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MULTI-PARAMETRIC EVALUATION OF INNOVATIVE CLT CONNECTIONS DEVELOPED FOR DFMA AND DFD

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ABSTRACT: The environmental impact of the construction industry largely contributes to the total human footprint. Several studies have shown that the use of timber products as construction material can lead to a substantial reduction of the environmental impact. A change in the timber construction industry toward a Circular Economy (CE) is necessary, maximizing reuse and recycling. To achieve this, the disassembly phase must be considered at an early stage in the design of a structure. Recently the standard ISO 20887, presenting the principles regarding the Design for Disassembly (DfD), has been published: the standard highlights the central role of connections to permit disassembly and presents many principles of DfD that are common to Design for Manufacture and Assembly (DfMA). This paper has two main goals. In the first part, a holistic approach is presented to identify the key parameters that make a connection suitable for DfMA and DfD. These parameters were obtained considering the principles provided in the ISO 20887 standard. A comparison is then presented between innovative and traditional Cross Laminated Timber connections taken as case studies, in order to evaluate their advantages and disadvantages.

KEYWORDS: DfD, DfMA, connections, multi-parametric, sustainability

1 – INTRODUCTION

The construction sector has a significant impact on the environment. Greenhouse gas (GHG) emissions related to construction are estimated globally at 39% of the total GHG emissions, with 28% from building operations and the remaining 11% from building materials and construction [1]. Construction materials and products also represent about 50% of all raw materials extracted. The End-of-Life (EoL) stage [2] contributes significantly to these figures: construction and demolition activities represent 35-50% of all waste generated, and 60% of 3 billion tons of global construction and demolition waste is currently disposed of in landfills annually [3].

There is a need to reduce the impact of each life cycle stage (i.e. production, construction, use and EoL). Use of low-impact and renewable bio-based materials, optimization of material use, process efficiency, and implementation of Circular Economy (CE) principles can boost the building's sustainability during its entire service life.

The use of timber as a building material provides multiple benefits in terms of sustainability. Timber is a renewable and recyclable biobased material, produced by threes using solar energy and storing large amount of carbon. A building made of timber-based materials is lighter than a structure made using traditional building materials (e.g. concrete), thereby decreasing the size of foundations.

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Timber is also less energy-intensive than other building materials (e.g. concrete and steel) [4,5]. Being a natural thermal insulator unlocks the possibility to easily incorporate timber into buildings that have lower lifecycle energy consumption and lower CO2 emissions. Timber is recyclable, and the implementation of cascading use of wood has the potential to reduce both waste and energy consumption at the EoL.

Modern timber buildings are made of engineered timber products, such as Cross Laminated Timber (CLT), precisely pre-cut by CNC machines. For this reason, timber as structural material, and in particular mass timber, is appropriate to implement Design for Manufacture and Assembly (DfMA), an engineering strategy that improves ease of manufacture and efficiency of assembly, reducing the environmental impact of the Construction Stage [2] and increasing quality control. Using this design approach, the decision-making is shifted entirely to the early design phase, allowing a considerable part of the construction phases to be carried out in a factory environment, with controlled temperature and humidity and full availability of instrumentation, reducing waste and increasing recycling and reuse. Once manufactured, the various elements only need to be transported to site and assembled, reducing time and costs.

A substantial proportion of wood (26%) has been found to be suitable for further utilization [6-8], and deconstruction has been identified as a financially viable proposition [9]. Cascading has the potential to increase the efficiency of wood use in the European wood sector by 23 to 31%, accompanied by a reduction in global warming potential of 42 to 52% [10]. Recycling and reusing materials in demolition has been shown to reduce climate change potential by 77%, acidification potential by 57% and summer smog creation by 81% [11]. One of the main factors limiting the cascading use of wood is that deconstruction of a building is not usually considered at the design stage, and as a result less than 1% of existing buildings are fully demountable. [12]. To address this issue, Design for Disassembly (DfD) principles must be implemented at early design stages to facilitate the disassembly of a structure rather than its demolition, favouring reuse and recycling. DfD does not only benefit EoL reuse, but can also have a positive effect in extending the life of a building, allowing for repair and greater adaptability. Deconstruction and DfD instead of Demolition are fundamental concepts in the CE, producing environmental, economic and social benefits [13]. To accurately and quickly evaluate disassembly potential, it is essential to employ a methodology based on digital models, i.e. Building Information Modelling (BIM) and Finite Element Methods (FEM), in conjunction with digital product passports [14-17].

