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Advancing Timber for the Future Built Environment

REAL-LIFE PERFORMANCE OF SHAPE-OPTIMIZED TIMBER BEAMS

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ABSTRACT: The creation of sustainable living spaces drives the utilisation of mass timber products like Glued Laminated Timber and Cross Laminated Timber across the globe. They not only sequester significant amounts of carbon but also effectively complement and substitute carbon-intensive building materials in mid- to high-rise buildings. However, they also require a significant amount of raw material. In order to improve their resource efficiency, the optimisation of the shape in order to account for the actual stress distribution within the building member is a promising approach to get more out of the natural resource wood. The presented investigation shows the real-life performance of three-dimensionally optimized Glued Laminated Timber beams under four-point bending. Two shape optimisations were conducted, and a total of 34 samples (17 reference and 17 optimised beams) were tested until failure in laboratory conditions. The maximum force, deflection, and deformation were recorded and compared with the reference cross-section. The results showed that real-life material savings of about 30% can be achieved without any loss of the load-carrying capacity and without exceeding the deflection limits of Glued Laminated Timber beams.

KEYWORDS: Digital Image Correlation, Engineered Wood Products, Mechanical Performance, Resource Efficiency

1 – INTRODUCTION

Most Glued Laminated Timber (GLT) beams today ignore the actual stress distributions and are produced with a constant cross section over the full length of the beam [1]. This allows for highly standardized construction as well as high material throughput during production. But, due to an increasing demand in all kinds of bio-based materials, not only for construction, the sustainable supply of forest biomass will become a future challenge. Our society will need to make the most out of these resources in order to ensure a sustainable supply of bio-based raw materials. Therefore, the high demand of roundwood for the production of GLT needs be addressed in order to prevent severe raw material shortages in the future [2].

To improve the resource efficiency of GLT, while still achieving the necessary structural safety, shape optimization approaches like those proposed by Mayencourt & Mueller [3] have already shown their potential on a theoretical level. According to their findings, up to 70% in extreme cases and 30-50% in most spans and cross-sectional aspect combinations could be saved in timber beams. However, to this point, such values are mostly theoretical. Therefore, this paper presents the real-life performance of a 3D-optimised (changing width and height over the length) GLT-beam

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subjected to four-point bending and demonstrates the real-life applicability of these theoretical approaches.

2 – PROJECT DESCRIPTION

2.1 SAMPLE PREPERATION

Two different raw materials made of Norway spruce wood were chosen for testing. On the one hand, one GLT beam, provided by the company Mayr-Melnhof Holz Holding AG (Gaishorn, Austria), with a raw dimension of 13 500 × 100 × 160 mm. The beam was built-up from four finger-jointed lamellas with a thickness of roughly 40 mm and a melamine urea formaldehyde (MUF) adhesive. It was cut into nine sections of equal length (1500 mm) before delivery. On the other hand, four sawn timber boards with a raw dimension of 4000 x 350 x 40 mm were sourced from J.u.A. Frischeis Gesellschaft m.b.H. (Stockerau, Austria). The boards were visually selected to be as straight grained and defect-free as possible. This was done in order to avoid any bias through growth characteristics (e.g. grain angle deviations and density variations) and to obtain samples as "defect-free" as possible. Therefore, the samples from the sawn timber boards can be considered clear wood (CW). Both raw materials were stored in standard climate conditions [4] at 20+/-2 °C and 65+/-5 % relative humidity until an equilibrium moisture content of about 12 % was reached before further processing.

Subsequently, four beams per raw material were cut out using a circular saw. Two reference beams with a dimension of 1500 x 30 x 60 mm and two beams for shape optimization with a raw dimension of 1500 x 30 x 80 mm. The position within the raw material was chosen in order to enable a direct comparison between the reference and the optimised beam. Therefore, the two samples were positioned next to each other in the GLT beams (same lamella) and after each other in the sawn timber boards (same radial position in the stem). This is further depicted in figure 1, which also shows the approximate annual ring orientation in the final samples. The beams for the shape optimization were further processed using a five-axis CNC milling machine (HOMAG BMG 110, HOMAG Group AG, Schopfloch, Germany). The CNC milling was carried out in two steps. First, the variable width was milled on one side. Second, the variable width and height were milled on the other side, resulting in the final shape. The average processing time on the CNC machine was about 30 minutes.

