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EVALUATION OF THE RECYCLABILITY OF WOODEN BEAM STRUCTURES

Zsofia Varga.[1], Antonia Birkholz[2], Anna Wagner[3] Stefan Winter,[4]

ABSTRACT: The aim of this paper is to present a methodology for increasing the material recyclability of wooden beam structures. The methodology was developed as part of a research project in which the deconstructability of wooden beam structures of agricultural halls was investigated. The load bearing structure of six agricultural halls was documented and the connection points of their main structure were evaluated with regard to their recyclability. In the following, it will be investigated to what extent the choice of fasteners is relevant with regard to the recyclability of the timber. For further development the methodology could be applied to other beam structures such as roof trusses or a combination of plates and beam structures such as wood panel construction.

KEYWORDS: recycling, reuse, wood, material recycling, material utilization, deconstruction

1 INTRODUCTION

The increasing scarcity of resources and augmenting material costs are leading to a rethinking in the construction industry.

The aim of the German Resource Efficiency Program (ProgGressIII), which serves to implement the German sustainability strategy, is to identify ways of using resources sparingly and thus reducing the burden on the environment. One measure is to promote the use of renewable raw materials such as timber from sustainable forestry as a construction product. [1]

Timber as a construction material serves as a carbon store and should be kept in the material cycle for as long as possible, which is why reusing timber is in line with the German resource efficiency program. To keep the timber in the material cycle for as long as possible is necessary to not only extend one material life cycle for as long as possible, but also to use the wooden resource in cascades which means to reuse, recycle or utilize material substitution. Due to photosynthesis, timber stores CO_2 during the growth of the tree, which is why it is called a carbon reservoir. After the timber has been used to generate energy, the CO_2 is released back into the atmosphere. Therefore, the goal should be to keep timber in the material cycle for as long as possible in the form of cascade utilization. This means that the timber should be downcycled in another form. For example, a beam can be processed into a wooden slat and then into a chipboard.[2]

The research project is about developing a concept for design for reuse and recycling of the hall supporting structures made of timber. This should enable reuse, re-utilisation and thus a cascade use of timber. The aim is the renewal and extension of conceptual methods for the investigation of life cycle processes of bar supporting structures made of timber.

Reuse means that the timber beam can be used again in the same way as a beam in a new supporting structure. [3]

Recovery means that the beam can be used materially for the same application (equivalent material recovery) [4] or be downcycled, e.g. in the form of a chipboard, final material recovered or final energetical recovered as firewood [5].

According to [6] the reuse of timber components depends mainly on their installation situation and on the type of fastener used to join the components. In the case of detachable connections, disassembly is mostly possible in a non-destructive manner [6]. The choice of fasteners should be considered at the very beginning of the design of timber structures. The fasteners should be easy to find, accessible, and detachable with standard tools. Also, as few nail and adhesive connections as necessary should be used to promote non-destructive disassembly. [6]

In principle, as few and similar fasteners as possible should be used. In this way, faster dismantling is possible. In addition, there is less damage to the assembled components. By using similar, uniform fasteners, there is no need to change tools, which would otherwise slow down the dismantling process. The dismantling effort is

[1]Zsofia Varga, Research Associate, Technical University Munich, Chair for Timber Structures and Building Construction, Arcisstraße 21, D-80333 München. Email: zsofia.varga@tum.de
[2] Antonia Birkholz, former Research Assistant, Technical University Munich, Chair for Timber Structures and Building Construction, Arcisstraße 21, D-80333 München. Email: antonia.birkholz@web.de
[3] Anna Wagner, Research Associate, Technical University Munich, Chair for Timber Structures and Building Construction, Arcisstraße 21, D-80333 München. Email: anna.wagner@tum.de
[4] Stefan Winter, Professor, Technical University Munich, Chair for Timber Structures and Building Construction, Arcisstraße 21, D-80333 München. Email: winter@tum.de

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reduced and disassembly is faster, which reduces costs. To ensure rapid deconstruction, the fasteners should be easily identifiable and accessible even after the planned service life. [3] It is important to detach the fasteners after service life, because sometimes the building is be used longer then its planned service life.
The ongoing research project „*Entwicklung zukunftsweisender Konzepte zum landwirtschaftlichen Bauen mit Holz - von der Planung bis zum Rückbau (ZukunftLaWiBau)*“ is intended to give farmers the opportunity to take timber from their own forest and use it as building material for their agricultural halls. At the end of their life cycle, it should be possible to dismantle the halls as efficiently as possible, while leaving as much running meter of undisturbed timber as possible. Thus, farmers should be given the opportunity to use their timber for other purposes.
In the following, a methodology developed to evaluate and to increase the material recyclability of wooden hall structures is presented.