Connections play a fundamental role in the design of timber buildings. The correct design of connections is imperative to ensure optimal performance in both structural and non-structural elements. Connections are also critical in DfMA and DfD [18] and must be chosen carefully to satisfy both structural and DfMA and DfD requirements.

The aim of this study is to 1) identify the main parameters to evaluate the assembly and disassembly potential of a timber connection, and to 2) compare the performance of innovative and traditional CLT connections both in terms of structural and DfD performance.

2 – DFD AND DFMA PRINCIPLES OF CLT CONNECTION SYSTEMS

Past research identified parameters required to implement DfD [19,20,14]. The recently released ISO 20887 [21] is the first standard containing principles, requirements and guidance regarding DfD. It identifies 7 design principles: Ease of access to components and services, Independence, Avoidance of unnecessary treatments and finishes, Supporting re-use (CE) business models, Simplicity, Standardization and Safety of disassembly. These principles are very general and should be adapted to the different situations and systems considered. Another design principle is durability. This is not listed as a DfD principle but has a significant impact on the and reusability of a system. Other general design principles (not listed in the standard) may be beneficial, such as the use of mono-material and light-weight elements and the number of connection points as identified by Bogue [22].

In the general section, the ISO 20887 standard identifies five different design levels (i.e. Systems, Elements, Component or assembly, Subcomponents and Materials), emphasizing the importance of considering demountability at different levels of scale (e.g. a connection system or an entire building). The focus of this paper is on both the separation of the structural elements and the removal of the connector, assuming that the disassembly of connection systems is completely independent from other construction systems (e.g. thermal insulation, acoustic profiles, finishes, etc.). Not all the listed principles are relevant for the design of easily demountable connection. Table 1 shows DfD principles in the context of connections. These are partly

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given explicitly in ISO 20887 and partly identified by the authors. Additional design guidelines can be identified in literature. As mentioned by [23], permanent deformations could affect the reversibility of a connection. For this reason, reversible connections should remain in the elastic domain. Capacity design should be applied to concentrate ductility and energy dissipation in elements that could be replaced.

Several researchers have developed tools to assess the sustainable design of structural systems based on ISO 20887 [24,25], but currently there is no consensus on calculation methods to assess assembly and disassembly potential [26,27,14]. A notable development is the assessment of different connection systems as proposed by Pozzi [28]. The analysis considered different parameters (i.e. n. of elements, finishing, element complexity, ease of disassembly, prefabrication degree, end of cycle waste, ease of assembly, reusability, degree of freedom, costs and structural strength), whose weighted combination produces a final score.

Table 1. Design principles for demountable connection systems.

DfD principle	Application on CLT connection systems
1) Ease of access to components and services	Exposed and accessible connection systems
	Localized connections
2) Independence	Reversible connections (Connection type)
	Limited disassembly damage
3) Avoidance of unnecessary treatments and finishes	-
4) Supporting re-use (circular economy) business models	-
5) Simplicity:	Limited n. of elements and fasteners
	Limited n. of structural elements connected
6) Standardization	Use of standard tools
	Prefabrication
7) Safety of disassembly	-

As highlighted by many authors, DfD can be seen as an evolution of DfMA [16] For this reason, these two design strategies have many principles in common, such as the use of localized connections, the low number of elements, the use of standard tools and the adoption of prefabrication and off-site construction.