In total, 34 samples (17 reference and 17 optimised samples) were produced by subtractive manufacturing from GL24h beams (GLT) and defect free solid wood (CW).

2.2 MATERIAL SAVINGS

The weight difference between the reference and the optimised beam was chosen to evaluate the real-life material savings. Therefore, the weight of the beams was measured before testing with an accuracy of +/-0.1 g using a laboratory scale (DS 16K0.1, KERN & Sohn GmbH, Balingen, Germany). The material savings [%] were then calculated as the weight difference between the reference and the optimised beams.

2.3 MANUFACTURING ACCUARCY

In order to evaluate the manufacturing accuracy, the dimensions of the optimised beams were taken with an accuracy of +/-0.01 mm using a digital calliper (Mitutoyo, Kawasaki, Japan). The height was measured by dividing the samples into ten sections of equal length. The width was taken at the same position at the top and the bottom of the sample. Additonally, the width in de middle of the beams was measured by cutting two of the beams at the same positions for the height measurements and measuring the width at the top, bottom and middle part of the resulting sections.

3 – EXPERIMENTAL SETUP

3.1 REFERENCE LOAD CASE

The reference load case (see Figure 2) was based on EN 408 [5] and the abilities of the available testing machine. This resulted in a single-span length of 1150 mm and a height of 60 mm. A reference width of 30 mm was chosen due to the common height-to-width ratio in timber beams between 1:2 and 1:3. The benchmark section for optimization was therefore 1150 x 30 x 60 mm (length x width x height).

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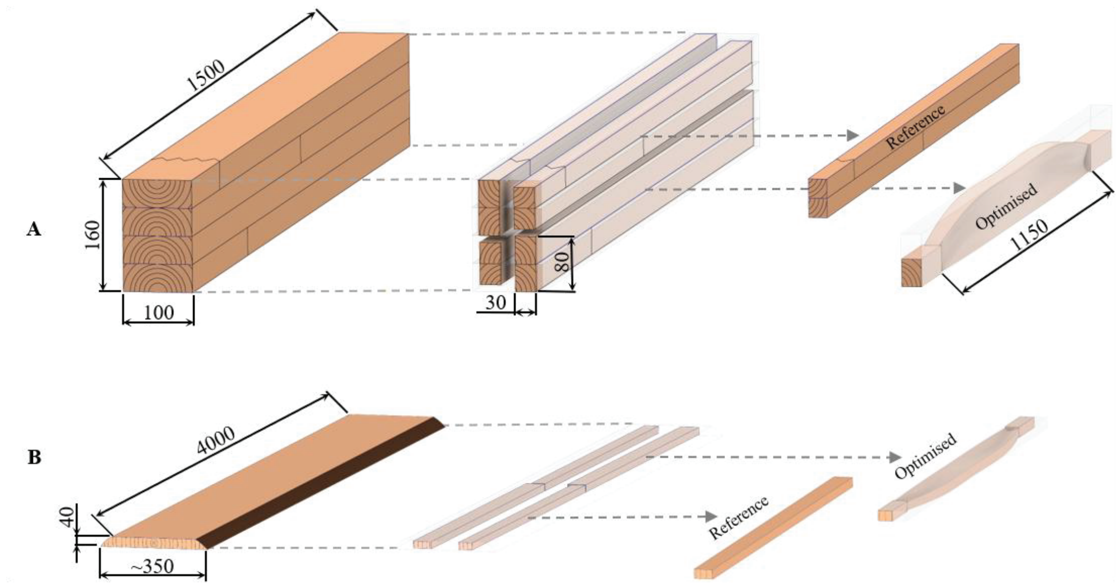

