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Condition Assessment of the Timber Structures of a Century-Old Industrial Building Using a Nondestructive Inspection Procedure

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Abstract. This paper reports an in situ inspection project conducted on heavy timber structures of a century-old industrial building at a paper manufacturing facility. A nondestructive inspection procedure was employed to evaluate the true condition of the heavy timbers that serve as the main framing structure of the building. The on-site investigation involved monitoring of the microclimate environment resulting from the paper machine operations, wood species identification, wood moisture content measurements, and internal decay detection using sounding, stress wave timing, and resistance micro-drilling methods. The testing results revealed that numerous locations were in poor condition indicated by widespread internal and external deterioration, reduced cross-sections from fire damages, and multiple failed members. Many timber members in the first floor exhibited a very high level of moisture condition (23 to 55%) as a result of high humidity air created by the paper making operations. This paper also showcases a new way of interpreting the evaluation results as straightforward as possible to the customer by creating 3D model-drawings and colored condition mappings.

Introduction

Deterioration of wood structures often occurs internally before any external signs of damage appear. The load-bearing capacity of the affected member is greatly reduced before surface deterioration is visible [1]. Determination of an appropriate load rating for an existing structure and rational decisions about rehabilitation, repair, or replacement can be made only after an accurate assessment of the existing condition. Knowledge of the condition of a wood structure can reduce repair and replacement cost by minimizing labor and materials and extending service life. In general, structural condition assessment requires the monitoring of some indicating parameters that are sensitive to the damage or deterioration mechanism in question [2]. Traditional inspection methods such as visual, sounding, and probing are limited to evaluating surface deterioration and severe internal rot conditions and often produce inaccurate or incomplete information. Hence, cost-effective NDT technologies are needed for accurately determining the conditions of individual structural members.

This paper reports a comprehensive inspection project conducted on heavy timber structures of a century-old industrial building at a paper manufacturing facility in Wisconsin, USA. The building has housed paper machine operations for nearly a hundred of years and was still in operation at the time of inspection. The high humidity air condition resulting from the paper making process, fire event, and water intrusions occurred in the past have all contributed to the unknown degree of deterioration in the main framing structure. The purpose of this investigation was to conduct an in situ physical condition survey of the large timber members using a nondestructive testing procedure and provide the facility engineers a fair assessment of the true physical conditions of the structure upon which a rational and cost-effective repair plan can be established.

(a) (b)

Figure 1. Heavy timber structures of a century-old industrial building. (a) Interior view of the first floor in the building showing a paper machine operation; (b) Interior view of the second floor in the building showing roof trusses and the floor.

The scope of the in situ physical inspection was limited to the areas that were under concern and specified by the facility engineers. The key structural members that were inspected included: 1) First floor (Fig. 1a): the timber columns at row A, B, and C, the longitudinal beams of row A, B, and C (see Fig. 2), and the transverse beams at cross sections 1 – 9 (see Fig. 2); and 2) Second floor (Fig. 1b): the timber columns at row B, the bottom chords of the roof trusses (Truss No. 1 – No.5), and the connections of the roof trusses (bottom chord level).

The on-site investigation involved monitoring of the microclimate environment resulting from the paper machine operations, wood species identification, wood moisture content measurements, and internal decay detection using stress wave timing and resistance micro-drilling methods.