A CLT building is usually composed of floor and wall elements. The connection between the foundation and walls commonly uses steel plates (hold-downs to avoid rocking and angle brackets to avoid sliding) and a large number of small diameter dowel type fasteners (typically nails and screws). Steel plates or screwed connections are typically used in floor-to-wall connections. Screwed connections are typically used in panel-to-panel connections (both floor-to-floor and floor-to-wall). Most connectors cannot be pre-installed, increasing assembly time and the amount of material to be transported. Most assembly work is carried out on the construction site, a place with unpredictable weather, limited availability of equipment and with difficulties in communicating with technicians. This has knock-on effects on the required duration to provide site offices, storage, and accommodation near the construction site, with increased cost. Yet, the possibility of installing on-site brings a few advantages. A less detailed design is required, and the construction process is more flexible, allowing some design changes to be made during the construction phase.

Recently, innovative timber connectors have been developed by researchers and industry to enhance DfMA and DfD in timber buildings [23,29]. In addition, methods to assess demountability have been partially investigated [28]. Yet, none of these have thoroughly examined the mechanical aspects that would allow a comparison of connections with similar functions and performance.

3 – MULIPARAMETRIC COMPARISON

In this section, a multiparametric comparison between traditional and innovative CLT connections is reported. One commercial hold-down, named WHT40 [30], and three commercial angular brackets, named TCN240 [31], TTV240 [31] and NINO 15080 [32,33], were compared with two innovative connections named RING90C and RING60T [34-36]. Connections with similar structural performance were compared considering both structural and non-structural parameters.

3.1 MATERIALS AND METHODS

Table 2 lists characteristics of traditional steel plate connections, and innovative connections (RING90C and RING60T), including weight, number of fasteners, fastener type and possibility of preinstallation. The traditional steel plate connections were fastened using wood screws, full-thread screws [35] and ring shank nails [36], either alone or in combination. Installation of the steel plates does not require CNC machining and

Table 2. Characteristics of the connection systems considered in the analysis.

Connection	Weight [kg]	Side A (Wall)			Side B (Floor or foundation)		
		N. fasteners	Fastener Type	Pre-installation	N. fasteners	Fastener Type	Pre-installation
WHT40	2.22	40	nails, LBA 4x100	NO	1	bolt, M24	NO
TTN240	1.50	36	screws, LBS 5x70	NO	2	bolt, M12	NO
TTV240	2.00	36	screws, LBS 5x70	NO	30 + 2	screws, LBS 5x70 + screws, VGS 11x200	NO
NINO15080	0.65	20	nails, LBA 4x60	NO	11 + 3	nails, LBA 4x60 + screws, VGS 9x140	NO
RING90C	0.94	6	screws, LBSH EVO 7x200	YES	1	bolt, M16	NO
RING60T	0.64	4	screws, LBSH EVO 7x200	YES	5	screws, LBSH EVO 7x200	NO

installation is performed on-site, with many fasteners used. The RING90C (see Fig. 1.a) is a special ring-shape connector made from a steel pipe of a nominal diameter equal to 90 mm, closed by a welded web on the back. Six Ø = 7 mm screws are used to install the connector to a timber element (typically CLT). A M16 steel bolt is installed in an additional hole on the opposite side (Side B), making the connector suitable for timber-to-steel or timber-to-concrete connections. In order to ensure correct installation of the screws, special guides are present on the external edge of the connector. The RING60T (Fig.1.b) is very similar to the RING90C. A pipe with nominal diameter of 60 mm is used, four holes are present on one side (Side A) and five on the opposite (Side B), in order to insert screws of 7 mm diameter, for a timber-to-timber connection. This connector also has guides for inserting the screws at the correct angle. It is noteworthy that the screws used in this connector (LBSH EVO [37]) are designed for use in hardwood (with a special tip and increased inner core diameter) and a special coating increases their durability. These characteristics can facilitate the disassembly of screws at the end of their life thanks to a better corrosion resistance and a lower probability of failure of the screw during disassembly due to the higher maximum torque.