Figure 1. Sample preparation for GLT (A) and CW (B) beams. Dimensions are in [mm]

3.2 SHAPE OPTIMIZATION

The mechanical properties for the optimization were based on a GLT beam of the type GL24h and were taken from EN 14080 [6]. The deflection (f) limit was set at 7.5 mm (l/200) based on Eurocode 5 (EC5) [7]. For proof-of-concept, isotropic material behavior was assumed for the optimisation. Two iterations were calculated based on two different shear strength limits (2.5 MPa and 3.5 MPa). This was done as shear failure is a critical factor in ultimate limit state design of timber beams. A detailed description of the optimisation approach can be found in a previous publication [3]. The optimization resulted in a theoretical material saving potential of about 47% for iteration one and 30% for iteration two (see Figure 3).

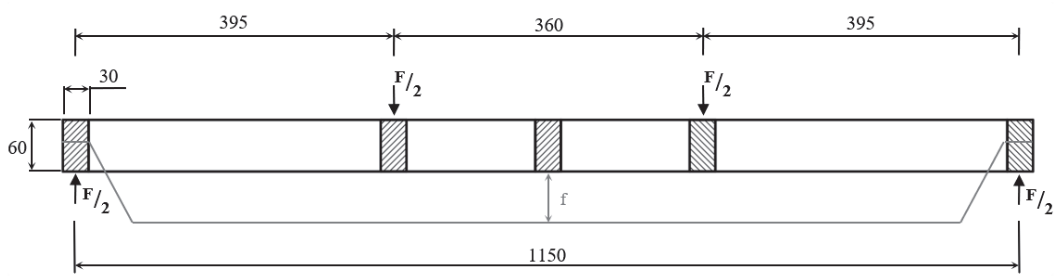

Figure 2. Reference load-case for the optimisation. Force (F) and deflection (f). Dimensions are in [mm]

3.3 FOUR-POINT BENDING TESTS

The samples were tested based on the setup depicted in Figure 2 using an univeral testing machine (Z100, Zwick/Roell, Ulm, Germany) with a load capacity of 100 kN and a resolution of 0.06 N. In order to prevent indentation of the samples during testing and ensure a constant bearing surface, the samples were placed on trapezoidal, rotatable bearings with a width of 40 mm. The deflection was measured globally in the middle of the samples using a mechanical extensometer (Makrosense, Zwick/Roell, Ulm, Germany). The samples were pre-loaded with 100 N to ensure full-surface contact with the supports and force introduction. The samples were then loaded at a constant displacement rate of 5 mm/min until a force drop of 90% of the maximum force (Fmax in [N]) was reached. After testing, Fmax as well as the deflection (f in [mm]) at a force of 2187 N (f2187N) were chosen for comparison. This force would result in a bending stress of 24 MPa in the reference sample and can be seen as the potential maximum deflection of a GL24h beam without considering any modification factors. The failure behaviour was evaluated using video and photo documentation of the tests. Testing data was recorded using testXpert III (version 1.51, Zwick/Roell, Ulm, Germany) and data handling as well as statistical analysis was performed using Microsoft Excel (version 1808, Microsoft, Redmond WA, United States).

3.4 DIGITAL IMAGE CORRELATION

The deformations and strains on the surface of the beams were measured using digital image correlation (DIC). Therefore, a 2D-DIC measurement setup was established using a Lumix DMC-GX80 (Panasonic, Osaka, Japan) and a lens with a fixed focal length of 20 mm. The field of view (FOV) included half the length (550 mm) and the full height (80 mm) of an optimised beam plus enough spave to view the beam at maximum deflection before failure. The camera was placed perpendicular to the beam with a distance of 1150 mm. The test was filmed with a resolution of 1280 × 720 pixels, 24 frames per second and autofocus switched off. The required speckle size between 1.2 and 2.2 mm [8], was applied randomly by hand using a commercial permanent marker. Sufficient contrast was ensured by a matt white paint finish on the surface. Subsequent image analysis was done using GOM Correlate (2020 Hotfix 5, Zeiss Group, Jena, Germany).

