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THE INFLUENCES OF MOISTURE CONTENT VARIATION, NUMBER AND WIDTH OF GAPS ON THE WITHDRAWAL RESISTANCE OF SELF TAPPING SCREWS INSERTED IN CROSS LAMINATED TIMBER

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Abstract: A large experimental campaign comprised of 470 withdrawal tests was carried out, aiming to quantify the withdrawal resistance of self-tapping screws (STS) inserted in the side face of cross laminated timber (CLT) elements. In order to deeply understand the "CLT-STS" composite model, the experimental tests considered two main parameters: (i) simple and cyclic changes on moisture content (MC) and (ii) number and width of gaps. Regarding (i), three individual groups of test specimens were stabilized with 8%, 12% and 18% of moisture content and one group was submitted to a six month RH cycle (between 30% and 90% RH). Concerning (ii), different test configurations with 0 (REF), 1, 2 and 3 gaps, and widths equal to 0mm (GAP0) or 4mm (GAP4), were tested. The influences of MC and number of gaps were modeled by means of least square method. Moreover, a revision of a prediction model developed by Uibel and Blaß (2007) was proposed.

The main findings of the experimental campaign were: the decrease of withdrawal resistance for specimens tested with MC=18% in most configurations; the unexpected increase of withdrawal resistance as the number of gaps with 0mm increased; and, the surprising increase of withdrawal resistance for REF specimens submitted to the RH cycle.

Keywords: Cross laminated timber; self-tapping screws; moisture content variation; withdrawal resistance; axial loading.

1. Introduction

During the last decade, cross laminated timber (CLT) has gained great relevance as a structural material. It shapes large timber plates that can be easily assembled by means of simple metal connectors, such as self-tapping screws (STS). Due to their high axial load-bearing capacity and economical application without pre-drilling, STS's has shown to be the perfect ally of CLT. Therefore, several studies have focused on the model "CLT-STS" with the aim of updating procedures proposed by existing design standards. The goal is to introduce some new parameters to the suggested equations, such as: material specificities (e.g. CLT specific lay-up or the number of lamellas penetrated), moisture content (MC), temperature or characteristics of screws.

The present research aims to evaluate the withdrawal resistance ($f_{ax,k}$) of STS inserted in the side face of three layered CLT panels. This evaluation considers two main parameters: simple and cyclic moisture changes (i) and the number and width of gaps (ii).

1.1 Cross laminated timber and moisture changes

Despite the significance of moisture effects on timber structures, research published about this subject is reduced when compared with other subjects, such as: fire resistance or seismic behavior. As it is well known, wood shrinks and swells depending on the surrounding environment, which is defined by air temperature and relative humidity (RH). Wood hygroscopic behavior varies between wood species, but it can also vary between solid wood and timber engineering materials built from the same wood species. One example is CLT which with its cross-wise lamination restrict moisture induced movements obtaining reduced rates of shrinkage/swelling in plane directions when compared with solid wood of the same species. Brandner (2013) [1] indicates that the rates for swelling and shrinkage of CLT of Norway spruce (*Picea abies*), with MC kept between 6% and 22% are: 0.02% per each percentage unit of MC added, for both directions in the plane. Bengtsson (2001) [2] performed tests on solid timber of the same species with MC kept between 8% and 20% and obtained the following range values: 0.001-0.035%/% and 0.18-0.46%/% for longitudinal and tangential directions, respectively.

Besides the changes on geometry, moisture variations can also lead to changes on timber mechanical properties, such as shear strength and modulus and, consequently, changes on the load-carrying capacity of timber elements. Gülzow et al. (2010) [3] studied the effect of moisture on MOE and shear modulus of CLT and concluded that, similarly to solid timber, both parameters decrease at their mean level towards an increase of MC. Besides that, cracking resulting from the reduction of MC leads directly to a distinct decrease in the bending stiffness perpendicular to the grain direction on the face layers.

Moisture gradients (MG) are another important moisture effect which may cause strain and stresses in perpendicular to the timber grain direction. MG resulted from fast cyclic humidity changes (climatic variations) which do not let timber reach the equilibrium moisture content in the entire cross section of timber elements, resulting on the so-called moisture induced stresses (MIS). Either timber strain or stresses are parameters treated in Eurocode 5 [4] as material properties instead of being treated as actions (as is the case of temperature induced stresses in steel structures). Some studies have been developed in an attempt to quantify the loading action of MG on glulam elements, either on bending [5] or on tensile strength perpendicular to the grain [6], concluding that MG is a predictable action. Sjödin & Johansson (2003) [7]**Erro! A origem da referência não foi encontrada.** tested the influence of initial MIS on glulam multiple steel-to-timber dowel joints. Authors verified that the highest decreases of load bearing capacity were linked to connection configurations which restrained the shrinkage deformations. Gereke (2009) [8] developed a study focused on quantification of MIS on CLT elements, pointing out that the free swelling and shrinkage of adjacent layers differs by a factor of 10 (radial/longitudinal) to 20 (tangential/longitudinal) resulting in serious structural damages and shape distortions which may reduce the material serviceability. Often MIS exceeds the tensile strength of timber perpendicular to the grain, leading to cracks (either on the surface of timber or in the central part of timber sections), shape distortions and reduction of load bearing capacity (by splitting failure).

To understand the effects of timber shrinkage/swelling as well as the effects of RH cycles on the performance of the composite model CLT-STS, it is mandatory to determine the withdrawal resistance (f_{ax}) for screwed timber elements stabilized in different environments and after aging cycles.

1.2 Self-tapping screws and withdrawal resistance

Despite the large variety of fasteners and types of connections compatible with CLT construction, nowadays STS's are widely used. They are positively known as an easy and economical solution and recommended by manufacturers for most joint details. Therefore, the interest in obtaining further knowledge about STS's performance has been growing.

When compared with standard screws, STS present some important advantages, such as: (i) the special shape of the thread region allows a high load transmission into the surrounding wood; (ii) generally, they are hardened after rolling the thread, increasing the yield moment, the torsional strength and the steel tensile capacity; (iii) the stiffness of the connection increases while the danger of "slipping" decreases [9]. Furthermore, STS are characterized by a high load-carrying capacity when axially stressed, essentially due to the combination of two characteristics: (i) the long thread lengths and (ii) the hardened steel with tensile strengths up to 1200N/mm^2 [10].

The characteristic withdrawal resistance of a fastened timber connection is an essential parameter to be considered, especially if the screws are inserted at an angle (α) to the timber grain. In this case, the load-carrying capacity of screws loaded in withdrawal becomes more important than the load-carrying capacity of screws loaded perpendicular to their axis. Eurocode 5 [4] specifies the methodology to determine characteristic withdrawal resistance ($\mathrm{f_{ax,k}}$) for the composite model "timber-screw", which is based on a relation between screw penetration depth ($\mathrm{l_{ef}}$), screw nominal diameter (d), timber characteristic density ($\mathrm{\rho_k}$) and the angle between the screw and grain direction (α).

In recent years, several studies have been performed aiming to improve this standardized proposal, considering advances on screws technology and timber products as well as introducing new parameters to the equation. Recent publications are focused on the study of the slenderness of screws [11], the angle between screws and grain direction [12] [13] [14], the moisture content [15] [16] [10] and temperature [17].