2 BACKGROUND AND METHOD

To apply the method, six agricultural halls made of timber with span widths equal to the modular construction hall shown in Figure 1 Figure 6[7], were inspected. The beam structures of the halls consist of solid timber wood, glued laminated timber and steel fasteners. The foundations are made of reinforced concrete. An as-built survey helped to identify and to record the dimensions as well as the type of detail points of the main supporting structures.
Further, the inspection and documentation of the detail points helped to find out in which way and by using which fasteners the detail points have been assembled. Based on the results of the as-built survey, the **equivalent material recovery** of the timber structures could be determined. The detail points were assessed in terms of their **deconstructability**. To do so, a ranking of the fasteners of each detail point was carried out, and the results were included in a detail catalogue. Based on this, a methodology could be developed to increase the recyclability of timber structures.

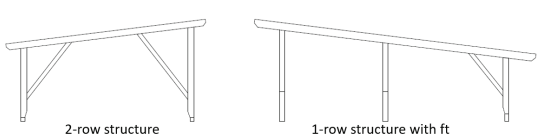

Figure 1: *Profile modular construction hall, Modulbausystem Grub-Weihenstephan according to [7]*

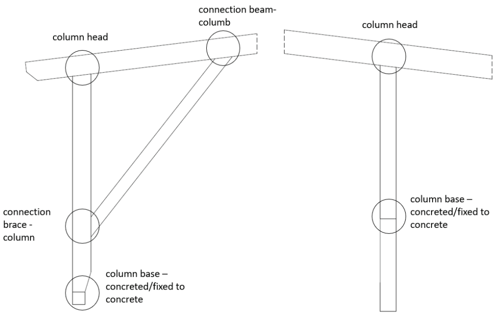

Figure 2: *Considered detail points of main structure*

2.1 EQUIVALENT MATERIAL RECOVERY OF THE TIMBER

By equivalent material recovery amount of recyclable material within one wooden beam is meant after the areas affected by fasteners would have to be cut out by a saw in the worst case. It is being assumed that the saw cut is made with the maximum necessary edge distance to the fastener. The edge distances were determined according to DIN EN 1995-1-1/NA:2013-08, p.45 ff.; DIN EN 1995-1, p.78ff [8]

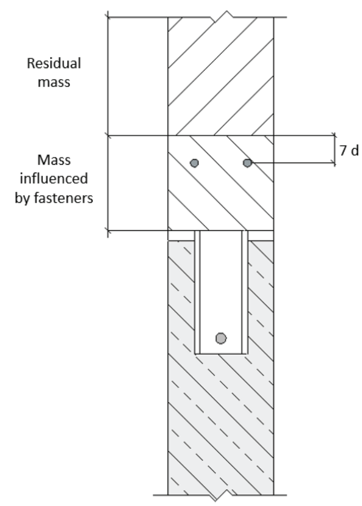

Figure 3: *detail column base, connection wood-concrete*

2.2 DECONSTRUCTABILITY

In addition to the equivalent material recovery, the evaluation of the fastener regarding fast deconstruction was carried out in terms of removability, accessibility and recognizability, because these aspects ensure fast deconstruction according to [5].

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Table 1: *definition and evaluation of removability according to DIN 8593-0 [9]*

	removability sign	evaluation
without damage	+	(3)
with (sufficiently) low damage	0	(2)
with damage	-	(1)

For the evaluation of the removability, the recycling tool of the research project *Ressourcennutzung Gebäude* [10] was used and modified. (Table 1)
A subdivision was made according to the accessibility of the detail points and the fasteners.