4 – RESULTS & DISCUSSION

4.1 MATERIAL SAVINGS

The real-life material savings for the first optimization were 41.3 % on average, ranging from 38 % to 43.8 %. For the second optimization, the real-life savings were 27.9 % on average, ranging from 23.4 % to 31.1 %. As depicted in Figure 4, both optimizations yielded lower average real-life material savings than the model (47.4 % and 29.9 %) predicted. This could be attributed to a higher density (ρ in [g/cm³]) leading to a higher actual volume of the optimised beams. This could have an impact on the material saving potential based on measuring the weight, when the density of the reference beams is significantly lower than the density of the optimised beams. However, the density does not show a significant difference between the reference and the optimizations. Overall, the density of the reference beams made from GLT was on average 0.457 g/cm³, ranging from 0.397 g/cm³ to 0.502 g/cm³. The optimised beams made from GLT ranged from 0.369 g/cm³ to 0.479 g/cm³, with an average of 0.436 g/cm³. These values are slightly above the 420 kg/m³ given by the standard [6] for GL24h. However, EN 14080 does allow for a higher moisture range (at bonding between 6% and 15%), which also influences the resulting moisture content and therefore density of the final beams. Furthermore, the supplier gives a mean density of 0.450

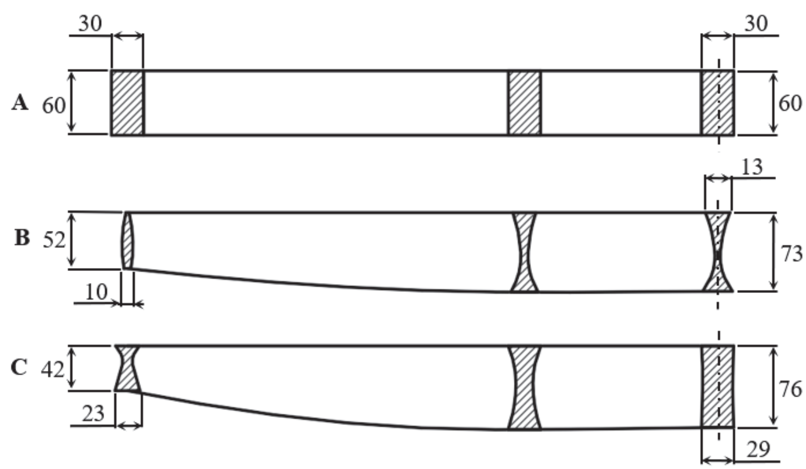

Figure 3. Half-sections of reference (A) and shape-optimised beams (B and C). A: Reference with constant cross-section (17 samples). B: First iteration with a material saving potential of about 47% (5 samples). C: Second iteration with a material saving potential of about 30% (12 samples). Dimensions are in [mm].

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g/cm³ at a moisture content of 12 % +/-2 % for their GLT made from Norway spruce. The reference beams made from CW had an average density of 0.437 g/cm³, ranging from 0.397 g/cm³ to 0.470 g/cm³ and the optimised beams made from CW ranged from 0.407 g/cm³ to 0.465 g/cm³, with an average of 0.437 g/cm³. These values are in line with Wagenführ [9], who reported a density between 0.330 and 0.680 g/cm³ for Norway spruce.

Besides density, the uncertainty in measuring the width of the beams could have caused this deviation and also suggests that the actual volume of the optimised beams is higher than provided by the model. Furthermore, this points to different manufacturing accuracies when milling the samples.