Considering the specific case of CLT, some important researches were developed looking for a withdrawal equation that considers CLT specificities. Uibel & Blaß (2007) [18] performed an extensive test program to analyze withdrawal resistance of self-tapping screws inserted, either in plane side or in narrow side, in CLT plates. As a result, they suggest a withdrawal equation which combines the following parameters: nominal or outer diameter (d) of the screw, effective pointside penetration length (l_{ef}), angle (α) between screw axis and grain direction and CLT density (ρ). In the present study, this prediction equation is adjusted in order to include new variables related with the changes in MC and the existence of gaps. Muñoz et al. (2010) [19] developed an experimental study in which the withdrawal resistance of a CLT wall-to-floor connection using self-tapping screws, was tested. Test results were compared using various withdrawal equations concluding that most equations tend to over-estimate the withdrawal resistance, which leads to the need of revising the proposed equations, especially those proposed by design standards. Aware about the differences between solid timber and laminated timber products, Ringhofer et al. (2015) [10] developed a stochastic model, verified by laboratorial test results, in which they treat withdrawal resistance as dependent on the density and on the number of layers penetrated by the screw. Ringhofer et al. (2014) [15] collected, from different sources, data related with the effect of changes in MC on withdrawal resistance of STS inserted either in solid timber, CLT and Glulam (GL). Authors used data collected to develop a simple bilinear model approach for a MC range between 8% and 20%. The same bi-linear model is applied in the present paper adding new variables: the number and width of gaps.

Regarding the effect of number and width of CLT gaps in withdrawal resistance, Silva et al. (2014) [20] briefly presents the results obtained by laboratorial tests performed at the Institute of Timber Engineering and Wood Technology which are treated in more detail in the present paper.

2. Experimental program

2.1 Parameters involved and test configurations

The experimental campaign described on the present paper was divided in two main phases. The first phase was carried out at the Institute of Timber Engineering and Wood Technology, at Graz University of Technology (Austria), where 270 specimens were tested in order to evaluate the effect of simple moisture changes [20]. The second phase was performed at the University of Minho (Portugal), where 200 specimens were tested with the purpose of quantifying the effect of RH cyclic changes on the axial load bearing capacity of STS.

As explained before, the experiments aimed to understand the influence of two different parameters on the withdrawal resistance of STS inserted in the side face of CLT. The first parameter is related with simple and cyclic moisture content changes on CLT. Regarding simple changes, three different moisture levels were considered, namely: 8%, 12% and 18%. Concerning cyclic changes, test specimens were submitted to a six month RH cycle, in which RH varied between 30% RH and 90% RH at intervals of 21 days (Fig. 1). After the cycle was completed, specimens were stabilized with MC levels around 14% (Day 324), which was the MC value obtained for reference tests performed without being submitted to the RH cycle (Day 0).

The second parameter is related with the existence of gaps on the screw path through a three-layered CLT panel. It is called gaps to the space between two boards glued side by side in a CLT panel. To explore this parameter, CLT specimens were carefully produced in order to ensure the screw insertion through a different number of gaps. As a result, five different gap configurations were defined, namely: 1) reference

(REF), the screw is inserted without the presence of gaps; 2) gap in the first layer (GAP_FL), the screw is inserted through one gap present in the first layer; 3) gap in the middle layer (GAP_ML), the screw is inserted through one gap present in the middle layer; 4) gap in outer layers (GAP_OL), the screw is inserted through two gaps present in outer layers; and 5) gap in three layers (GAP_3L), the screw is inserted through three gaps present in all three layers. A sixth configuration, with glulam specimens (GL) and without any gaps, was tested in the second phase of the experiments. This configuration was introduced as an attempt to understand the significance of cross-wise lamination of CLT. The drawings depicted in Fig. 2 illustrate these six configurations. In addition to the number of gaps, two different gap widths were tested, namely: 0mm and 4mm. Gaps with 0mm (GAP0) were selected as the reference for the better scenario and gaps with 4mm (GAP4) were selected to simulate the worst scenario. The decision on a maximum width of 4mm was based on the literature survey developed by Brandner et al. (2013) [1], who presented a summary of the main geometrical characteristics of European CLT producers. They concluded that the most common gap width varies between 2mm and 6mm. However, authors also refer that producers are looking for improvements for CLT pressing procedures, namely lateral pressing, in order to reduce the width of the gaps. So, considering these future improvements, the worst scenario was considered to be the insertion of STS through gaps with 4mm.

The combination of the studied parameters resulted in ten different test configurations and 470 specimens, divided in five sets of ten specimens for each test configuration and for each test condition.

2.2 Specimens production and test development

Test specimens used to perform the first phase of the experiments were carefully produced in laboratory, once CLT pieces should be free of significant knots and a similar density distribution between groups should be guaranteed. In order to avoid significant knots, small CLT panels (600x400x102mm^3) were produced. All panels were shaped with three similar timber layers with a thickness of 34mm each. CLT layers were glued with PURBOND® HB110, applied by MINDA gluing equipment, and pressed by a hydraulic pressing device for 3 hours with a pressure of 0.4 N/mm^2. The timber used to produce CLT was spruce (nominal strength class C24 according to EN 338 [21]) with a density range between 371kg/m^3 and 561kg/m^3 (CoV=0,[jb1]08 and mean=464kg/m^3) and a moisture range between 8,9% and 11,7% (CoV=0,09 and mean=10,2%).

Later on, the CLT panels were cut into small specimens (170x170x102mm), and predrilled with a hole of 5mm (similar to the core diameter of the threaded part of the screw, as recommended by the European Technical Approvals for softwood application [22]), in order to ensure the correct insertion of the screw through CLT gaps. At the end, full threaded screws, Rapid® Vollgewinde from Schmid, with a diameter of 8 mm and length of 180 mm, were fully inserted through CLT. Geometry defined for specimens, depicted in Fig. 2, followed almost all the recommendations present at BS EN 1382:1999 [23]. Being one of the objectives to nullify the screw tip effect, only the recommendation related with the relation between screw penetration depth and the thickness of specimen was not followed. This decision was taken once the relation between withdrawal capacity and screw penetration was already proved to be linear [15].

Finally, three groups of specimens with identical configurations and similar densities, were conditioned in three different environmental conditions, namely: 20 ºC and 29 %RH to reach 8 % of moisture content (specimens conditioned during a period of twenty days); 20 ºC and 65 %RH to reach 12 % of moisture content; and 20 ºC and 90 %RH to reach a moisture content of 18 % (specimens conditioned during a period of forty five days) [24]. Once stabilized, specimens were tested following the axial withdrawal test procedure for screws suggested in BS EN 1382:1999 [23].