Table 2: *definition and evaluation of the accessibility of the detail points according to VDI 2243[5]*

		accessibility sign
directly accessible	no optimization necessary	+
indirectly accessible	improve possible disassembly	0
not accessible	depth check modification for axial accessibility	-

The evaluation of the accessibility of the detail points was neglected, because in a hall structure all detail points are accessible with a ladder. (Table 2)
The accessibility of the fasteners was evaluated according to VDI 2243. [5] The shortcut F stands for fastener

Table 3: *definition and evaluation of the accessibility of the fasteners according to VDI 2243[5]*

				accessibility of the fastener
		sign	fastener	element
directly accessible	no optimization necessary	F +		
In-directly accessible	improve possible disassembly	F 0	slotted-in steel plate	when fish plate removable
not accessible	depth check modification for axial accessibility	F -	hidden slotted-in steel plate, split ring	completely hidden by the element

The third evaluation was made according to the recognizability of the connecting means. The definition of recognizability of the connecting means of the bar supporting structures is based on VDI 2243 [5].

Table 4: *definition and evaluation of the recognizability of the fasteners according to VDI 2243[5]*

			Recognizability of the fastener
		sign	fastener
definitely visible	No optimization necessary	R +	carpenter joints
Not visible, but with indication	Provide labeling	R 0	slotted-in steel plate
Not visible, no indication	Provide notice and labeling	R -	split ring

The recognizability of the fasteners was evaluated according to VDI 2243 [5]. The shortcut (R) stands for recognizability. The *slotted-in steel plate* was defined as not visible, but with indication (R0), since it was hidden by the timber structure on the outside as an internal fastener, but the bar dowels give an indication of it from the outside. *Split ring* was considered to be a non-findable fastener (R-). The fastener is *not directly visible*, only after removing the timber structure. There is also no indication of the fastener. All other fasteners, as well as *carpenter joints* were defined as definitely visible (R+), because the type of the fastener is definitely visible.

3 EVALUATION METHOD

3.1 EVALUATION OF EQUIVALENT MATERIAL RECOVERY

To evaluate the part of a wooden beam structures, which could be equivalent material recovered, it was necessary to determine how much additional timber, potentially damaged, had to be removed by a saw in the area influenced by the fasteners.

For example, if the fasteners cannot be removed due to aging, such as rust, or there are other reasons, the fasteners can be cut out with a saw. In this way, a wooden beam is obtained which can be equivalent material recovered. The remaining material around the fastener can be further processed and be recycled. Sawing out the fasteners is possible in this case of the bar structure, since it is not a flat component consisting of several layers.

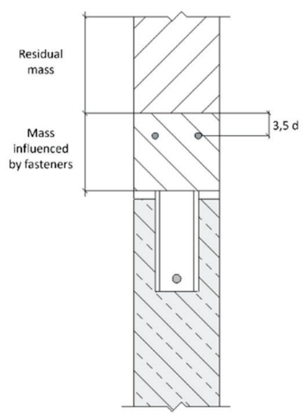

Figure 4: *detail column base, connection wood-concrete*

3.2 DECONSTRUCTABILITY, EVALUATION OF THE FASTENERS

The evaluation method should be shown as an example on Figure 5.

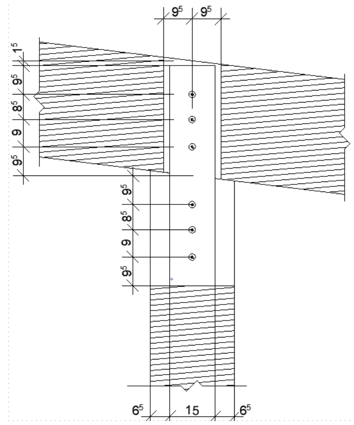

Figure 5: *Detail column head-beam: bracket + fully threaded screw*

First, the individual joints of the components and fasteners were evaluated among themselves. For this purpose, the individual components and fasteners that come into contact with each other were compared in a table. Based on the documented detail point, the removability of the layers was evaluated with numbers (Figure 5) (+ (3); 0 (2); - (1)) and divided by the maximum possible scoring combination ((3) for each joint). Thus, the percentage evaluation of the removability of the detail point was obtained. (Figure 6)

