IMPACT OF REASSEMBLY ON THE MECHANICAL PROPERTIES OF STRUCTURAL FLOOR ELEMENTS MADE OF INDUSTRIAL WOOD RESIDUES

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ABSTRACT

Background and aim. Considering the significant amount of timber constructions that end up in landfills or are incinerated, promoting efficient and circular use is essential. Designing structural elements for dis- and reassembly can extend their lifespan. However, uncertainties remain about these elements' material properties and functional performance after being disassembled, and whether they meet technical requirements for structural building products. This study investigates the impacts of using industrial wood residues to produce I-beams and multiple disassembly cycles on the mechanical properties of floor elements.

Methods and Data. The E-modulus and bending strength of elements were measured with bending tests performed according to EN 408:2010. The effects of dis- and reassembly on flooring elements made from a combination of graded sawn timber and industrial wood residues in the form of ungraded sawn timber offcuts were tested and evaluated after repeated cycles and compared to reference values. Initially, six elements were disassembled once or twice, and three elements were tested until failure to be considered as reference elements.

Findings. Two different types of reassembly processes were considered for the elements. The first reassembly type resulted in a decrease in both bending strength and E-modulus mean values. In contrast, the second reassembly type led to an approximately 78% increase in bending strength and a slight 9% decrease in E-modulus.

Theoretical / Practical / Societal implications. Using industrial wood residues in the form of ungraded sawn timber offcuts and graded sawn timber to produce load-bearing systems increases industrial wood residue utilization in structural elements. Studying the mechanical properties of elements after one or two dis- and reassembly processes ensures the user of the quality of elements after disassembly and increases the reuse rate and carbon storage time. The study shows that new end-of-life scenarios can be defined for flooring elements and industrial wood residues.

KEYWORDS: Circularity, Design for Disassembly, Experiment, Flooring Systems, Wood Residues.

1 INTRODUCTION

The construction industry's resource dependency and consumption, global greenhouse gas (GHG) emissions, and waste generation are massive (Munaro et al., 2021). The implementation of the circular economy concepts is recognized as the main solution to the existing environmental impacts of the construction sector and its transition to a more sustainable industry (Çimen, 2021). Studies on strategies to reduce the construction sector's embodied carbon emissions mention using materials with low embodied energy, such as timber, better design practices, reduction, reuse, and recovery of construction materials, refurbishment of existing buildings, and increased use of local materials. (Pomponi & Moncaster, 2016; Akbarnezhad & Xiao, 2017).

While timber is recognized as one of the most sustainable construction materials, increased demand and use of timber results in increased volumes of wood processing residues (Saal et al., 2017). Although, it is known that industrial wood residues are mostly incinerated or used in the production of engineered wood products such as chipboards; Saal et al. (2017) mention the utilization of these residues as a question that needs further analysis due to unknown available quantities, no clear internal or external consumption extents, and a few available studies

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on utilization scenarios. Apart from sawn timber residues at the material processing phase, the significant amount of construction timber lost at landfills at their end-of-life phase or incinerated cannot be neglected either.

A construction project's linear life cycle starts with material extraction, processing, and manufacturing of components. It continues with the building assembly and use phase and ends with the demolition and waste creation stages (Crowther, 2005). The transition of this linear life cycle to a real cyclic one needs defining alternative end-of-life scenarios also known as closing the material loop. In the proposed cyclic life cycle model of a built environment the demolition stage is replaced with deconstruction and alternative end-of-life scenarios are defined as relocation or reuse of the entire building, reuse of components in a new building, reuse of material in production of new components, and recycling new material to produce new material. (Crowther, 2005).

Deconstruction as an alternative end-of-life scenario is defined by Rios et al. (2015) as salvaging material from a dismantled structure for reuse or recycling. Deconstruction has both opportunities and challenges. Opportunities existing in deconstruction can be categorized as environmental, social, economic, and other benefits (Rios et al., 2015). Deconstruction's challenges can be disregarding elements or materials that are damaged during deconstruction as they are not usable any longer.

Uncertainties also remain regarding the material properties and performance of elements after disassembly, and whether they meet technical requirements for structural building products (Rios et al., 2015). Jockwer et al. (2020) mention the lack of existing methods to evaluate the performance of the dismantled elements before reuse as one of the reasons that the circularity concepts are not yet effectively established in timber buildings. This can also be due to considering buildings to be long-lasting and not anticipating disassembly and reuse of their elements (Jockwer et al., 2020).