The RING90C and RING60T can be installed in circular holes with 90 mm and 60 mm diameter respectively, therefore CNC machining is needed for this type of connection. Both the connectors could be used in different configurations, presenting good behaviour in both tension and shear.

(a)

(b)

Figure 1. (a) RING90C and (b) RING60T

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In order to ensure a fair comparison, connection systems with very similar strength capacity were compared. This is since connection systems are usually selected based on strength. The evaluation of other mechanical aspects makes it possible to assess the possibility of using the different connection systems in combination.

Two comparisons in tension configuration and two in shear configuration are presented in this paper. For wall-to-foundation connections in tensile configuration the following comparison is presented:

- WHT40 (full-pattern) vs RING90C (full-pattern)

For wall-to-floor connections in tensile configuration the following comparison is presented:

- TTV240 (partial-pattern) vs RING60T (full-pattern)

For wall-to-foundation in shear configuration the following comparison is presented:

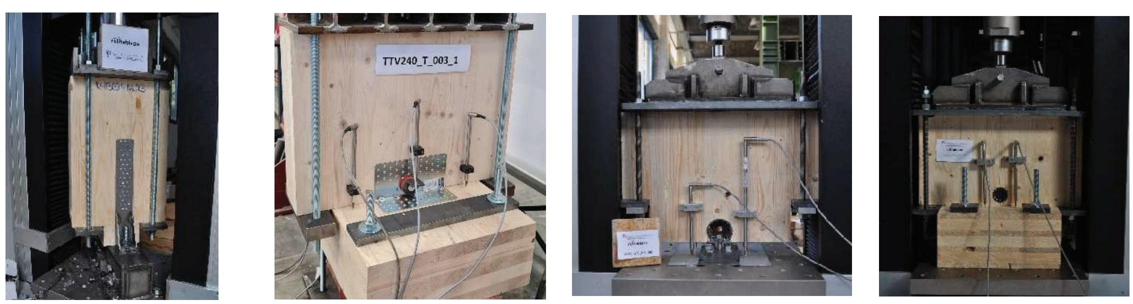
- TCN240 (full pattern) vs RING90C (full-pattern)

For wall-to-floor in shear configuration the following comparison is presented:

- NINO 15080 (full pattern) vs RING60T (full pattern)

Both mechanical and non-mechanical parameters were considered in the comparison. The strength capacity F (defined as the maximum load F_{max} or, if this occurred after 15mm, the value F_{15} at a displacement equal to 15 mm), the stiffness K (calculated between the 10% and the 40% of F_{max}) and the static ductility μ (calculated as the ultimate and yield displacement ratio) were obtained during several experimental campaigns at the Laboratory of Mechanical Testing of the Institute of Bio-Economy of the National Research Council of Italy (CNR - IBE) in San Michele all'Adige (Italy) and at the CIRI Laboratory of the University of Bologna (see Fig. 2 and Fig. 3) All the monotonic tests were performed in accordance with EN 26891 [39].

The other parameters considered in the analysis were chosen based on the parameters identified in the literature and reported in Section 2 as follows: number of fasteners N_f, weight of the entire connection W (considering both connector and fasteners), the connection type C_t (to consider the reversibility of a connection system), disassembly damage D_d (to consider the reuse potential of both structural elements and connection system) and prefabrication degree P. Some of the non-mechanical parameters are not directly measurable, hence a scale between the value 0 to 5 was defined (Table 3).



(a) (b) (c) (d)

Figure 2. Experimental campaign (tensile configuration) on (a) WHT40, (b) TTV240 (c) RING90C and (d) RING60T.

(a) (b) (c) (d)

Figure 3. Experimental campaign (shear configuration) on (a) TTN240, (b) NINO15080 (c) RING90C and (d) RING60T.

Table 3. Scale of values for non-measurable principles.