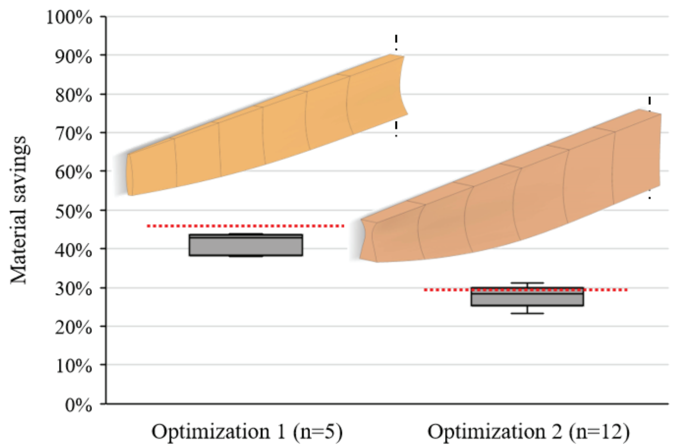

Figure 4. Real-life material savings [%] in comparison with the predicted potential by the model (dotted line).

4.2 MANUFACTURING ACCURACY

Based on the measured dimensions, the height was on average +0.1 % (+0.05 mm) above and the width on average -0.6 % (-0.14 mm) below the target dimensions with a maximum of +0.77 mm and -0.81 mm, respectively. These deviations were mainly caused during CNC milling, as the beams could only be fixed at the two support areas at the end. This resulted in a free clamping length of 1150 mm. Therefore, a slight vibration during milling could have led to a larger removal in width and a partial swerve of the beam to a smaller removal in height. However, the manufacturing accuracy is satisfactory, especially as the deviations are for example within the required dimensional accuracy for GLT (+/- 1 mm) according to EN 14080 [6]. Yet, for a large-scale implementation a full surface clamping could further improve the accuracy and at the same time allow for a higher production speed. This could be easily implemented as the top of the beam will remain flat in the majority of cases, allowing for a fixation along the full length during milling.

It needs to be mentioned that while these results indicate a high manufacturing accuracy, the measured values include a high level of uncertainty, due to the complexity of measuring the width of the optimised beams. On the one hand, this was only done for two of the optimised beams, as it required cutting the samples without testing. On the other hand, the actual position of the thickness measurement could deviate from the theoretical position, since the strong curvature of the first optimization in particular made it difficult to precisely place the digital calliper.

4.3 MECHANICAL PERFORMANCE

The results for Fmax [N] and f2871N [mm] of each individual beam are depicted in figure 5. The optimised sample is always compared with the corresponding reference. In addition, the minimum values for force and the maximum values for deflection according to EC5 [7] are also indicated. Based on a two-sample t-test ($\alpha = 0.05$), the first optimisation showed a significant decrease in Fmax compared to the reference cross-section. In contrast, the second optimisation did not show a significant difference. Similar statistical results can also be reported for deflection.