CLT specimens used during the second phase of the experiments were produced in a partnership with a Portuguese timber industry, *Rusticasa*. Due to industry limitations, the production procedure was not so rigorous regarding avoiding knots and density distribution. CLT and GL were produced in the shape of big beams (4200x170x102mm), laminated with adhesive 1247 from *AkzoNobel* and pressed by a hydraulic pressing device with a pressure of 1 N/mm^2 for a period of 2.5 hours. Similarly to the first phase of experiments, CLT elements were produced with three layers with a thickness of 34mm each. Despite the non-controlled position and the quantity of knots, CLT specimens (Fig. 2) were cut from the big beams and divided in groups also considering a similar density distribution. The timber used for CLT production was again spruce C24, with a density range between 410kg/m^3 and 513kg/m^3 (CoV=0,05 and mean=460kg/m^3) and a moisture range between 16,5% and 20,2% (CoV=0,08 and mean=18,4%). The high moisture content at production time allowed to understand if the CLT lamination with higher levels of moisture content has some effect on the withdrawal resistance when comparing the results obtained by REF configuration for both phases of the experiments.

Back to the lab, specimens were conditioned in a climatic controlled room (20 ºC and 65 %RH) in order to reduce the MC. Reaching MC~14 %, specimens were predrilled with a hole of 5mm and the same full threaded screws used in the first phase of the experiments were inserted in CLT specimens (Fig. 2). At this stage, one set of each configuration was tested, following exactly the same test procedure used for first phase of experiments, while the remaining sets were conditioned in a climatic chamber and submitted to the RH cycle for a period of 324 days (Fig.1). After the cycle was finalized, specimens were tested also following exactly the same procedure.

As referred before, the second phase of the experiments also considered one group of GL specimens with the same dimensions and prepared and conditioned exactly in the same way of the CLT specimens (Fig. 2). This configuration was used as an attempt to evaluate the influence of cross lamination in withdrawal resistance of STS inserted in the main face of CLT elements.

3. Results and discussion

3.1. Data analysis

Following the mechanical tests, four main tasks were performed before initiating the statistical analysis: firstly, the withdrawal resistance ($f_{ax,test}$) was calculated through equation (1), which was derived from the method suggested in BS EN 1382:1999 [23][23]; secondly, the real moisture content at the time of the test was obtained (2) as recommended in ISO 13061-1:2014 [25]; thirdly, in order to compare equally density values ($\rho_{W,i}$), the equation (3) was applied to avoid the effect of different moisture levels and to calculate densities with a fixed MC=12% ($\rho_{12,corr}$), as suggested by BS EN 384:2010 [26]; and fourthly, the maximum withdrawal resistance was also corrected ($f_{ax,corr}$) regarding the influence of moisture content on density values, again a MC=12% was fixed (4) as suggested by CUAP 06.03/08 [27].

$$f_{ax,test} = \frac{F_{max}}{\pi \cdot d \cdot l_p} \quad (1)$$

Where $f_{ax,test}$ is the withdrawal resistance obtained by mechanical test, in N/mm^2, F_{max} is the maximum withdrawal load given by the test machine, in N, d is the screw diameter, in mm, and l_p is the length of screw penetration, in mm.

$$MC = \frac{m_1 - m_2}{m_2} \cdot 100 \tag{2}$$

Where MC is the moisture content level, in %, m_1 is the mass of specimen before drying, in g, and m_2 is the mass of specimen after drying, in g.

$$\rho_{12,i} = \rho_{MC,i} \cdot (1 - (0.5 \cdot MC - 0.12)) \tag{3}$$

Where $\rho_{12,i}$ is the density with MC=12 %, $\rho_{w,i}$ is the density with a different moisture content and MC is the moisture content, different of 12 %

$$f_{ax,corr,i.} = f_{ax,test,i} \cdot \left(\frac{\rho_{ref,i}}{\rho_{12}}\right)^{0,8} \qquad ((4)$$

Where $f_{ax,corr,i}$ is the corrected withdrawal resistance for each test specimen, in N/mm^2, $f_{ax,test,i}$ is the withdrawal resistance for each specimen resulted from the test machine, in N/mm^2, $\rho_{ref,i}$ is the density of reference (mean value for ρ_{12} obtained with the entire data of the tests performed), in kg/m^3 and ρ_{12} is the density of each specimen with MC=12%.

3.2. Test results.

In the first stage of the analysis of the obtained results, different groups and test configurations were considered individually. Table 1 shows the sampling (some extreme outliers had to be excluded from the analysis, either due to test failure or because obtained data points lie upper or lower the outer fences defined by each individual boxplot construction), the mean values and CoV values for MC, $f_{ax,corr,i.}$ and $\rho_{12,corr}$ obtained for all five test conditions and for each test configuration. The mean values of MC registered at the testing time during the first phase of the experiments were: 8.0%, 11.3% and 17.3% for specimens expected to reach, 8%, 12% and 18%, respectively. In the second phase, groups tested on Day 0 and Day 324, were tested with mean MC equal to 14.4% and 13.5%, respectively. Considering both phases of the experiments, corrected densities presented values around 455 kg/m^3, and a distribution between groups fairly similar, with a range for CoV values between 0.02 and 0.13.

Despite the differences between production of specimens from the first and second phases, two test series were considered comparable. The comparison between both focus on the influence of higher moisture content at production time on the withdrawal resistance. Once the strength classes of timber boards (C24) used for CLT production as well as the specimens configurations were equal, possible influences of CLT pressing method or the composition of the glue used for lamination were ignored.

Observing the results presented in Table 1 some preliminary conclusions, concerning the effect of gaps and moisture content on withdrawal resistance, can be pointed out:

- In the first phase of the experiments and regarding the GAP effect, it was observed a gradual increase of f_{ax} for all moisture groups, as the number of gaps with 0mm increased. It was expected a decrease of f_{ax} for the group with MC=8%. However, timber shrinkage and consequent opening of gaps did not negatively affect the withdrawal resistance. Taking REF groups as a reference, GAP0_3L was the configuration with higher increases. So, it can be pointed out that the insertion of a screw in a gap with 0mm has no negative influence on f_{ax}, even if the number of gaps increases. Our belief is that this tendency is related with crosswise lamination of CLT. However further research is required in order to deeply understand this phenomena;
- Results obtained during the second phase does not exhibit the same tendency. For the group tested on Day 0, the relation between f_{ax} and the number of gaps with 0mm does not exhibit a growing trend, but rather a constant trend. This trend is more in line with the initial expectations. However lamination with a high moisture level can be the cause of it. As a result of RH cycle and agreeing with the initial expectations, GAP0 configurations tested in Day 324 presented a declining trend, f_{ax} decreasing as the number of gaps increase;
- As expected, GAP4 configurations expressed a declining trend of f_{ax} as the number of gaps increased. Regarding the first phase of the experiments, GAP4_18% configurations presented the lowest decrease of f_{ax} once the increase of moisture content caused swelling of timber significantly reducing the width of the gaps. In contrast, GAP4_8% configurations presented the highest decrease of f_{ax}, once the reduction of moisture content and consequent timber shrinkage increased the width of the gaps. Concerning the second phase of the experiments, GAP4 configurations exhibited higher decreases of f_{ax} than the decreases observed on the first phase of the experiments. Decreases observed for GAP4_Day0 configurations must be related with the high moisture content during the lamination process and the consequent increase of width of the gaps. The higher decreases of f_{ax} observed for GAP4_Day324 are directly related with the damages caused by the RH cycle;

- Regarding moisture effects during the first phase of the experiments, and taking the groups with MC=12% as reference, results obtained for configurations REF and GAP0 expressed no moisture effect when MC = 8 % and a slight decrease of f_{ax} when MC = 18 %. For GAP4 configurations, it was observed a significant decrease of f_{ax} when MC = 8 % while the gradual increase of the number of gaps tends to nullify the decrease of f_{ax} caused by the increase of moisture content (MC=18%);
- The effect of RH cycle evaluated during the second experimental campaign presented no significant consequence in the majority of the configurations, REF stands out, which showed an important increase of f_{ax} and GAP_3L, which exhibited substantial decreases of f_{ax}.