Table 5: *definition and evaluation of the removability of fastener according to [11]*

	removability of the fastener
	sign
without damage removable	+
removable with sufficiently low damage	0
with damage removable	-

	fully threaded screw	outer wooden beam	inner wooden beam	wooden column
fully threaded screw		0	0	0
outer wooden beam	0		0	+
inner wooden beam	0	0		+
wooden column	0	+	+	

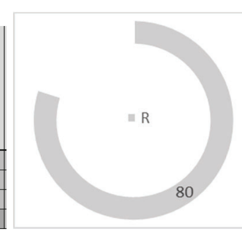

Figure 6: *removability of the layers, Graphical evaluation of removability*

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4 EVALUATION OF THE AGRICULTURAL HALLS

As both detail points, the column head and the connection beam column, are constructed in the same way with the same fasteners (Figure 2), the removability of the column head is the same.
Therefore, the faster deconstruction of the detail points

1. column base
2. connection beam-columb
3. column head

is discussed below. Since all detail points of the 2-row structure are represented in the 1-row structure, only the 1-row structure is considered in the following. (Figure 1)

4.1 EQUIVALENT MATERIAL RECOVERY OF THE TIMBER

In order to determine the equivalent material recovery of the timber, the amount and the type of fasteners were calculated and dimensioned for the load case of the worst load case. A sensitivity analysis was carried out to find out to what extent the choice of fasteners plays a role for the equivalent material recovery of the timber or if deconstruction of the fasteners plays a neglectable role.

For this purpose, the main structure was divided into different areas. Their beginning and end were delimited by the detail points (DP). The sections were named according to their location; *apex column* (*AC*), *center column (CC)*, *eaves column (EC)*, *eaves brace (EB)*, *apex brace (AB)*). The beam (B) was divided into five sections (B1-B5). (Figure 7)

The aim was to find out to what extent the choice of fasteners has an influence on the length of the timber components after the removal of the areas affected by the fasteners. For this purpose, the distances between the fasteners were determined for the respective structural members according to the standard. [8]
The minimum edge distances for the worst case to remove the fasteners were calculated.

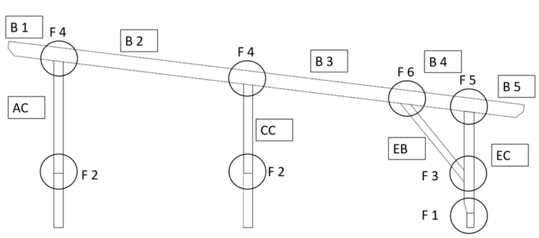

Figure 7: *1-row feeding trough (ft) structure: overview elements and detail points*

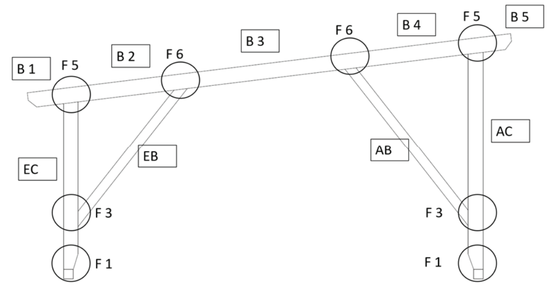

Figure 8: 2-row structure: elements and detail points

The shortcuts for the fasteners are listed in Table 6 and Table 7:

Table 6:*acronyms for different fasteners*

fastener	acronym
slotted-in steel plate	SP
split ring	SR
staggered joint	SJ
pin	P
fully threaded screw	FS
ear	E
U-steel profil	U
Steel profil	S
steel dowel pin	DP
staggered joint	SJ

Table 7: *Overview of possible combinations within one detail point (F)*

F1	F2	F3	F4	F5	F6
SP	SR + P +S	SJ+P	SP +DP	SR + P +E	E+FS
U+ SR	SP	SP +DP	SR + P	SR + P	SR +P+E
S+SP+DP	U+SR		SR +P+E		
	E+FS	SR + P			

In (Figure 9-Figure 11) the remaining lengths after cutting out the areas of the connection points for the different variants are compared to the initial length. It was found out, that there was no fastener which was responsible for cutting the less wood out. When comparing the different variants, only one recommendation can be made for the choice of the connection means of column base (F1 and F2) (Figure 9 and Figure 10) and the connection eaves column bottom (F3) (Figure 11). For this detail points following fasteners should be taken, so that the smallest area is cut off from the supports around the fasteners: F1:S+SP+SD/ SP, F2:SP and F3:SJ +P. By choosing these fasteners, the maximal length of the beams could be achieved.
The highlighted dark beams indicate the maximum and minimum, respectively, after cutting out the fasteners.