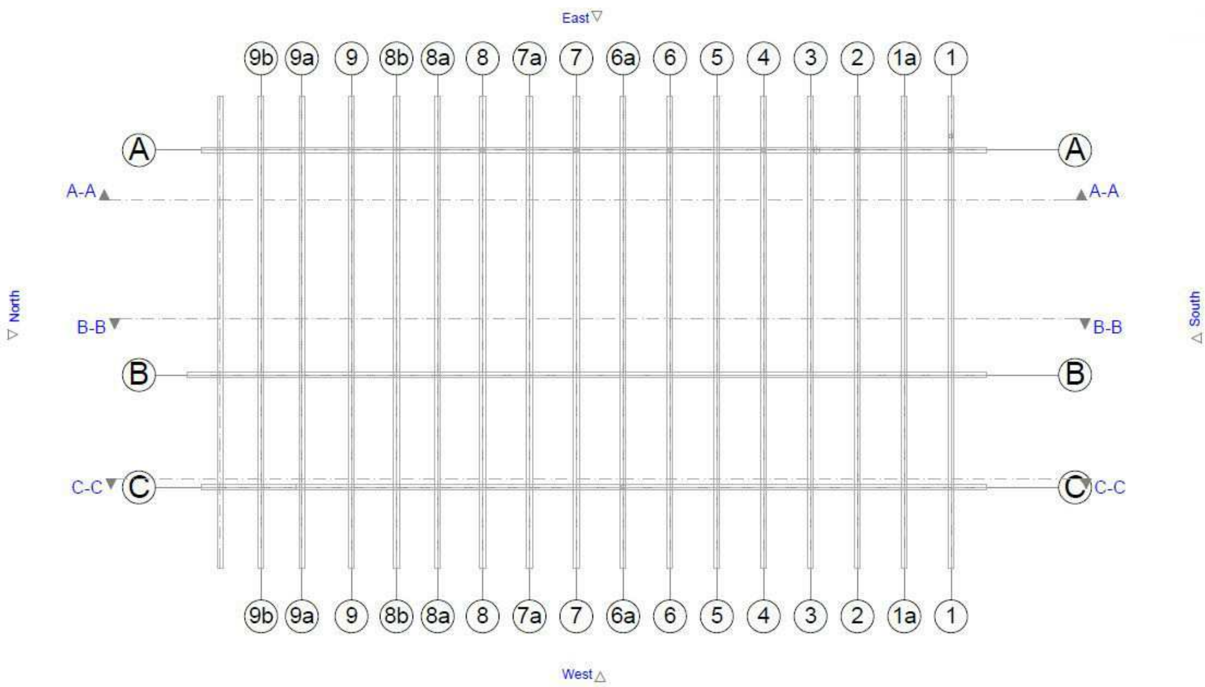

Figure 2. Plan view of the paper mill building (Level 1)

Inspection Methodology

The field investigation was conducted in two phases. In phase one, an initial survey of the timber structures of the paper mill building was conducted at a time when the production line was shut down for maintenance. The specific tasks performed in this phase included the following: 1) documentation of the heavy timber structures with dimension measurements in the concerned areas; 2) collection of three wood core samples from the structural members (column, beam, and truss) for preliminary species identification; 3) inspection of a portion of the longitudinal beams in row A through a boom lift; and 4) installment of a temperature and relative humidity data logger to monitor the indoor air condition (temperature and relative humidity) inside the building during normal operations. The data logger was mounted in the ceiling of the first floor and located by the paper machine line which produces a significant amount of water vapor during operation.

In the second phase, a thorough inspection of the timber structure was conducted during normal mill operations. A combination of visual, hammer sounding, stress wave timing, and resistance micro-drilling techniques were used to inspect the timber members in the concerned areas specified by the facility engineers. Following are the inspection procedure we used during the 3-day on-site investigation:

1. Collect wood core samples from representative timber members;
2. Measure moisture content of the timber members at various locations using an electrical-resistance moisture meter with 76-mm-long insulated probe pins;
3. Perform stress wave timing tests on beams, columns where two faces are accessible (Fakopp Microsecond Timer, Fakopp Enterprise, Agfalva, Hungary);
4. Perform resistance micro-drilling tests on beams, columns at selected locations (IML-RESI F400, IML, Inc., Kennesaw, Georgia, USA);
5. Obtain the microclimate data for the indoor air condition of the building, which was monitored for a period of one month during normal operations.

Stress Wave Timing. Stress wave timing (SWT) measurement for decay detection is based on the concept that stress wave propagation is sensitive to the presence of deterioration of wood members [3]. Stress waves travel faster through sound wood than they travel through decayed wood. Conducting stress wave timing measurement on a wood member requires access to two opposite sides of the member for attaching sensor probes. The timber members tested with stress wave timing method included the columns and beams in sections No. 1 to No. 9 in the first floor (see Fig. 2) and the columns and truss members in the second floor.

Resistance Micro-Drilling. Resistance micro-drilling enables detection of internal deterioration in a timber through measuring the relative resistance in the drilling path. The micro-drilling tool is typically consisted of a power drill unit, a small-diameter drill bit (1.5−3.0 mm), a paper chart recorder, and an electronic data storage. The output of a micro-drilling test is a resistance profile showing density changes along the drilling path. The high output characterizes high resistance or high density and the low output characterizes low resistance or low density. Internal decay or cavities in a timber is typically characterized as extremely low resistance or zero resistance in the resistance charts [4]. In this inspection project, the purpose of conducting micro resistance drilling test were two-fold: 1) to confirm and determine the extent of decay in members and locations that had been identified by visual and stress wave timing tests; and 2) to determine the internal conditions of the timber members that cannot be tested using stress wave timing method.