3.3. Modeling test results

In order to more accurately evaluate the influence of gaps and moisture content, linear fittings based on the method of least squares were performed. Considering the REF configuration of each test group as a reference $\left(\frac{f_{ax,gap(i)}}{f_{ax,REF,mean}}\right)$, linear fittings, depicted in Fig. 3, Fig. 4 and Fig. 5, were performed and mean k_{gap} values, shown in Table 2, were defined. The effect of each gap added in the withdrawal resistance was quantified by k_{gap} values which were defined by slopes given by linear fittings.

With the exception of the group tested on Day 324, configurations with GAP0 presented an unexpected tendency: f_{ax} presents a slight increase as the number of GAP0 in the screw path also increased (Table 2). These phenomena can be related with the crosswise lamination of CLT. Nevertheless, this study considered that GAP0 has no influence on the test results. On the other hand, as a result of the enlargement of the gap width, caused by RH cycle, the group tested in Day 324 presented an opposite trend exhibiting a decrease of 6.5 % per each GAP0 added.

As expected, configurations with GAP4 presented higher decreases for f_{ax} and a downward trend of f_{ax} as the moisture content increased. The test group with MC=8% and the test group tested on Day 324 registered the highest decreases of f_{ax}: 14.4 % and 16.5 % per each GAP4 added in the screw path, respectively (Table 2 and Fig. 4). Low f_{ax} values obtained by test group with MC=8 % resulted from the enlargement of the gap width due to wood shrinkage, while low f_{ax} values obtained by tests performed on Day 324 should be related with the damages caused by RH cycle and also with the high moisture content levels at lamination time. Considering the reduced decrease of f_{ax} (5.7 % per each GAP4 added), the test group with MC=18% shows that the increase of moisture content can be beneficial for withdrawal resistance in some scenarios. This phenomenon is related with the consequent reduction of gap width when wood swells. Despite the difference of approximately 2 % of moisture content between the test group with MC=12 % and the group tested on Day 0 (MC=14%), the results obtained are close: f_{ax} reduces 8.8 % and 10.6 % per each GAP4 added, respectively. The higher decrease presented by the group tested on Day 0 must be related with the high moisture content levels at lamination time, which resulted on the enlargement of the gap width.

Relatively to the tests performed with GL during the second phase of the experiments, it was observed that for the group tested on Day 0, GL presented f_{ax} mean values 7.8 % higher than REF specimens also tested on Day 0. However, considering the overlapping of notched boxplots (Fig. 5), the difference between GL and REF groups is not significant. Results obtained for groups tested on Day 324 are more significant, GL presents f_{ax} values 7.6 % lower than those obtained for REF configuration with no overlapping of notched boxplots observed (Fig. 5). A possible explanation for this tendency, also referred by Ringhofer et al. (2014) [15], can be related with CLT crosswise lamination.

Considering test configurations with MC=12% and/or test configurations tested on Day 0 as reference $\left(\frac{f_{ax,W(i/Day324)}}{f_{ax,W(12/Day0)}}\right)$, the effect of each percentage unit of moisture content added/subtracted as well as the effect of RH cycle in the withdrawal resistance were quantified. Table 3 shows slope values (k_{MC}) obtained by linear fittings depicted in Fig. 6, Fig. 7 and Fig. 8.

Values obtained during the first phase of the experiments show that REF and GAP0 configurations present similar behaviour for both moisture ranges considered. As shown in Table 3, Fig. 6 and Fig. 8, when MC is between 8 % and 12 %, f_{ax} remains the same, while when MC is between 12 % and 18 %, f_{ax} presents small decreases of 1.8 % and 1.7 % per each MC unit added, for REF and GAP0 configurations, respectively. Here it is important to mention that the obtained decrease for REF configuration is significantly lower than the decreases obtained for solid timber and GL. According to Ringhofer et al. (2014) [15], withdrawal resistance of a STS inserted in solid timber and GL decreases 3.1 % and 2.5 %, respectively, per each MC unit added to the timber element.

Due to wood swelling/shrinkage, GAP4 configurations present the opposite behavior (Table 3 and Fig. 7): lower levels of moisture content resulted in higher losses for f_{ax} as the number of gaps increased, while higher levels of moisture content tended to avoid the expected effect of moisture increase as the number of gaps increased.

Surprisingly, results obtained during the second phase of the experiments show that RH cycle resulted in an improvement of f_{ax} for REF configuration, which exhibits an increase of 13,5%. This phenomena should also be related with crosswise lamination and MIS caused by RH cycle. On the other hand, as a consequence of damages caused by RH cycle, GAP4_3L configurations presented high decreases for tests performed on Day 0 and Day 324: 10,2% and 10,0%, respectively. The remaining configurations presented reduced effects on withdrawal resistance.

As a result of this analysis, equations (5) and (6) present two bi-linear models, proposed to predict the influence of gaps and the influence of moisture content changes on the withdrawal resistance of STS inserted in different CLT configurations. The obtained values for k_{gap} and k_{MC}, presented in Table 2 and Table 3, respectively, are the variables that should be applied in the suggested models. It is important to underline that, despite the increase/decrease of f_{ax} observed for GAP0 configurations, these models considered that as the number of gaps with 0mm increases, f_{ax} remains the same. The obtained models are an important step to introduce the influences of the studied variables on practical applications. However, despite being based on results obtained with rigorous experimental tests, the presented models should still be verified and some further research is needed. The width of the gaps, for example, is a variable that should be deeply studied in order to complement the proposed models. Gaps with 1mm, 2mm and 3mm should also be tested in order to verify if the expected linearity exists.

$$\eta_{gap} = \frac{f_{ax,gap(i)}}{f_{ax,REF,mean}} = \begin{cases} 1.00, when\ gap = 0\ mm \\ 1.00 + k_{gap} \cdot N, when\ gap = 4\ mm \end{cases} \tag{5}$$

Where $f_{ax,gap(i)}$ is the mean withdrawal resistance of a given configuration, $f_{ax,REF,mean}$ is the mean withdrawal resistance of REF configuration with the same range of moisture content, k_{gap} is the effect of each gap added in the withdrawal resistance and N is the number of gaps.

$$\eta_{MC} = \frac{f_{ax,MC(i/Day324)}}{f_{ax,MC(12/Day0)}} = \begin{cases} 1.00, for \begin{cases} REF \\ GAP0 \end{cases}, when\ 8\% \leq MC \leq 12\% \\ 1.00 - k_{MC} \cdot (MC - 12), for \begin{cases} GAP4, when\ 8\% \leq MC \leq 18\% \\ REF, when\ 12\% \leq MC \leq 18\% \end{cases} \end{cases} \tag{6}$$

Where $f_{ax,MC(i/\mathrm{Day324})}$ is the mean withdrawal resistance of a given configuration with a moisture content range between 8 % and 18 % or tested after RH cycle, $f_{ax,MC(12/\mathrm{Day0})}$ is the mean withdrawal resistance of the same configuration with 12 % of moisture content or tested before the RH cycle, k_{MC}

is the effect of each percentage unit of moisture content added/subtracted as well as the effect of RH cycle in the withdrawal resistance and MC is the moisture content.