The empty frame indicates the original length of the beam. The shortcut F stands for the fasteners in the respective detail points. Figure 7

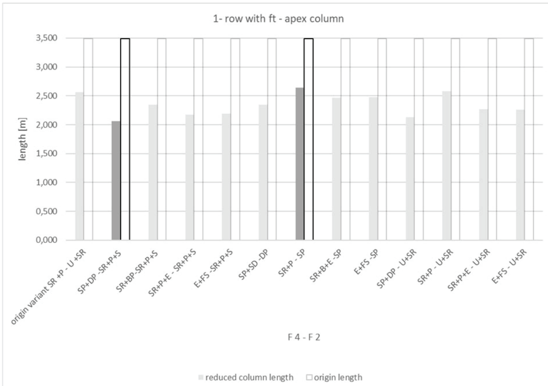

Figure 9:*1-row ft structure - apex column*

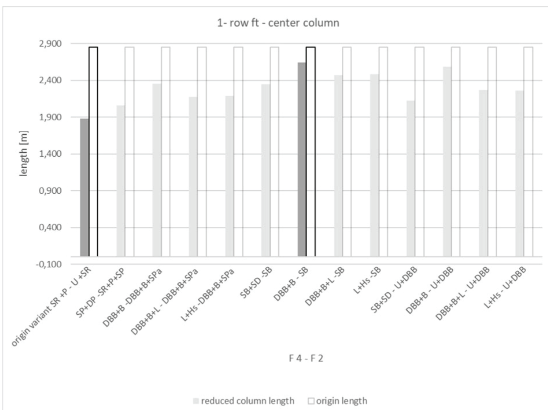

Figure 10:*1-row ft structure - center column*

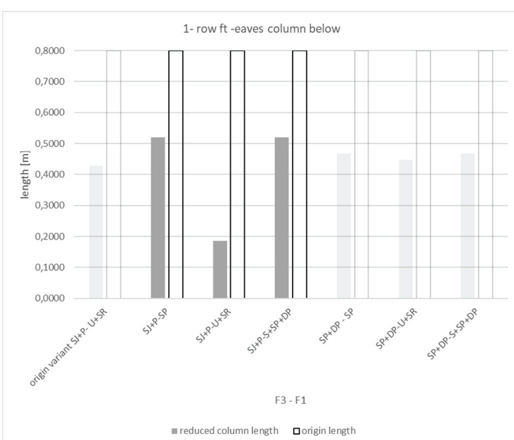

Figure 11: *1-row ft structure – eaves column bottom*

In all three cases, the variant with staggered joint and dowel pins has led to more residual length of the column, regardless of whether or not the staggered joint was concreted into the column base or the one attached to the concrete column. (Figure 11 and Figure 12)

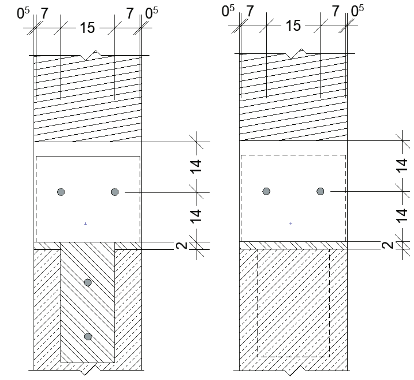

Figure 12: *slotted-in steel plate und dowel pins fixed on concrete column(le.) slotted-in steel plate und dowel pins, Steel profile set in concrete in support (ri.), F2*

For the fastener F, pin *eaves diagonal-eaves column*, the staggered joint and pin performed best in terms of the amount to be cut off and is preferable to the fixation slotted-in steel plate and dowel pins .(Figure 13)