Design for deconstruction (DfD) refers to the importance of considering deconstruction as the end-of-life scenario in the design stage of structures (Densley Tingley, 2013). Designing structural elements for easier disassembly, and reuse can extend their lifespan and enhance future circular use. Cristescu et al. (2020) summarized novel design concepts for deconstruction and reuse of timber buildings in a state-of-the-art with a focus on Design for Deconstruction and Reuse (DfDR) in low-rise timber structures (Cristescu et al., 2020).

1.1 RESEARCH AIM

This study aims to investigate the impact of multiple dis- and reassembly cycles on the mechanical properties of I-beams for floor elements and the impact of using industrial wood residues in the I-beams' flange production.

In this experimental research, flooring elements that were designed for deconstruction with I-beams made of a combination of graded timber and industrial wood residues in the form of ungraded timber offcuts were studied. The number of elements received from the producer to be tested was limited. Two research questions were defined:

1) How will the combination of offcuts and graded timber affect the material properties of flooring elements?
2) How will the material properties of these flooring elements change after one or more dis- and reassembly processes?

2 MATERIAL AND METHOD

2.1 FLOORING ELEMENTS

The structure of the load-bearing elements investigated in this study was a section of flooring systems built by Masonite Beams AB in Sweden. The width and length of these flooring systems' sections were 150 *mm* and 4800 *mm*, respectively. All studied sections were built with 10 I-beams connected with 9 noggings, chipboard on top, and batten at the bottom. A drawing of an element can be seen in Figure 1.

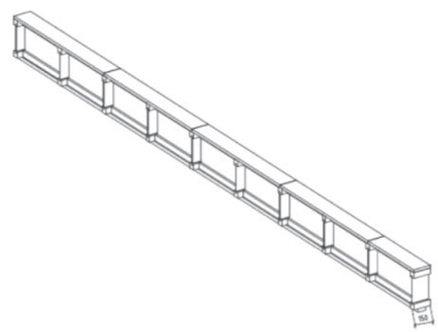

Figure 1: Drawing of an element investigated. Source: Masonite Beams AB.

The I-beams and noggings were made of H300s beams from Masonite Beams AB production where the total height of the beams was 300 *mm*, with 47×47 *mm* flanges, and 10 *mm* web. The chipboard thickness was 22 *mm*, and the width was 150 *mm*. The width of the battens used at the bottom of the elements was 70 *mm*, and the height was 34 *mm*. The flanges of the I-beams used in these elements were produced with finger jointing industrial wood residues in the form of ungraded timber offcuts with a minimum length of 150 *mm* and graded timber with strength class C30. To use the industrial wood residues, a new finger joint machine was added to the production line that could combine pieces with a minimum length of 150 *mm*. Different properties of these new finger-jointed pieces had to be tested before being used in the production of I-beams' flanges.

2.1.1 Labeling system

A total number of nine elements were studied. The elements' labels include a letter followed by two numbers separated by a dot. The letter indicates the group to which the element belongs to. The groups were called A, B, and R. Groups A and B included elements that experienced the dis- and reassembly processes twice and once, respectively. Group R refers to the reference elements. The first number refers to the number of the element within its group, and the second number indicates the number of times the element was tested. As an example, the element labelled A2.3 was the second element in group A tested for the third time.

2.2 METHOD

To answer both research questions defined earlier in this study, the mechanical properties of elements must be investigated. The European Standard EN 408:2010 includes laboratory methods to determine the mechanical properties of structural-size timber. In this study, the Swedish national version of EN 408:2010 that is SS-EN 408:2010+A1:2012 was used to investigate the mechanical properties of flooring elements. In accordance with this standard, the displacement (w) of elements was measured at the centre of the elements' span under the four-point bending test. Figure 2 shows a flooring element under the four-point bending test setup.

Figure 2: One of the flooring elements under the four-point bending test setup.