Results

Species Identification. Fifteen wood core samples (eleven from first floor and four from the second floor) were collected from different types of wood structural members and different locations for species identification. All coring locations were filled with wood plugs after coring.

Wood core samples were examined at the Wood Anatomy Research Center of the USDA Forest Products Laboratory. The sample and species information are shown in Table 1. The microscopic examination of the wood samples indicated that white pine is the major species for the wood columns, beams and trusses in this century-old industrial building. These white pine timbers were most likely from the local areas where white pine used to be the dominating softwood species. The core sample from column C6 was identified as Douglas-fir, and the core sample from the transverse beam above column B6 was identified as red pine. It is likely that the original members at this area were replaced in the past due to wood deterioration or failure. However, no specific repair record exists to support this speculation.

Table 1. Species identification of wood samples from the paper mill building (Identified by the Wood Anatomy Research Center of the USDA Forest Products Laboratory).

Sample No.	Member	Floor level	Location	Species ID
1	Longitudinal beam	1	Between A1 and A2	White pine
2	Column	1	B7	White pine
3	Transverse beam	1	B1 column 6 ft east	White pine
4	Transverse beam	1	1A, midpoint	White pine
5	Column	1	C6	Douglas-fir
6	Column	1	C4	White pine
7	Column	1	B7	White pine
8	Longitudinal beam	1	Above A9, adjacent to No.3 hood	White pine
9	Corbel	1	Column A4, near brick wall	White pine
10	Transverse beam	1	B6, 12 ft east, adjacent to machine	Red pine
11	Longitudinal beam	1	Above B6, between B6 and B7	White pine
12	Bottom chord	2	Truss No. 2	White pine
13	Bottom chord	2	Truss No. 3	White pine
14	Column	2	4B	White pine
15	Bottom chord	2	Truss No. 4	White pine

Wood Moisture Content and Microclimate. All timber columns in the first floor were generally in a dry condition (8 to12.8% MC) except the columns in row A, which were from 26% to 28% MC, indicating possible moisture or water intrusion. Almost all the longitudinal beams and transverse beams in the first floor exhibited very high levels of moisture condition (23 to 55% MC). Most longitudinal beams were around fiber saturation point (30% MC), whereas all the transverse beams were almost fully saturated (30 to 55% MC). This high moisture level in the timbers was presumably caused by the high humidity and wet air condition created by the paper making operations. Note that the paper machinery is located between rows A and B and below the beams No. 6 to No. 9. The temperature and relative humidity of the air monitored at this location was shown in Figure 3. The monitoring record shows that the air temperature fluctuated between 22.2 ºC and 34.4ºC most of the time, and the relative humidity ranged from 83% to 96%, indicating an extremely wet condition resulting from the paper making operations. This constant high humidity environment is considered very detrimental to the physical conditions of the timber members in this area. This has been proved by the subsequent stress wave timing and resistance micro-drilling tests. The timber columns and bottom chords of the trusses in the second floor were in a good dry condition (8 to 11% MC).