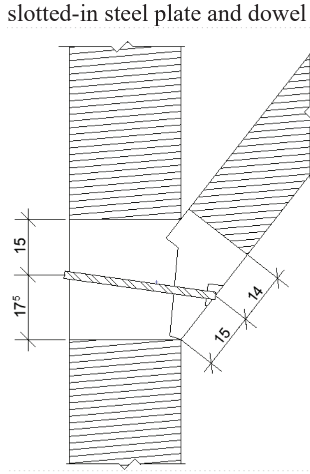

Figure 13: *staggered joint and pin, F3*

The evaluations of the detail point are shown in Figure 14-Figure 16

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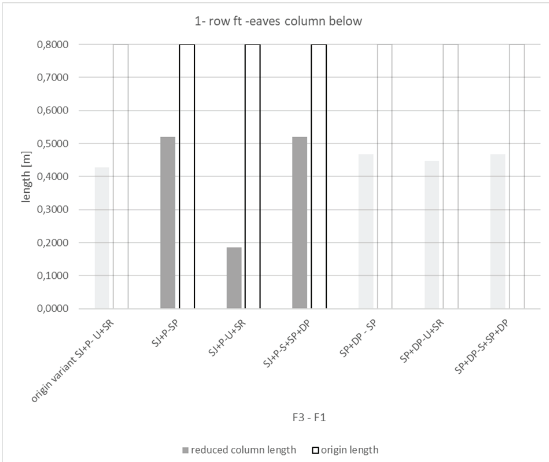

Figure 14: *1-row FT structure – eaves column, bottom*

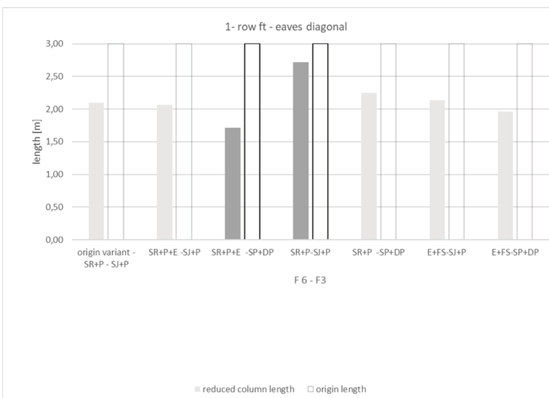

Figure 15: *1-row FT structure – eaves diagonal*

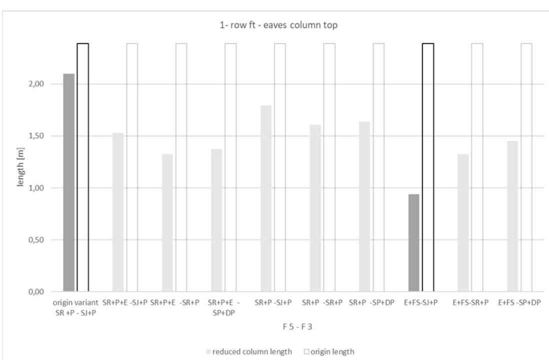

Figure 16: *1-row ft structure – eaves column top*

For the fasteners connecting the columns/diagonals to the beams, always different fasteners performed best or worst, depending on the combination.
The choice of fastener does not seem to have a significant influence on reusability.

4.2 FAST DECONSTRUCTABILITY

Since all fasteners are accessible with a ladder and, in the case of agricultural sheds, the structural components are generally not cladded, an evaluation with regard to recognizability and accessibility is neglected. The classification of fasteners according to their accessibility and recognizability was already conducted in chapter 3.1 and could easily be applied to all considered connections. Only the removability of the fasteners will be considered in more detail.
Of the variants identified, the fasteners for the best possible removability of the detail points are presented:

4.2.1 Column base

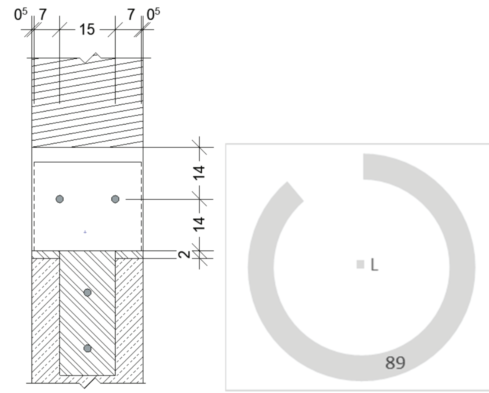

Figure 17: *slotted-in steel plate laterally fixed to concrete (left), removability [%] (right)*