3.4. Applying η_{gap} and η_{MC} to the Uibel & Blaß Model

In order to evaluate the defined η_{gap} and η_{MC} parameters, the model proposed by Uibel & Blaß [18], was applied as it is shown in equation (7). Fig. 9 shows the relation between test results and the predicted values resulted from (7). Despite the good data trend, mean values obtained by tests present higher values than the predicted withdrawal resistance, suggesting that Uibel & Blaß model is too conservative. As k_{gap} and k_{MC} were suggested based on the average of slops obtained by linear fittings performed for different configurations (e.g. GAP4_OL and GAP4_3L), some test configurations did not present such conservative predicted values, namely: GAP4_3L_18 and GAP4_3L_0 (Fig. 9 (e)). Representing the worst scenario, these configurations obtained the higher values for k_{gap} and k_{MC}, but considering the average with other configurations (GAP4_OL_18 and GAP4_OL_0, respectively) the final values were reduced.

The most conservative results, for the majority of the test configurations, are expressed by tests performed during the second phase of the experiments. This fact is related with the reduced linearity obtained by linear fittings, when different number of gaps were considered. As a consequence high k_{gap} values were suggested and more conservative results obtained.

$$F_{ax,pred} = 0.44 \cdot d^{0.8} \cdot l_{ef}^{0.9} \cdot \rho^{0.75} \cdot \eta_{gap} \cdot \eta_{MC} \tag{7}$$

Where $F_{ax,pred}$ is the predicted withdrawal resistance, for STS inserted in the plane side of CLT, considering moisture content level, number of gaps present in screw path and width of gaps, d is nominal or outer diameter of the screw, in mm; l_{ef} is effective pointside penetration length, in mm; ρ is density of CLT (whole cross section), in kg/m³

5. CONCLUSIONS

The present research showed and discussed the results of an experimental campaign focused on the quantification of effects caused by moisture content variation, RH cycles, the existence of gaps and their width on the withdrawal behavior of axially loaded STS inserted in the side face of CLT panels.

Moisture content covered a range between 8 % and 18 %, RH cycle oscillated between 30 % and 90 %, number of the gaps presented in the screw path varied from 0 to 3 and gap widths were of 0mm and 4mm.

After the analysis and modeling of the test results, some important conclusions can be pointed out:

- Relatively to the first phase of the experiments, it was observed that the insertion of gaps with 0mm in the screw path can result on an improvement of f_{ax}, while the insertion of gaps with 4mm result on a decrease of f_{ax}, which tends to reduce its significance as the moisture content increases. The surprising behavior of GAP4 configurations is related with timber swelling which causes the closing of gaps and consequently results on an improvement of the withdrawal resistance. The behavior of GAP0 configurations can be related with CLT crosswise lamination. Nevertheless, further research is needed to solidify the conclusions;
- The results obtained during the second phase of the experiments suggest that the high values of k_{gap} observed on tests performed on Day 324 resulted from damages caused by RH cycle, while the high k_{gap} obtained for GAP4_DAY0 must be related with the high level of moisture content at the time of CLT production;
- It was observed that for a MC range between 12% and 18%, REF configuration presented a decrease for f_{ax} of 1.8% per each percentage unit of moisture content added. This result proves that the reduction of withdrawal resistance caused by increase of moisture is lower for STS inserted in CLT than for solid timber and GL;
- A comparison between effects of RH cycle on CLT (REF configuration) and GL was made. The results obtained also suggest a better performance for CLT which exhibits an increase of f_{ax}, while GL presented a slight decrease of f_{ax}. However, in order to properly quantify these differences more research is needed;
- The adjusted Uibel & Blaß (2007) model showed accuracy in predicting the obtained test results.

Beyond the suggestions for future research already mentioned, another theme that should be studied is the influence of moisture content variations and gaps on withdrawal capacity of STS inserted in lateral side of CLT panels.

ACKNOWLEDGEMENTS

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TABLE CAPTIONS

Table 1 - Mean values of MC, $f_{ax,corr}$ and $\rho_{12,corr}$ and sampling used to the tests results treatment for the different configurations tested in first and second phase of experiments.

Table 2 - Obtained values for $\boldsymbol{k_{gap}}$, depending on moisture content and gap width.

Table 3 - Obtained values for $\mathbf{k_{MC}}$, depending on moisture content, gap width and number of gaps.

Table 1 - Mean values of MC, $f_{ax,corr}$ and $\rho_{12,corr}$ and sampling used to the tests results treatment for the different configurations tested in first and second phase of experiments.