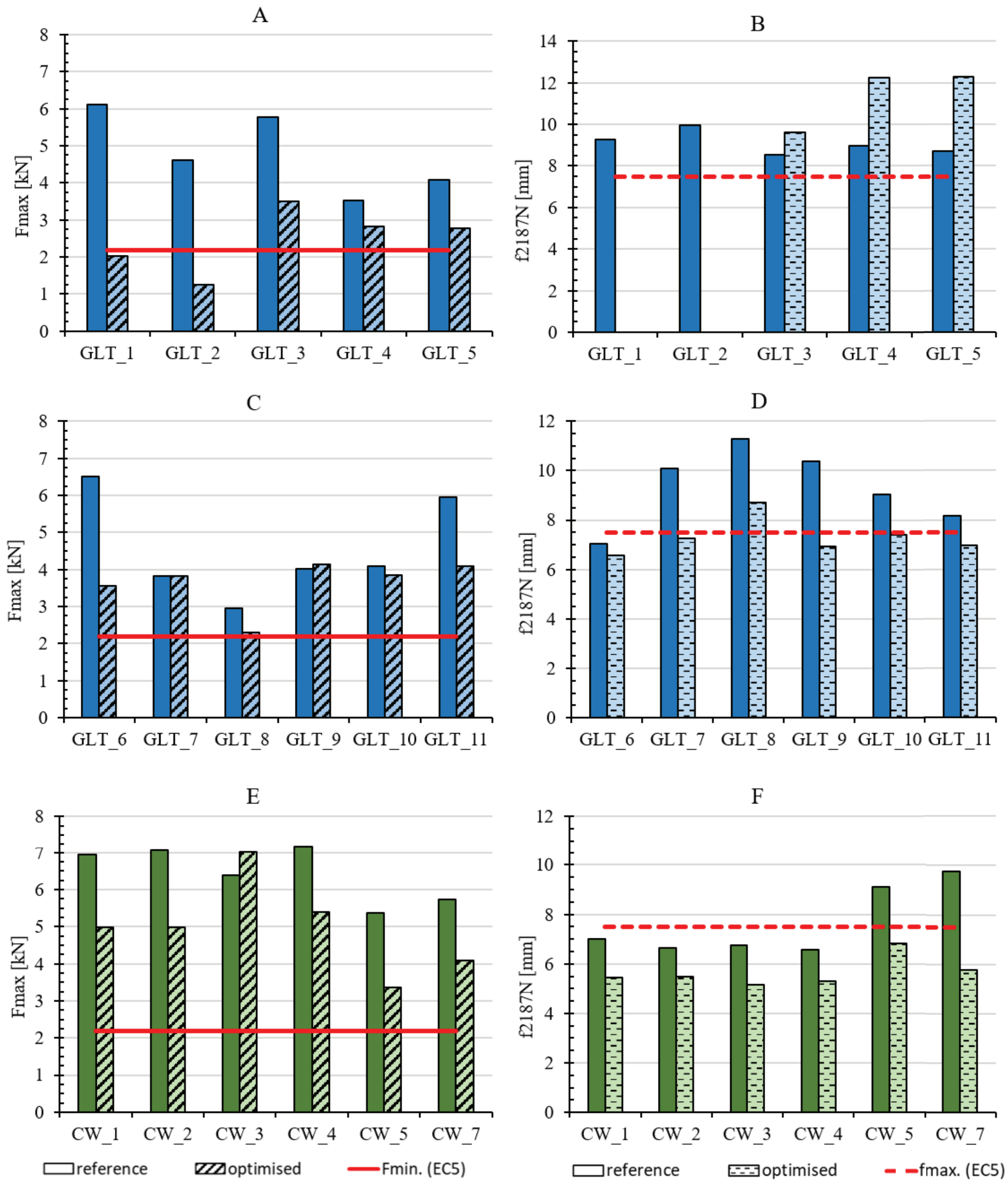

Figure 5. Comparison of the mechanical performance of the reference and optimised beams based on maximum force (Fmax) and deflection at a force of 2187 N (f2187N). A-B: Optimisation one made from GL24h. C-F: Optimisation two made from GL24h (C-D) and clear wood (E-F)

Taking a look at Fmax it can be seen that in the majority of cases the minimum required force of 2187 N was surpassed. Especially in the case of CW samples, which had little to no wood characterisics (e.g. knots). However, they do not necessarily represent reality as a certain amount of e.g. knots are allowed for GLT lamellas. Furthermore, the rather high Fmax for CW can be explained by the fact, that the acutall strength of the material will be significantly higher compared to the lamellas used for the GLT beams. Nevertheless, the GLT samples also achieved the required load-carrying capacity. Only “GLT_1” and “GLT_2” (see figure 5A) did fail before the target load of 2187N. This was due to instabilities caused by the slenderness of the beams in the outer sections (see figure 3B). Overall, a certain homogenisation of Fmax can be seen for the optimised samples. This is a logical result of the optimisation approach, which aims to use material only where it is necessary for the underlying load case.

Moving on to deflection, figure 5 shows that the deflection limit was only fulfilled in the second

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optimisation. Twelve out of the 17 reference samples and six of the optimised samples did not achieve the required limit of 7.5 mm. This can be explained be the greater maximum height and the resulting higher moment of inertia for the optimised beams. Similar to Fmax, optimisation one did not achieve an improved behaviour due to higher instabilities resulting in tilting and buckling of the beams before the required force was reached.