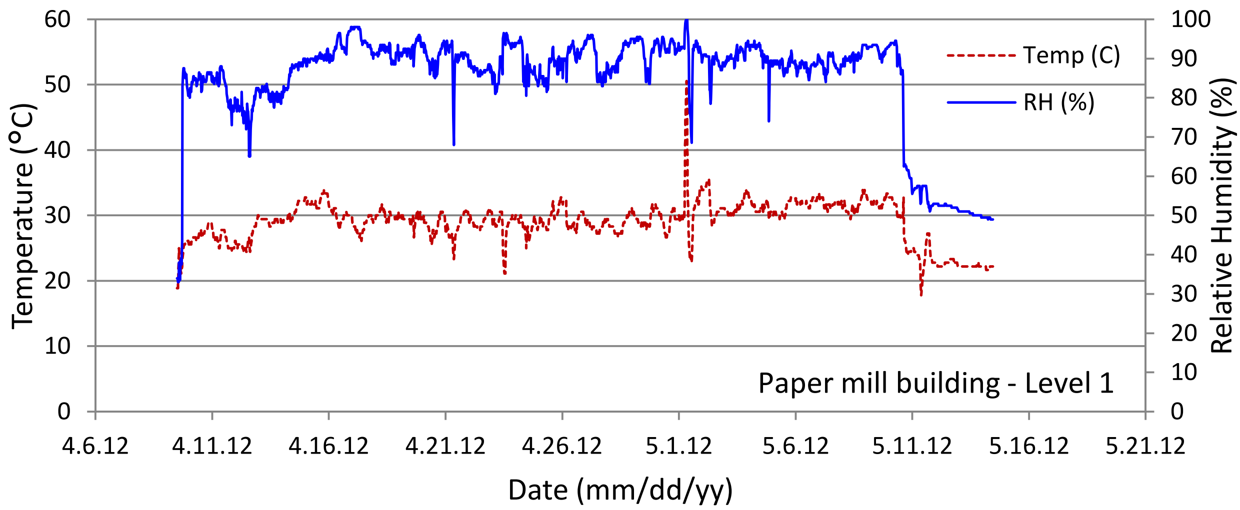

Figure 3. Indoor air temperature and relative humidity inside the paper mill building monitored over a period of one month.

Physical Conditions of the Structural Timbers. The physical conditions of the heavy timber structures in the paper mill building are summarized and presented in color-coded maps as shown in Figure 4 and 5. The condition maps are 3D model-drawings created by using an ArchiCAD software and reflect the inspection results made by the team using a combination of visual, sounding, stress wave timing, micro-resistance drilling, and moisture content checking techniques. Only members with deterioration or mechanical failures were color painted using a color scheme defined for different levels of deterioration. Although not every timber member or every location were physically tested due to limited accessibility, these condition maps represent the best assessment of the true conditions of the timber structures in this building through the implementation of a nondestructive testing based inspection procedure.

The longitudinal beams in row A and the transverse beams between column A and the east wall, including corbels, are in poorest condition exhibited by widespread severe deterioration, reduced cross-sections by fire damage, and multiple failed members. Resistograph tests in these areas show little resistance or no resistance – an indication of severe internal deterioration (Figure 6). High moisture coming from the paper making operation is the leading cause of the severe deterioration in this area. Most members in this area are saturated or show signs of past wetness. As an example, Figure 7 shows the longitudinal beam between A8 and A9a exhibiting fire damage.

The transverse beams No. 3 – 6, and No. 8 – 9 between row C and the west wall also exhibited extensive deterioration as a result of water leaks from the water sink in the second floor. Resistograph tests on these beams show almost zero resistance. The longitudinal beams in row C No. 7 – No. 9 appear to have failed in the past and are currently reinforced by a steel beam. Moderate deterioration was also found in the beam connection areas where two longitudinal beams meet and sit on a timber column.

Transverse beams between row A and row B were found in relatively good condition exhibited by higher relative resistance and less deterioration, except beam No. 1 has extensive mechanical failures and can be deemed as a failed member. Most transverse beams in this area exhibited high level of moisture condition (>30%MC). This condition has two implications: 1) a significant strength reduction comparing with normal dry condition; 2) potential of decay development.

Minor to moderate deteriorations were found in some columns in row C near the concrete supporting pier. Column C4 was found leaning to west, an indication of stability problem. The transverse beam (between C4 and the west wall) above column C4 exhibits severe deterioration, and moderate decay was found in the lower portion of column C4.

In the second story, Truss No. 1 has extensive mechanical failures and decay damage as evidenced by large deflection and shear failure on the bottom chord, failed steel bar connection, end decay, and delamination on the top chord. The roof beams under the top chord exhibit severe decay and delamination. The lower roof beam is actually broken at the location connecting to the top chord. The column supporting the Truss No. 1 next to the east wall also shows significant deterioration and delamination.

The bottom chords of Truss No. 3 and 4 have mechanical failures at the center connection area where two chords meet together and connected through a steel bar and two steel plates. All the bottom chords show minor to moderate deteriorations at the ends. The steel bar connections at the quarter-span of the bottom chords are currently loosed in almost all five trusses and no load acting on the bars. The center columns that support the trusses in the second story (column B) are generally sound, with minor to moderate deterioration detected near the floor level.