The highest removability of 89% was achieved for the detail column base by the fastener alternatives *slotted-in steel plate laterally fixed to concrete*. (Figure 17)

4.2.2 connection brace – column

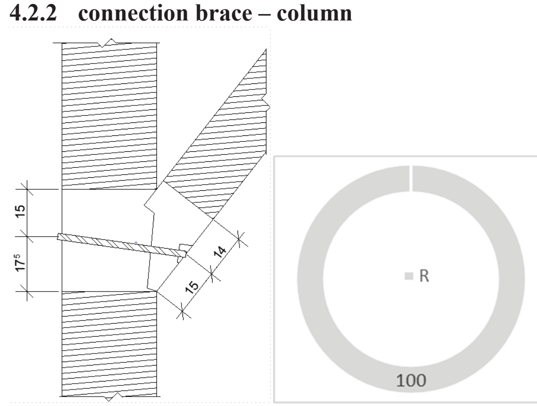

Figure 18: *staggered joint and pin (left), removability [%] (right)*

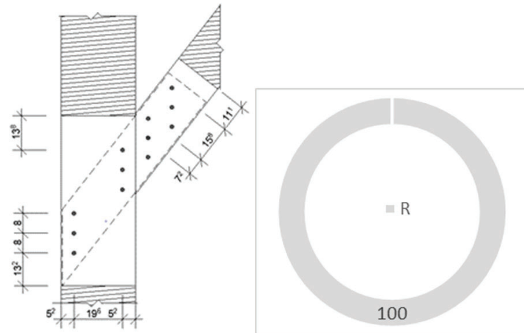

Figure 19: *slotted-in steel plate und dowel pins (left), removability [%] (right)*

The highest removability with 100% was achieved for the connection brace-column fastener alternatives *staggered joint and pin* and *slotted-in steel plate and bar dowels.(*Figure 18-Figure 19)

4.2.3 Connection column head

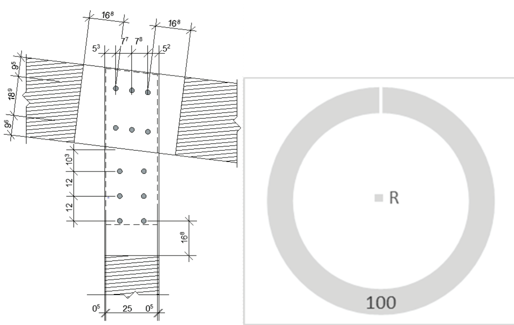

Figure 20: *slotted-in steel plate and dowel pins (left), removability [%] (right)*

The highest removability of 100% for the detail column head fastener alternatives had *slotted-in steel plate and dowel pins.* (Figure 20)

5 CONCLUSIONS

In the worst case, the areas of the construction affected by the fasteners can be removed by means of a saw, which is why the focus was on the rapid recoverability of the hall and thus, in a narrower sense, the detail points. [11]
A recommendation regarding the equivalent material recovery of the wood can only be given for the detail points *brace -column connection*. For the remaining detail points, no fastener can be identified that could significantly account for an increased number of running meter (lfm) of equivalent material recovered timber.
With regard to the fast deconstructability of the fasteners, the variant *slotted-in steel plate und dowel pins fixed on concrete column* can be recommended for the column base, for the connection brace-column: staggered joint and pin and slotted-in steel plate und dowel pins and for the detail point connection column head the fasteners *slotted-in steel plate* and *dowel pins* can be recommended. The only match between the two criteria of equivalent material recovery of the timber and fast deconstructability is in the detail item *staggered joint and pin.*
The general equivalent material recovery of the timber could not be clearly attributed to a fastener.
In order to determine the equivalent material recovery of wooden beam structures, it should not first be determined as fast deconstructability and equivalent material recovery of the timber as assumed at the beginning. Rather, the focus should be on the removability of the fasteners, since the fastener selection does not significantly affect the beam length remaining after deconstruction.
Accordingly, the methodology for determining the recyclability of timber agricultural beam structures can be further developed and transferred to other beam structures or a combination of beam and sheet structures made of timber. For example, the deconstruction potential of roof structures or elements of wood panel construction could be determined. The focus should also be on further development with regard to the evaluation of the removability of the fasteners.

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