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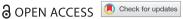Niclas Björngrim, Olena Myronycheva & Per-Anders Fjellström

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The use of large-scale X-ray computed tomography for the evaluation of damaged structural elements from an old timber bridge

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ABSTRACT
This paper shows how timber structures in our cultural heritage can be evaluated by large-scale X-ray computed tomography (CT) to supplement visual inspection and conventional strength and biological degradation tests. Approx. 25 year old preservative-impregnated timber beams from a nearly 300-year-old timber bridge were replaced due to severe degradation. The condemned beams were examined by CT scanning, and three-point bending and decay tests were performed. The CT imaging gave a good overview of the internal structure of the beams, and features such as rot, nails and cracking could easily be detected and quantified. The CT images indicate that mild-steel nails from the decking of the bridge were the main cause of subsequent degradation by rot fungus. The load at breakage and the modulus of elasticity (MOE) values of the condemned beams were approx. half those of the undamaged reference beam. Large-scale CT scanning is a powerful tool for the non-destructive inspection of timber members in historical structures.

Introduction

Comprehensive work is in progress to preserve wood cultural assets such as buildings, infrastructure and objects in museums (Bachtiar *et al.* 2022). X-ray computed tomography can be a technique for supporting and improving the inspection and evaluation of such objects.

The Lejonström bridge is Sweden's oldest timber bridge dating back to 1737 and, until 1913, it was the only way to cross the river without using a boat (Jonsson 2007). It is also the second longest timber bridge in Sweden, spanning 173 m over the Skellefteå river with a total length of 207 m. Since 1994, the Lejonström bridge is a listed building, the strongest legal, historical and cultural protection used in Sweden. All bridges in Sweden are inspected every year, regardless of building material. During the inspection of the Lejonström bridge several of the main load-bearing beams were deemed deficient for the construction due to decay and were replaced already after 25 years in use. These beams where tested for mechanical properties and microbial growth, and large-scale computed tomography (CT) was used to obtain additional visual information of the internal beam volume to better understand the deterioration in the wood material in order to learn how to improve the protection and maintenance of the bridge. Large-scale CT scanning has been used for a long time in the medical sphere but is now also being introduced industrially in e.g. sawmill production (Olofsson *et al.* 2021). The purpose of this study was to evaluate the possible use of large-scale computed tomography (CT) in the maintenance of ancient wooden structures.

Materials and methods

Seven beams from the Lejonström bridge and one unused reference beam, all of copper-impregnated Norway spruce (*Picea abies* (L.) Karst.) were used, Table 1. The beams were approx. 127(R) × 127(T) × 1000(L) mm in size and originated from a renovation in 1996. The beams were scanned by large-scale X-ray CT in a Siemens Somatom Emotion Duo Computed Tomography scanner (Siemens, Germany) before strength testing and the isolation of decaying fungi from the material. Large-scale CT scanning in this context means that specimens of free length and a cross-section which can be fitted within a circle with a diameter of 600 mm can be scanned. A three-point bending test, loaded in the radial direction, based on EN 408 (CEN 2010) was carried out to determine the maximum load and modulus of elasticity (MOE). For testing in the universal testing machine, the beams had to be divided longitudinally into two parts with final dimensions of approx. 60 × 127 × 1000 mm (A and B in Table 1 indicate the two parts from the same beam). All the beams were sampled for identification of rot-fungus. The isolated material was placed on a malt-extract medium with antibiotics to avoid bacterial growth.

Results and discussion

The preliminary microbial analysis found rot fungus in the vicinity of the nails in all the beams. The discarded beams had approx. 70 nails per meter which originated from the bridge decking. Figure 1a shows a CT cross-section view of beam No. 1 where a crack and a mild-steel nail are clearly

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Table 1. Cross-sectional dimension of the beams after cleavage.

Specimen No.	Width (mm)	Height (mm)	Load at breakage (N)	MOE (MPa)
1A	126.2	60.8	11,020	4584
1B	126.1	58.8	13,120	5505
2A	126.0	61.1	12,670	5401
2B	127.7	61.4	9780	6006
3A	127.6	61.5	14,260	5289
3B	127.7	60.3	11,350	4946
4A	128.1	62.9	12,720	5058
4B	127.0	62.0	6930	4579
5A	126.0	60.8	11,360	6553
5B	127.5	61.2	16,780	5215
6A	128.7	62.0	14,570	6426
6B	128.1	64.0	10,270	3966
7A	129.1	62.6	12,800	5855
7B	128.6	61.7	12,210	5087
Mean ± Std. dev.	127.5 ± 1.1	61.5 ± 1.2	12,131 ± 2364	5319 ± 720
Reference A	125.6	60.3	22,110	9586
Reference B	124.9	61.9	22,700	10,542
Mean value	125.2	61.1	22,406	10,064

Notes: The length of the beams was 1000 mm. Load at breakage and MOE of the cleaved beams.
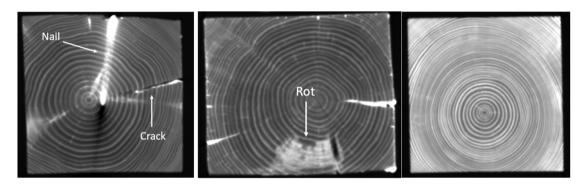

Figure 1. X-ray CT images (cross-section views) of (a) beam No. 1 showing a deep crack and a nail, (b) beam No. 2 showing rot and, (c) the reference beam.

visible. Each nail hole acts as a breeding ground for microbes. Figure 1b shows rot in the vicinity of a nail hole. Figure 1c is the reference beam without defects.

The damaged beams had a much lower load at breakage and MOE than the reference beam (Table 1). The reduction in load and MOE appears to be due to decay that has started predominantly in connection with the nailing.

Conclusions

Large-scale X-ray computed tomography (CT) has here been used to evaluate damage in load-bearing timber beams that had been deemed deficient as constructional elements in a bridge. The CT images were be used for the non-destructive identification of features such as cracks, mild-steel nails, and rot throughout the volume of the beam. The fungus attack started in the vicinity of the nails due presumably to increased moisture exposure, and the subsequent degradation by rot reduced the load at breakage and the modulus of elasticity (MOE) of the beams by approx. 50% compared to an undamaged reference beam. CT can be a powerful technique for non-destructive studies of damaged timber members from structures in our cultural heritage.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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