Mean Values											
		Sampling MC [%] $f_{ax,corr}$ [N/mm²] $\rho_{12,corr}$ [kg/m³]									
		1st Phase						2nd Phase			
Groups		8%		12%		18%		Day 0		Day 324	
		Mean	*CoV*	Mean	*CoV*	Mean	*CoV*	Mean	*CoV*	Mean	*CoV*
REF		10		9		10		10		10	
		8.4	*0.04*	11.7	*0.06*	17.45	*0.02*	14.3	*0.01*	13.7	*0.01*
		6.48	*0.06*	6.46	*0.03*	5.75	*0.04*	7.04	*0.08*	7.99	*0.07*
		466	*0.12*	463	*0.13*	472	*0.11*	448	*0.04*	452	*0.02*
GAP0	**FL**	10		10		10		10		8	
		8.0	*0.03*	11.0	*0.04*	17.0	*0.03*	14.5	*0.01*	13.6	*0.01*
		6.85	*0.07*	6.95	*0.07*	6.32	*0.06*	7.68	*0.04*	7.83	*0.08*
		446	*0.09*	452	*0.09*	452	*0.09*	461	*0.05*	461	*0.04*
	ML	10		10		10		9		8	
		8.1	*0.03*	11.2	*0.04*	17.0	*0.03*	14.4	*0.01*	13.2	*0.02*
		6.46	*0.07*	6.74	*0.05*	6.11	*0.03*	7.50	*0.05*	7.29	*0.05*
		446	*0.08*	453	*0.08*	451	*0.07*	431	*0.08*	438	*0.05*
	OL	10		10		10		9		9	
		8.0	*0.04*	11.1	*0.04*	17.4	*0.02*	14.3	*0.01*	13.4	*0.02*
		6.80	*0.05*	6.97	*0.04*	6.24	*0.04*	6.83	*0.12*	6.58	*0.10*
		454	*0.09*	461	*0.08*	460	*0.09*	476	*0.07*	487	*0.03*
	3L	10		10		10		10		10	
		8.1	*0.03*	11.2	*0.04*	17.3	*0.02*	14.6	*0.01*	13.6	*0.01*
		7.42	*0.02*	7.36	*0.04*	6.31	*0.04*	7.64	*0.07*	6.86	*0.07*
		453	*0.08*	456	*0.07*	456	*0.07*	448	*0.05*	443	*0.04*
GAP4	**FL**	9		10		10		10		10	
		8.1	*0.02*	11.9	*0.04*	17.4	*0.03*	14.5	*0.01*	13.6	*0.01*
		5.57	*0.00*	5.97	*0.06*	5.36	*0.06*	6.91	*0.04*	6.70	*0.05*
		458	*0.08*	454	*0.08*	453	*0.08*	439	*0.05*	451	*0.05*
	ML	8		10		10		10		10	
		7.9	*0.04*	11.2	*0.02*	17.3	*0.03*	14.4	*0.01*	13.3	*0.01*
		5.41	*0.02*	5.87	*0.02*	5.34	*0.04*	5.83	*0.06*	6.36	*0.07*
		454	*0.08*	461	*0.09*	461	*0.08*	444	*0.04*	449	*0.02*
	OL	10		10		10		10		10	
		8.0	*0.02*	11.4	*0.05*	17.4	*0.02*	14.3	*0.01*	13.5	*0.01*
		4.48	*0.07*	5.32	*0.07*	5.28	*0.07*	5.61	*0.20*	5.81	*0.09*
		487	*0.09*	463	*0.08*	461	*0.08*	437	*0.06*	439	*0.06*
	3L	10		10		10		10		10	
		7.8	*0.02*	11.30	*0.04*	17.4	*0.01*	14.3	*0.01*	13.5	*0.03*
		4.04	*0.07*	4.68	*0.06*	4.72	*0.07*	3.90	*0.13*	3.51	*0.19*
		466	*0.08*	468	*0.08*	467	*0.07*	439	*0.03*	442	*0.04*
GL								9		9	
								14.4	*0.01*	13.3	*0.01*
								7.59	*0.07*	7.39	*0.07*
								455	*0.05*	468	*0.06*

MC – moisture content. $f_{ax.corr}$ – corrected maximum withdrawal resistance. $\rho_{12.corr}$ – corrected density of reference. **CoV** – Coefficient of Variation. **REF**- test configuration with no gaps. **GAP0_FL**- test configuration with a gap of 0mm in first layer. **GAP0_ML**- test configuration with a gap of 0mm in middle layer. **GAP0_OL**- test configuration with a gap of 0mm in outer layers. **GAP0_3L_324** - test configuration with a gap of 0mm in three layers. **GAP4_FL** - test configuration with a gap of 4mm in first layer. **GAP4_ML**- test configuration with a gap of 4mm in middle layer. **GAP4_OL** - test configuration with a gap of 4mm in outer layers. **GAP4_3L**- test configuration with a gap of 4mm in three layers. **GL** – glulam test configuration with no gaps.

Table 2 - Obtained values for $\boldsymbol{k_{gap}}$, depending on moisture content and gap width.

Moisture content (MC)		8%	12%	18%	Day 0	Day 324
$\boldsymbol{k}_{\mathbf{gap}}$	**GAP0**	0.03	0.05	0.05	0.03	-0.07
	GAP4	- 0.14	- 0.09	- 0.06	-0.11	-0.17
	GL	-	-	-	0.08	-0.08

Table 3 - Obtained values for $\mathbf{k_{MC}}$, depending on moisture content, gap width and number of gaps.

<table>
<tr><th rowspan="2">Moisture Range/RH cycle</th><th colspan="4">k_{MC}</th></tr>
<tr><th>REF</th><th>GAP0</th><th>GAP4 FL/ML</th><th>GAP4 OL/3L</th></tr>
<tr><td>8%-12%</td><td>0.00</td><td>0.00</td><td>-0.02</td><td>-0.05</td></tr>
<tr><td>12%-18%</td><td colspan="3">0.02</td><td>0.00</td></tr>
<tr><td>Day324</td><td>0.14</td><td>0.04</td><td colspan="2">0,06</td></tr>
</table>

FIGURE CAPTIONS

Fig. 1 - RH cycle performed during second experimental campaign. Relative humidity and temperature registered by climatic chambers during 324 days.

Fig. 2 - All ten test configurations tested during first and second phases of experiments. (Dimensions in mm).

Fig. 3 - Linear regressions performed between REF configurations and specimens with different GAPs with 0mm tested during first and second phase of experiments. k_{gap} and R^2values are presented in tables bellow respective graphs.

Fig. 4 - Linear regressions performed between REF configurations and specimens with different GAPs with 4mm tested during first and second phase of experiments. k_{gap} and R^2values are presented in tables bellow respective graphs.

Fig. 5 - Linear regressions performed between specimens with no GAPs (REF and GL) tested during second phase of experiments. k_{gap} and R^2values are presented in tables bellow respective graphs.

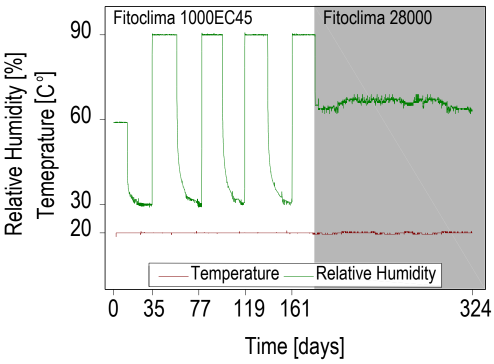
Fig. 6 - Graphs of linear regressions between different moisture levels tested on first phase of experiments and between tests performed before and after RH cycle performed during second phase of experiments for configurations with GAPs with 0mm. k_{MC} and R^2 values related with same linear regressions are presented bellow respective graphs.

Fig. 7 - Graphs of linear regressions between different moisture levels tested on first phase of experiments and between tests performed before and after RH cycle performed during second phase of experiments for configurations with GAPs with 4mm. k_{MC} and R^2 values related with same linear regressions are presented bellow respective graphs.

Fig. 8 - Graphs of linear regressions between different moisture levels tested on first phase of experiments and between tests performed before and after RH cycle performed during second phase of experiments for configurations REF and GL. k_{MC} and R^2 values related with same linear regressions are presented bellow respective graphs.

Fig. 9 - Relation between test results and predicted values resulted from the adjusted Uibel & Blaβ model. a) mean values for all tested configurations; b) mean values for GAP_FL configurations; c) mean

values for GAP_ML configurations; d) mean values for GAP_OL configurations; e) mean values for GAP_3L configurations.