The global modulus of elasticity in bending, $E_{m,g}$, in N/mm^2, was determined based on equation (1).

$$E_{m,g} = \frac{3al^2 - 4a^3}{2bh^3(2\frac{w_2 - w_1}{F_2 - F_1} - \frac{6a}{5Gbh})} \quad (1)$$

where a = distance between a loading position and the nearest support, in mm, b = width of cross-section, in mm, and h = depth of cross-section, in mm. Defining $F_{max,est}$ as the estimated maximum load, in N, $F_2 = 0.4F_{max,est}$ and $F_1 = 0.1F_{max,est}$. The displacement values corresponding to F_2 and F_1 are w_2 and w_1, respectively. G = shear modulus. Here, based on the recommendations from standard EN 408:2010, G was considered infinite. The bending strength of beams was calculated according to Equation (2).

$$f_m = \frac{3Fa}{bh^2} \quad (2)$$

where a, b, and h were defined same as Equation (1). f_m = bending strength, in MPa and F = load, in N.

2.3 TEST STEPS

The steps taken to test the elements were different based on the group they were labelled as. The test was performed at RISE's laboratory located in Skellefteå, Sweden.

2.3.1 Reference group

Three of the nine elements, labelled group R, were tested until failure occurred under a four-point bending test following SS-EN 408:2010+A1:2012. The aim was to investigate the mechanical properties of elements built with I-beam flanges produced from a combination of industrial wood residues and graded sawn timber.

2.3.2 Dis- and reassembled groups

The other six elements, from groups A and B, were built with the same I-beams and noggings as group R. Moreover, they were designed for easier future disassembly leading to less damage to the materials by using screws and glue instead of nails and glue to attach the batten at the bottom to the I-beams and noggings in a 976 mm length, where the disassembly of elements was planned. The producer provided the instruction plans for the dis- and reassembly of elements.

The effects of deconstruction on the mechanical properties of these two groups were studied by testing them under a four-point bending test up to a certain load level, disassembling, reassembling, and bending the elements afterward. This cycle was done once or twice. Two different reassembly processes, type 1 for group A and type 2 for group B, were implemented for the dis- and reassembly of elements. In other words, the type of the dis- and reassembly processes performed on the elements was the classification factor for elements in groups A and B. The following subsections describe the disassembly process and the type of reassembly for each group of elements.

2.3.3 First-time disassembly for groups A and B

Both groups A and B, were designed in a way that they could be disassembled into two unequal parts in terms of size for easier handling and transportation from the first to the second location of use. An example of a disassembled element can be seen in Figure 3. The disassembly process included five steps as follows:

1) Removing the screws of the batten from underneath.
2) Removing the glued batten using a crowbar.
3) Removing the screws connecting the I-beam to its adjacent nogging.

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4) Cutting the chipboard from the top of the I-beam's flange.
5) Taking two parts of the element apart.

Figure 3: An example of a disassembled element after its first four-point bending test.

2.3.4 First-time reassembly, type 1 for group A

It should be mentioned that based on producer's instruction plan, this reassembly type is recommended if the surface of the nogging's flange was destroyed less than 50% after the first disassembly and has enough surface for gluing back the batten. The reassembly process type 1 had four steps including:

1) Adding a 45×45 *mm* piece of timber on the upper part of the cross-section cut, between the nogging and the I-beam. The piece can be glued and nailed or glued and screwed.
2) Connecting the chipboard on top to the added 45×45 *mm* piece of timber with glue and screw.
3) Adding screws connecting the I-beam to its adjacent nogging.
4) Attaching the batten underneath with screws and glue.

2.3.5 First-time reassembly, type 2 for group B

This reassembly type had five steps. It should also be mentioned that this reassembly type is recommended by the producer if the nogging's flange surface was destroyed for 50% or more during the first disassembly and does not have enough surface for gluing back the batten. The mentioned recommendation does not rule out the use of this reassembly type if the nogging's flange surface was destroyed for less than 50%. The steps included:

1) Adding a 45×45 *mm* piece of timber on the upper part of the cross-section cut, between the nogging and the I-beam. The piece can be glued and nailed or glued and screwed.
2) Connecting the chipboard on top to the added 45×45 *mm* piece of timber with glue and screw.
3) Adding screws connecting the I-beam to its adjacent nogging.
4) Four pieces of 34×70×200 *mm* timber screwed and glued to both sides of two I-beams in the middle.
5) Attaching two parts of 28×70×976 *mm* battens underneath the element. The battens were laterally shifted and were glued and screwed.

Figure 4 shows a view of the elements from underneath with both types of reassemblies.

Figure 4: View of the elements from underneath with reassembly types 1, group A, (on the top) and type 2, group B, (at the bottom) after the first dis- and reassembly.