	[0]	[1]	[2]	[3]	[4]	[5]
Connection Type	Concrete or chemically bonded connection.	Welded connection	Nailed connection	Screwed connection (laterally loaded)*	Screwed connection (axially loaded)*	Bolted connection
Disassembly damage	Fasteners remain fully or partially inserted in one element	Many holes in both elements	Many holes in one element	Few holes in both elements	Few holes in one elements	No damage
Prefabrication	"Hardening" connection, meaning that at least one of the components of the connection is in a fluid state during assembly	The connection system should be fastened completely onsite	-	Connection is pre-installed on one element. The connection to the second element should be done onsite by few actions	-	Connection is pre-installed on one element. The connection to the second element should be done onsite by one action

*as reported in [23], is easier to remove axially loaded screws instead of laterally loaded screws

This scale was based on the *Disassembly Potential Tool* [40] developed by the University of Queensland and the University of Navarra. Considering both the separation of the structural elements and the removal of the connector, it was necessary to distinguish between side A (the wall side) and side B (the floor/foundation side) for some parameters (i.e. number of fasteners N_f and connection type C_t). Some of the principles identified in Section 2 were not considered: similar standard tools were used for the assembly and disassembly of all connection systems and only two structural elements were connected in each case. The principle of localized connections was not considered since no distributed connections were considered in the analysis. Finally, each connection system was considered to be completely visible and accessible, assuming complete independence between structural and non-structural elements.

3.2 – RESULTS AND DISCUSSION

Load-displacement curves of monotonic tests are shown in Fig.4 and in Fig. 5. For direct comparison, graphs of the innovative connections are plotted with those of the traditional reference connections.

The graphs show that, in the selected cases, the innovative connections achieve similar strength. It is important to note that, in cases where the maximum resistance was obtained after 15 mm displacement, F_{15} was used instead of F_{max}. For this reason, the curves are represented using a dot line after the displacement equal to 15 mm. For the calculation of static ductility μ, the entire curve of each test was considered. The tests showed a different stiffness K. An exception is the comparison between RING90C and TTN240 in shear, which have very similar stiffness (9.7 and 9.4 kN/mm respectively). Similar values of static ductility were obtained in the comparison between RING90C and WHT40 in tension (3.8 and 4.0 respectively).

Radar charts are used to compare traditional and innovative connections using a multi-parametric approach, see Fig.6 and Fig.7. It should be noted that the graphs represent a comparison between two different connection systems. For this reason, the graphs have been obtained by normalising each value with the maximum of the two values considered. A maximum value in the graph should not be considered as the maximum value obtainable, but only as the maximum between the two considered in the comparison. For this reason, it is not possible to make comparisons between connection systems shown in different graphs.

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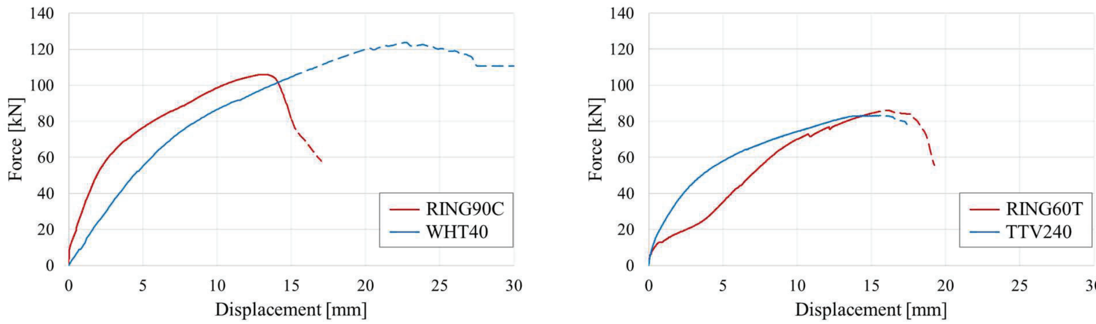
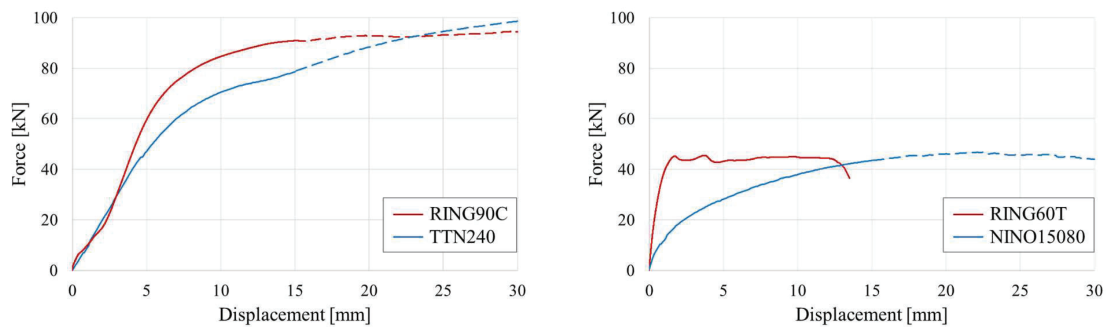