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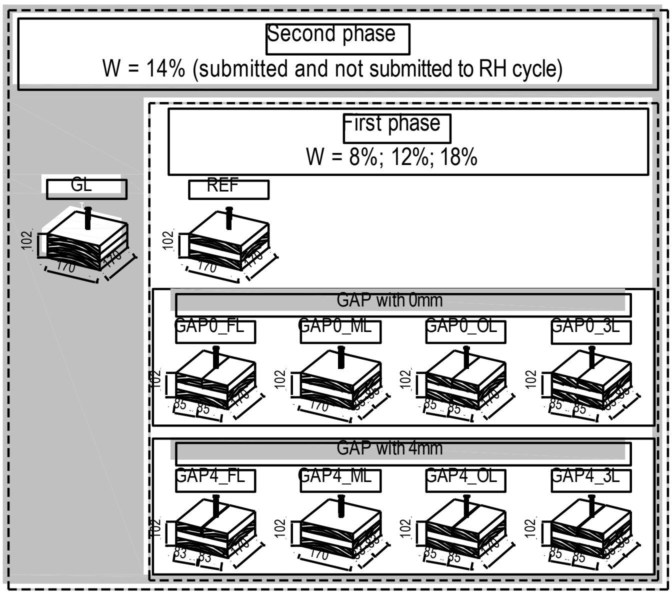


Fig. 2 - All ten test configurations tested during first and second phases of experiments. (Dimensions in mm).

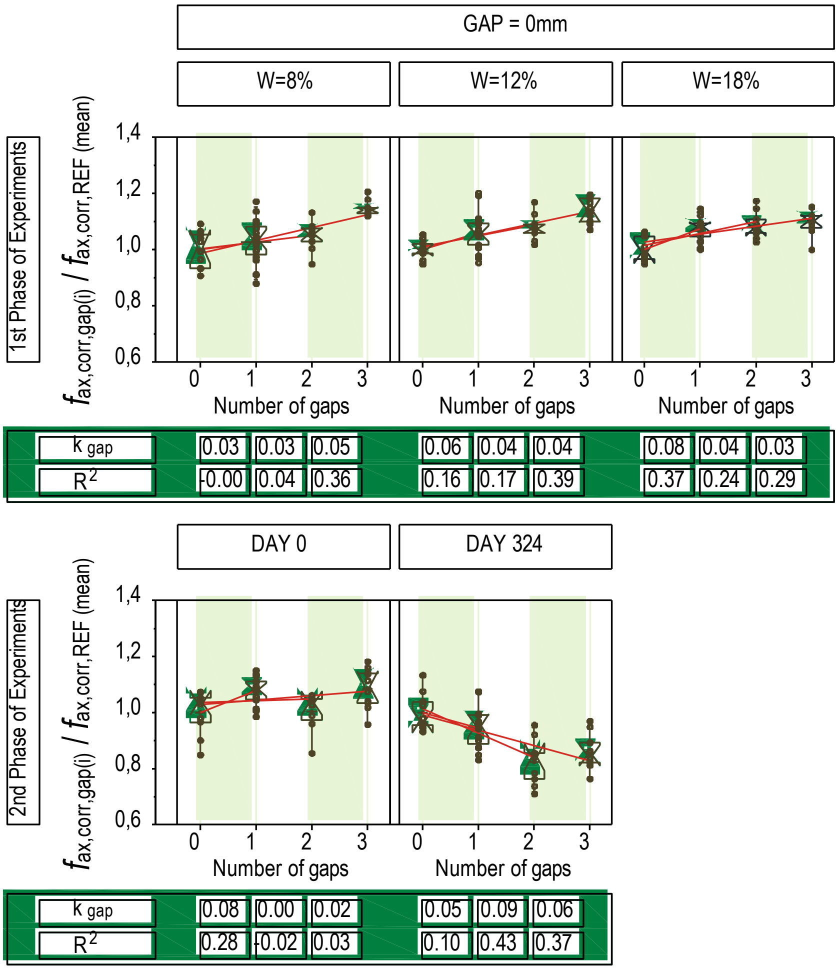


Fig. 3 - Linear regressions performed between REF configurations and specimens with different GAPs with 0mm tested during first and second phase of experiments. k_{gap} and R^2values are presented in tables bellow respective graphs.

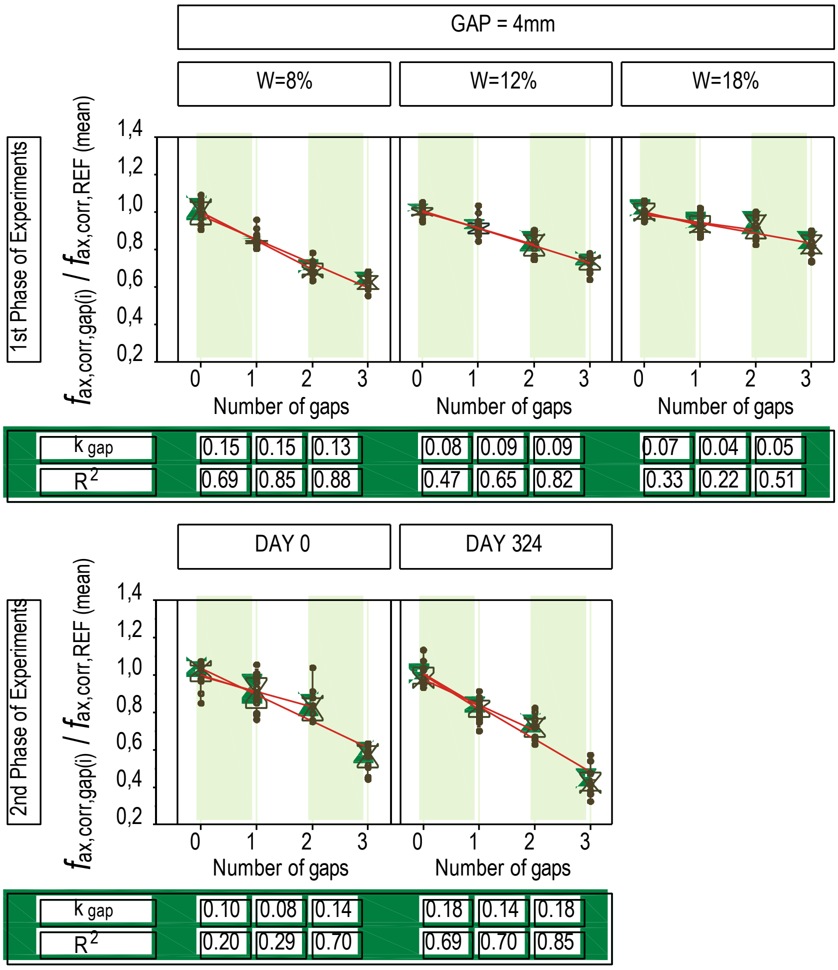


Fig. 4 - Linear regressions performed between REF configurations and specimens with different GAPs with 4mm tested during first and second phase of experiments. k_{gap} and R^2values are presented in tables bellow respective graphs.