2.3.6 Second-time disassembly for group A

Disassembling the elements of group A for the second time had 5 steps similar to the first-time disassembly. The difference can be seen in step 4 where the section to cut the chipboard changes from the vicinity of the I-beam's flange to the vicinity of the 45×45 *mm* piece added during the reassembly process.

1) Removing the screws of the batten from underneath.
2) Removing the glued batten using a crowbar.
3) Removing the screws connecting the I-beam to its adjacent nogging.
4) Cutting the chipboard from the top close to the added 45×45 *mm* piece of timber.
5) Taking two parts of the element apart.

2.3.7 Second-time reassembly, type 1 for group A

Before running the four-point bending test for the third time on elements in group A, they were reassembled once again under the following process including five steps:

1) Adding another 45×45 *mm* piece of timber on the upper part of the cross-section cut beside the 45×45 *mm* piece added to the element on the first reassembly process. The piece can be glued and nailed or glued and screwed.
2) Connecting the chipboard on top to the 45×45 *mm* piece added in step 1 with glue and screw.
3) Adding screws connecting the I-beam to its adjacent nogging.

4) Two pieces of 34×70×200 *mm* timber screwed and glued to one side of two I-beams in the middle.
5) Attaching one part of 34×70×976 *mm* batten underneath the element.

3 FINDINGS

This section presents the results from the four-point bending tests on all the tested elements. In all tables, w_{max} (*mm*) is the displacement value when reaching the maximum force F_{max} (*kN*), $E_{m,g}$ (*N/mm²*) and f_m (MPa) are the E-modulus and bending strength values, respectively.
Table 1 presents the results of the reference elements R1-3.

Table 1: Results of testing reference elements under four-point bending test until failure and corresponding E-modulus and bending strength values.

Element	F_{max} (*kN*)	w_{max} (*mm*)	$E_{m,g}$ (*N/mm²*)	f_m (*MPa*)
R1.1	15. 9	33.8	8250	15.2
R2.1	15.2	33.8	7398	14.5
R3.1	16.3	33.0	8019	15.6
Mean	15.8	34.9	7889	15.1

Table 2 presents the results related to elements A1-3 before disassembly. Tables 3 and 4 provide the results of elements A1-3 after their first and second dis- and reassembly processes, respectively.
The results indicated a decrease in all the mean values after each cycle of dis- and reassembly processes. Compared to the mean values related to elements tested before disassembly, maximum force (F_{max}) and correlatively bending strength after the first and second dis- and reassembly processes decreased by 33%, and 41%, respectively. Modulus of elasticity also showed around 11% decrease in values after both dis- and reassemblies compared to the state before disassembling elements.
Looking at the dis- and reassembly steps related to this group, these lower values can be explained by the impact of the two disassembly processes on the integrity of the elements by cutting the chipboard, unscrewing, and screwing back the I-beam to their adjacent noggings. All these factors lead to lower strength and enable more deflections under lower applied stress in the elements.

Table 2: Results of testing elements A1-3 under four-point bending test before disassembly and corresponding E-modulus and bending strength values.

Element	F_{max} (*kN*)	w_{max} (*mm*)	$E_{m,g}$ (*N/mm²*)	f_m (*MPa*)
A1.1	7.0	16.8	6514	6.7
A2.1	7.1	17.4	6068	6.8
A3.1	6.0	16.5	4764	5.8
Mean	6.7	16.9	5782	6.4

Table 3: Results of testing elements A1-3 under four-point bending test after one dis- and reassembly process and corresponding E-modulus and bending strength values.

Element	F_{max} (*kN*)	w_{max} (*mm*)	$E_{m,g}$ (*N/mm²*)	f_m (*MPa*)
A1.2	1.7	6.3	5123	1.7
A2.2	5.5	17.7	5367	5.2
A3.2	6.2	18.6	4943	6.0
Mean	4.5	14.2	5144	4.3

Table 4: Results of testing elements A1-3 under four-point bending test after two dis- and reassembly processes and corresponding E-modulus and bending strength values.

Element	F_{max} (*kN*)	w_{max} (*mm*)	$E_{m,g}$ (*N/mm²*)	f_m (*MPa*)
A1.3	3.8	11.2	5163	3.7
A2.3	3.9	10.2	5359	3.7
A3.3	4.0	11.4	4770	3.8
Mean	3.9	10.9	5098	3.7

Tables 5 and 6 present the results of elements B1-3 before and after their dis- and reassembly processes, respectively. With the reassembly type 2, the elements' F_{max} and correlatively the bending strength increased by around 78%, while a slight decrease of 9% was shown in the modulus of elasticity.