(a) *(b)*

Figure 4. Examples of load-dispacement curves, in tensile configuration, of (a) RING90C vs WHT40 and (b) RING60T vs TTV240

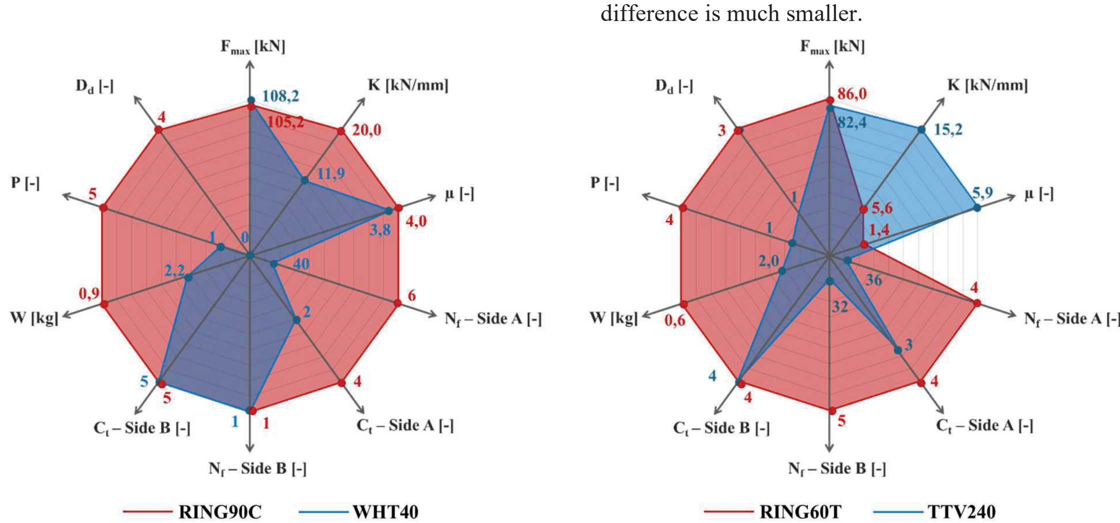


(a) *(b)*

Figure 5. Examples of load-dispacement curves, in shear configuration, of (a) RING90C vs TTN240 and (b) RING60T vs NINO15080.