Conclusions

A nondestructive inspection procedure was employed to evaluate the physical conditions of the heavy timbers that serve as the main framing structure of a century-old industrial building. The on-site investigation involved monitoring of the microclimate environment resulting from the paper machine operations, wood species identification, wood moisture contents measurements, and internal decay detection using sounding, stress wave timing, and resistance micro-drilling methods. The testing results revealed that numerous locations were in poor condition indicated by widespread internal and external deterioration, reduced cross-sections from fire damages, and multiple failed members. Many timber members in the first floor exhibited very high levels of moisture content (23 to 55%MC) as a result of high humidity air condition created by the paper making operations. This paper also showcases a new way of interpreting the evaluation results as straightforward as possible to the customer by creating 3D model-drawings and colored condition mappings.

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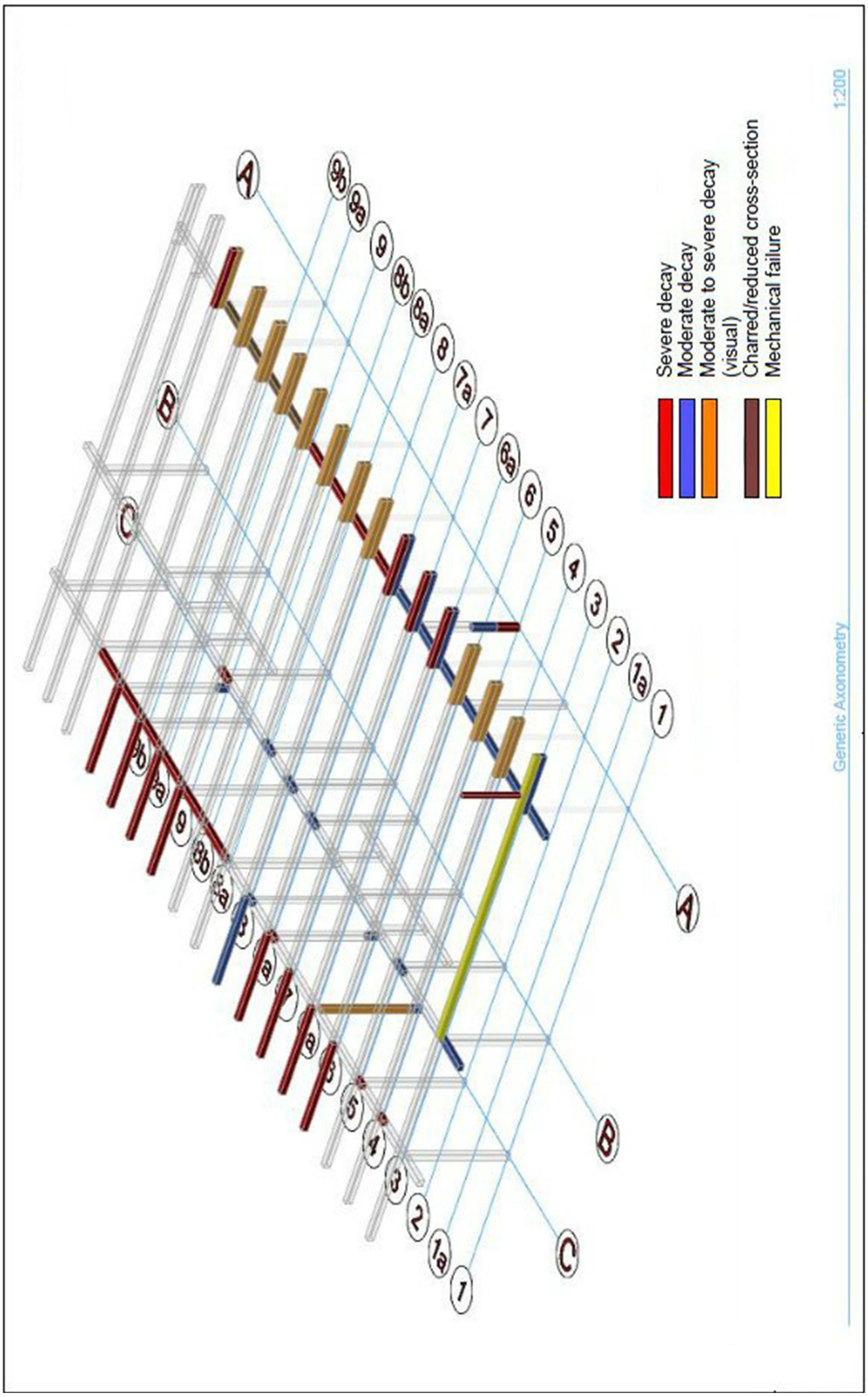