4.4 FAILURE BEHAVIOUR

As mentioned in the previous section, the main failure behaviour of the first optimisation was tilting and buckling of the sample. Therefore, the results of the DIC measurements are of little significance as the sample shifted out of the focus area of the camera early on during testing. Therefore, only the results of the second optimisation are presented in Figure 6. The DIC measurements revealed a strain concentration on the lower side of the beams between the location of the force introduction and the supports at the moment of failure (see figure 6A). This indicates a possible weak point of the second optimisation. It could be caused by two reasons. Firstly, the adhesive joint between the two GLT lamellas is located in this area. This could have led to an initial crack during CNC milling, which leads to this strain concentration as the forces increase. Secondly, the transition from variable height to constant height could be too sharp. As this strain concentration is also present in the CW samples, although not as pronounced, it can be assumed that the transition is too sharp.

5 – CONCLUSION

The main objective of the optimisation, to maintain structural integrity while using less material, was only partly achieved. Based on the results, it can be concluded that a real-life savings potential of at least 30% can be realised with 3D-shape optimisation of GLT beams without reducing the load-carrying capabilities or the deflection limits. It demonstrates that the theoretical results can be applied to more complex cases with greater potential savings. Additionally, it underlines the need for accurate design values (e.g. shear) as the optimisation is only as good as the applied material properties.

In further research, the anisotropy of the material and the fire safety should be incorporated into the optimisation procedure. In order to prevent tilting and buckling of the beams when loaded, stability factors need to be implemented as well. Furthermore, the utilisation of alternative raw materials such as veneers or strands from OSB production should be investigated in order to enable a “zero-waste” production of the resulting beams.

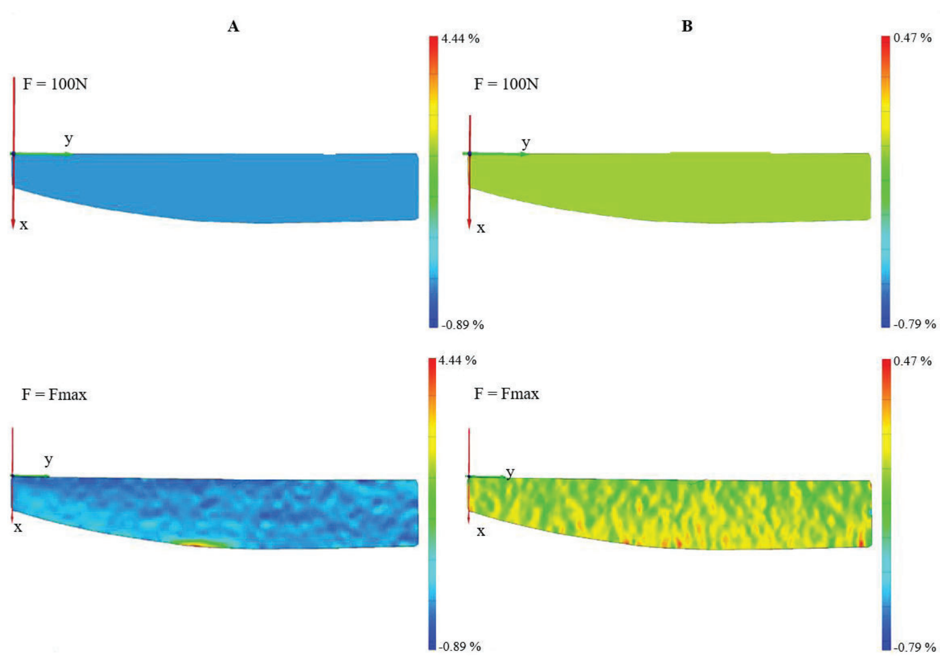

Figure 6. Failure behaviour of optimised beams (optimisation two) based on DIC. A: Strain in x-direction at pre-load (100N) and at Fmax. B: Strain in y-direction at pre-load (100N) and at Fmax.

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