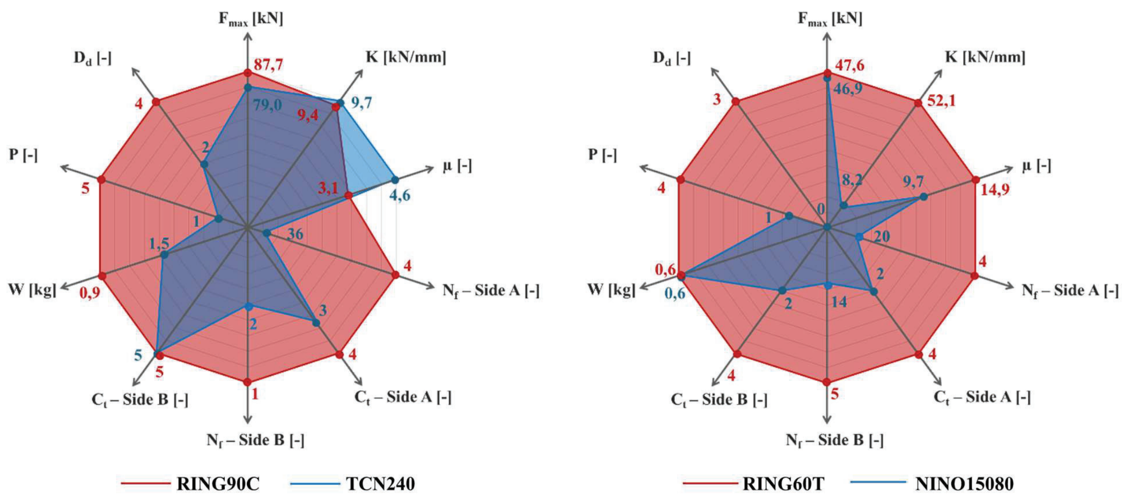
The comparison in mechanical terms shows that it is possible to achieve similar performance in terms of strength *F*. In some cases, however, it is necessary to consider the different static stiffness *K* and static ductility μ of certain connections. It is worth noting that in one case (RING90C vs TTN240 in shear) very similar values were also obtained in terms of stiffness and static ductility. Therefore, it is allows to consider the possibility of using this connection instead of more traditional steel plates.

It can be seen that the innovative connection systems considered had a reduced steel weight W in all cases, showing that there is an optimization of the material used. The number of fasteners on side A (the wall element) is also lower for innovative systems. On side B, especially in the case of wall-foundation connections, this difference is much smaller.



(a) *(b)*

Figure 6. Multi-parametric comparison of connection systems in tensile configuration, (a) RING90C vs WHT40 and (b) RING60T vs TTV240, where mechanical parameters, weight W, number of fasteners N_f, connection type C_t, prefabbrication P and disassembly damage are considered.



(a) (b)

Figure 7. Multi-parametric comparison of connection systems in shear configuration, (a) RING90C vs TCN240 and (b) RING60T vs NINO15080, where mechanical parameters, weight W, number of fasteners N_f, connection type C_t, prefabbrication P and disassembly damage are considered.

4 – CONCLUSION

A review of DfD and DfMA principles with a particular focus on CLT connections was presented in this paper, identifying eight main principles: exposed and accessible connection systems, localized connections, reversible connections (connection type), disassembly damage, n. of elements and fasteners, n. of structural elements connected, use of standard tools, prefabrication.

Four different comparisons between traditional steel plates and innovative timber connections called RIN90C and RING60T were presented. The innovative connection systems were able to achieve strength values *F* very close to those obtained with traditional steel plates. In some cases, similar values of stiffness *K* and static ductility μ were obtained, opening the possibility of using this connection instead of more traditional steel plates, or in combination with them.

Innovative connections designed for prefabrication and demountability always have fewer fasteners N_f, less weight *W* and a higher prefabrication degree *P* in comparison with traditional steel plates. The disassembly of the structural elements and the entire removal of the connection system produces less damage in the case of innovative connections, allowing a higher percentage of reuse at the end of the useful life.

It is important to emphasise that, in the cases analysed, a high level of prefabrication implies the need for CNC machining of the CLT, which is not always possible or economic, and in some cases well-established construction methods may be more efficient.

Future work is planned to develop a method to assess the assembly and disassembly potential, and to derive a score based on the parameters considered in the paper. All the parameters will be combined using different weightings and it is anticipated that the method will be validated on real cases.

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