Figure 4. Condition map of the timber structures in level 1 of the paper mill building (3D view)

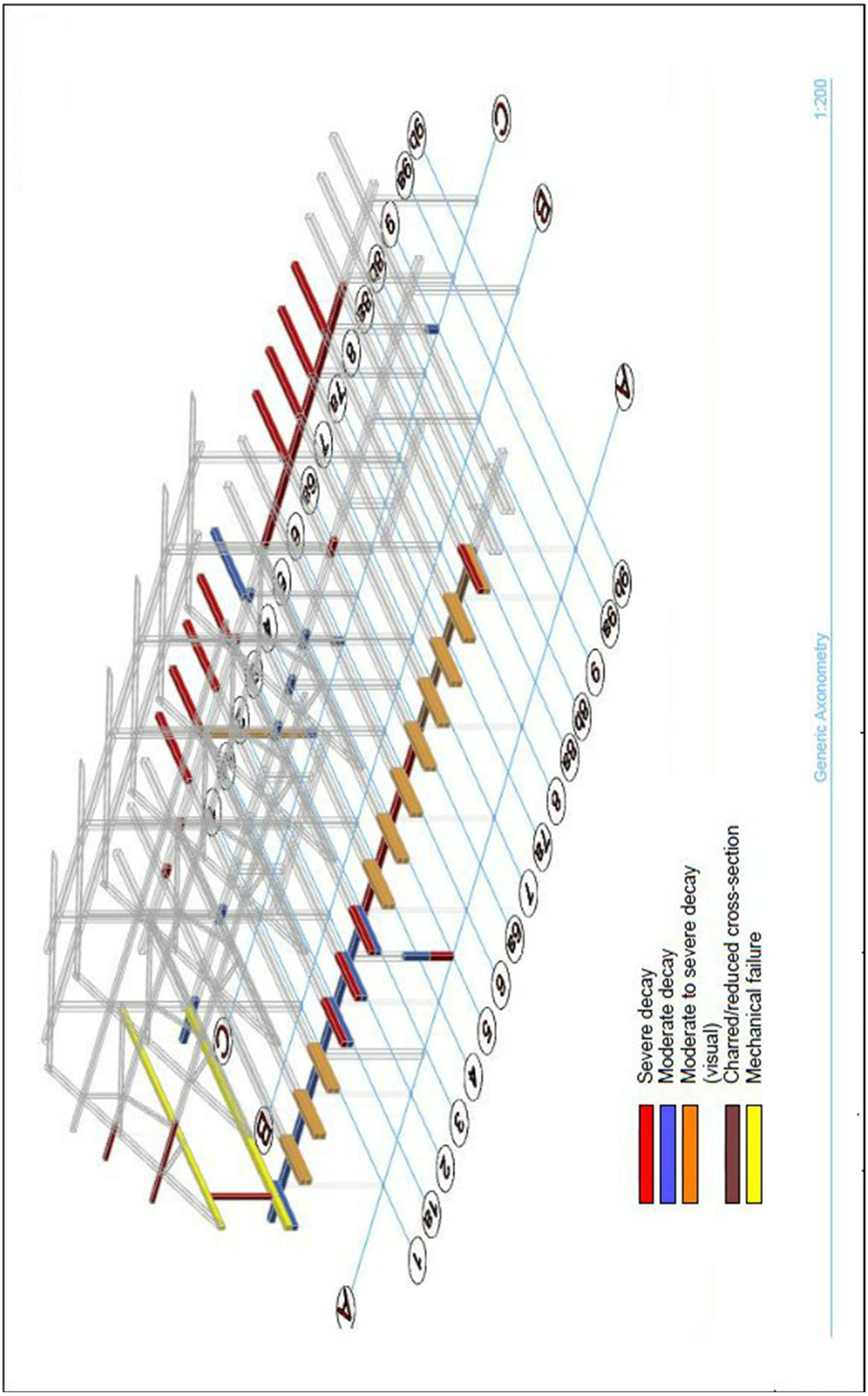

Figure 5. Condition map of the timber structures in levels 1 and 2 of the paper mill building (3D view)

Figure 6. Longitudinal beam in row A: resistance drilling test showed little or no resistance, an indication of severe internal rot.

Figure 7. Longitudinal beam between A8 and A9a exhibits fire damage. The effective cross-section of the charred beam has been reduced significantly.

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