failure can be explained by seeing Figure 9a, in which the out-of-plane strains in Z direction are shown. The strains are demonstrated as a function of applied displacement by loading plates. Applying the vertical displacement on the beam, both strain gauges initially displayed a small increase in the out-of-plane strain. This is due to the out-of-plane tensile stresses that were described above. Increasing the applied displacement resulted in a jump in the value of strain gauge_2. This corresponded to the failure at the interface in the bottom right side of the strip. Afterwards, the same type of failure was observed in the bottom left side of the strip. Regarding this state, the contour of out-of-plane displacement is shown in Figure 9b. It is clearly seen in the figure that the rear side of the CFRP strip was disconnected from the timber beam and its front side followed the out-of-plane deformation of the beam. Following that, the beam failed by a shear failure in timber in the upper right side of the strip and suddenly, the tensile failure perpendicular to the grains occurred. Figure 10 depicts the step by step failures schematically.

Even though the failure load of locally reinforced shows a high variation, the aforementioned procedure of failure was observed in nearly all of them. This is attributed to the fact that the load bearing capacity of the connection between the CFRP strip and timber beam was different for various experiments. In order for the locally reinforced timber beams to obtain higher load resistance, the premature failure of the interface between CFRP and adhesive must be prevented. As a result, parameters such as surface preparation, quality of execution, type of adhesive, the amount of shear and tensile stresses directly affect the effectiveness of this reinforcement method.

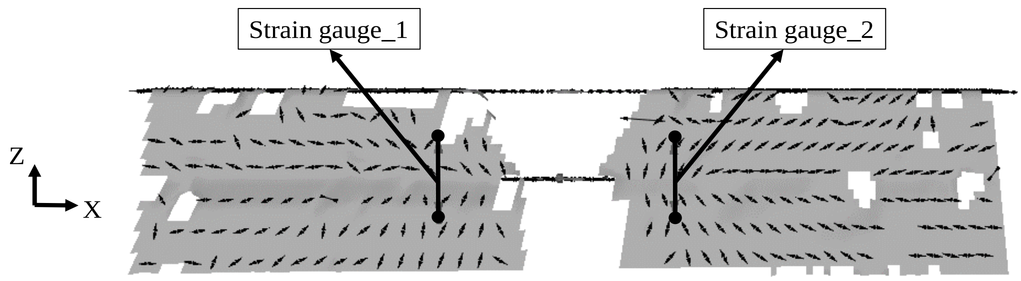
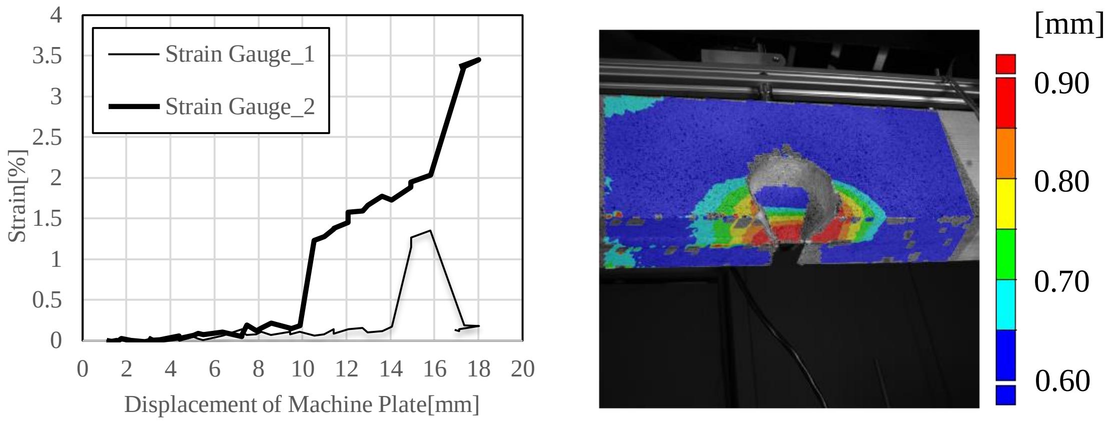
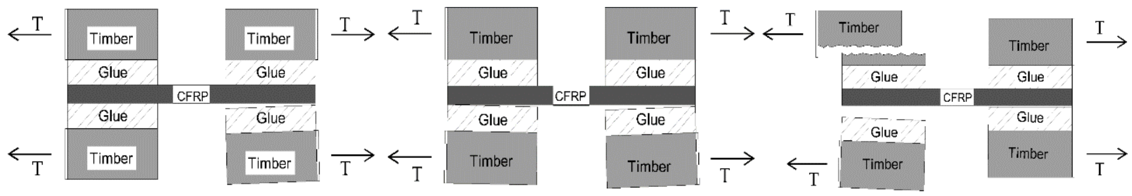


Figure 8. Location of strain gauges and dicrection of major strain on the bottom surface of the timber beam.



(a) (b)

Figure 9. (a) History of out-of-plane strain and (b) contour of out-of-plane displacement before failure.



(a) (b) (c)

Figure 10. Schematic picture of the step by step failure respectively at (a) right interface, (b) left interface and (c) timber beam.

5 CONCLUSION AND FUTURE DEVELOPMENTS

The main goal of this study was to assess the effectiveness of the reinforcement using D-Shape CFRP strips on timber beams carrying knots. The results confirmed that the reinforcing method is capable of enhancing the mechanical properties particularly the stiffness of such beams. Even though the flexural strength of reinforced beams showed an increase compared to the beams with knots, it had a notable scatter. The flexural strength of locally reinforced timber beams depends on the failure mode of the reinforcement. The lowest values of increase was observed when a premature debonding occurred at the interface of CFRP and adhesive. This is attributed to the combination of tension and shear stresses, which is applied to the CFRP in the out-of-plane direction due to the geometry of the reinforced beam. Failure in the interface needs to be studied more in detail before the method can be applied in practice.

By increasing the number of CFRP strips, the generated stresses will distribute among the strips and there will be more potential for shear failure in timber instead of premature debonding. Therefore, to increase the strength as well as stiffness, applying more reinforcement seems beneficial and shall be studied in future.

6 Aknowledgment

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