Table 5: Results of testing elements B1-3 under four-point bending test before disassembly and corresponding E-modulus and bending strength values.

Element	F_{max} (*kN*)	w_{max} (*mm*)	$E_{m,g}$ (*N/mm²*)	f_m (*MPa*)
B1.1	5.3	11.6	6624	5.0
B2.1	5.1	13.0	6268	4.8
B3.1	5.4	12.0	6988	5.1
Mean	5.2	12.2	6627	5.0

Table 6: Results of testing elements A1-3 under four-point bending test after one dis- and reassembly process and corresponding E-modulus and bending strength values.

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Element	F_{max} (kN)	w_{max} (mm)	$E_{m,g}$ (N/mm^2)	f_m (MPa)
B1.2	9.1	23.8	6015	8.8
B2.2	9.8	27.1	5530	9.4
B3.2	9.0	23.0	6640	8.6
Mean	9.3	24.7	6062	8.9

The differences between the values of elements A1-3 and B1-3 before their first disassembly presented in Tables 2 and 5, respectively, can be interpreted by different factors impacting the mechanical properties and quality of timber elements. As the beams are made from a combination of graded timber and industrial residues in the form of ungraded offcuts, the impacting factors can be named as the number of ungraded offcuts and consequently, the amount of glue used in finger jointing in the production of elements.

The impact of the two different types of reassemblies can be seen in the values presented for A1-3 and B1-3 after their dis- and reassembly processes. While the disassembly processes impact the integrity of elements, reassembly type 2 showed to have a more compensating impact on the B1-3 elements' properties. Although the elements showed to experience higher deflections under lower applied stress leading to lower E-modulus, the impacts of added timber reinforcements to the sides and under the elements with screws and glue can be seen in the increased bending strength.

Compared to both groups of elements A1-3 and B1-3, reference elements had higher mean values. The decrease in the values of elements in groups A and B compared to the values from the reference elements can be explained by the fact that while the battens in the reference elements were one piece nailed and glued under the elements, the battens underneath the floor elements in groups A and B were cut in 976 *mm* length in the section that was planned for disassembly and were glued and screwed. The change caused a lower strength in bending and more flexibility in the elements.

4 CONCLUSIONS

In this research, the use of industrial wood residues in combination with graded sawn timber in the production of structural flooring elements and the effects on the mechanical properties of these elements was studied. To extend the lifespan of these elements and increase the carbon storage time they were also designed for easier disassembly. Existing uncertainties regarding the effects of dis- and reassembly on elements were also investigated by studying the mechanical properties of flooring systems after one or two disassembly cycles.

Looking at the values from the reference elements and comparing them to the elements that were designed for disassembly the reference elements have both higher E-modulus and bending strength. Although this can be interpreted as a need to improve elements that are designed for disassembly; compared to the values of the flooring systems made with only graded sawn timber from the same producer, these elements' properties are still within an acceptable range before disassembly.

The decrease witnessed in the mechanical properties of group A, enables using the elements in the structures with lower requirements after the first and second dis- and reassembly processes. For group B, although there was a small decrease in E-modulus value, the bending strength was increased significantly.

The results of this study emphasize that the production of structural elements from both industrial residues and graded sawn timber leads to an increase in industrial wood residues utilization rate in load-bearing systems and ensures the quality of structural elements after dis- and reassembly when the right reassembly type is chosen.

It is worth mentioning, that using industrial wood residues with a minimum 150 *mm* length required the manufacturer to add a new machine to the production line and test different properties of the finger-jointed pieces before producing I-beams' flanges. Although uncertainties about the available quantities of industrial wood residues and their consumption scenarios still exist, the results of this study highlight the possibility of defining new end-of-life scenarios for both industrial wood residues and the produced flooring elements.

In the built environment and construction industry, the results can emphasize the existing possibilities in defining alternative end-of-life scenarios for buildings and their elements, increased use of reused structural elements, and establishment of more circular transition concepts in this industry.

For future studies, performing the same tests with dis- and reassembly processes on more elements or computational simulations can verify the results presented in this study.

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