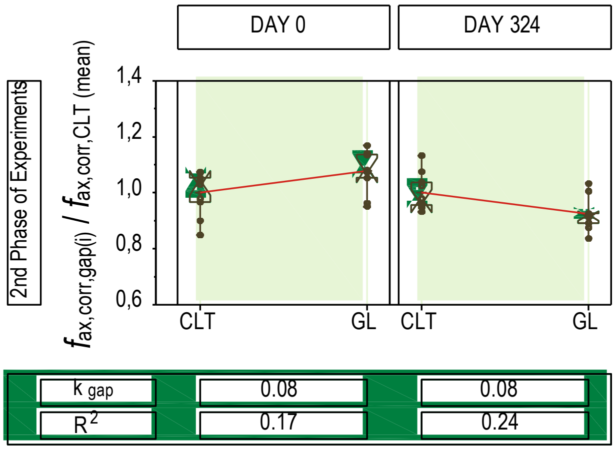


Fig. 5 - Linear regressions performed between specimens with no GAPs (REF and GL) tested during second phase of experiments. k_{gap} and R^2 values are presented in tables bellow respective graphs.

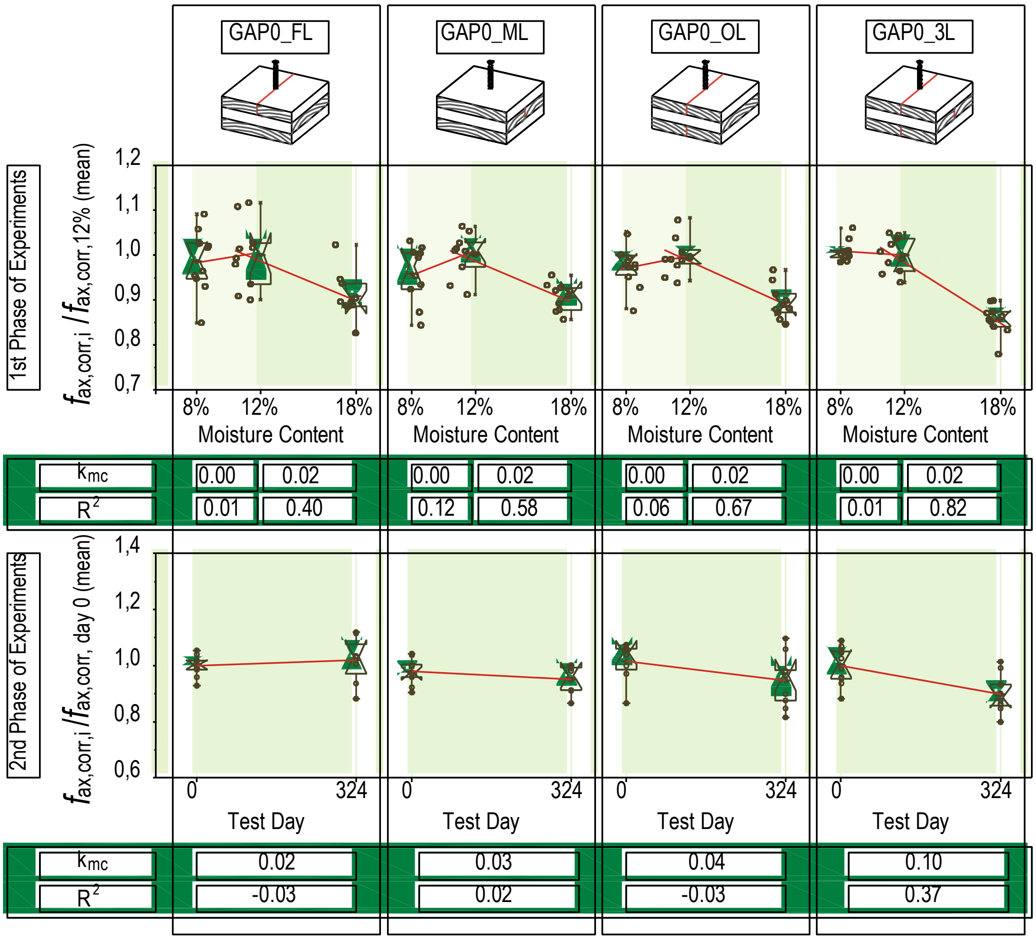


Fig. 6 - Graphs of linear regressions between different moisture levels tested on first phase of experiments and between tests performed before and after RH cycle performed during second phase of experiments for configurations with GAPs with 0mm. k_{MC} and R^2 values related with same linear regressions are presented bellow respective graphs.

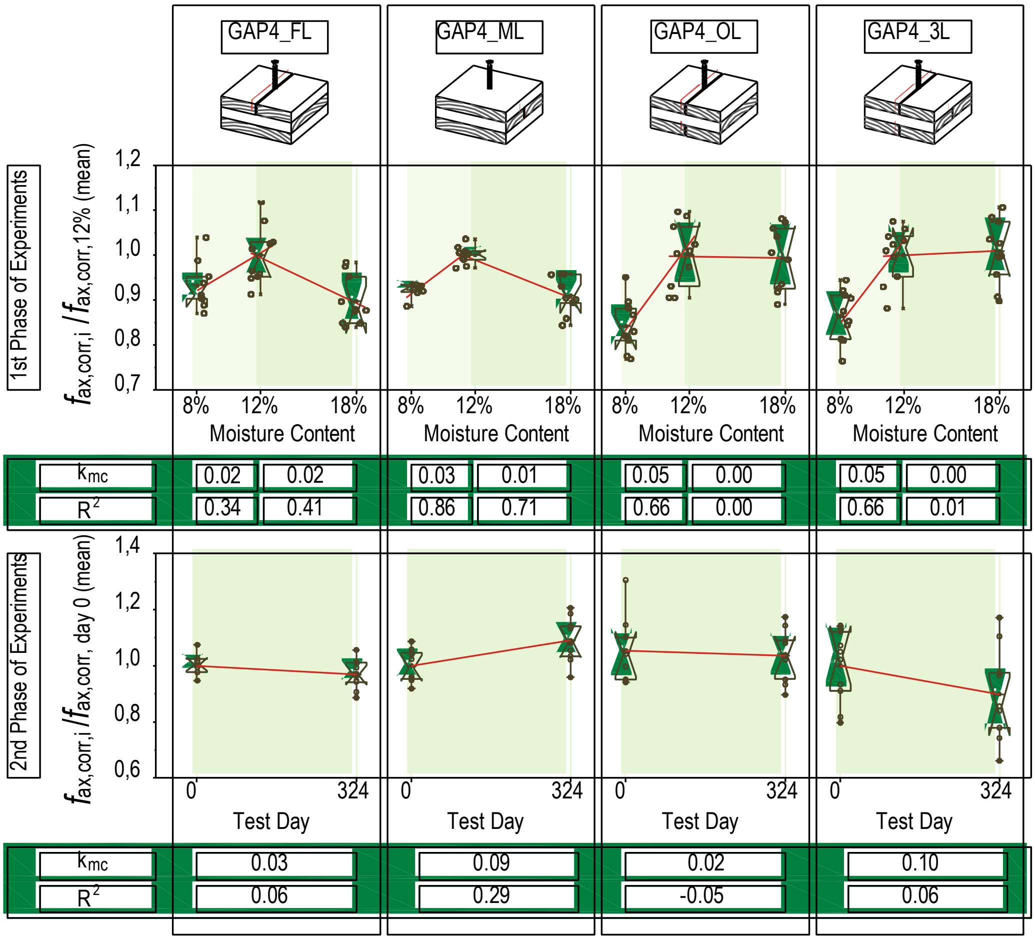
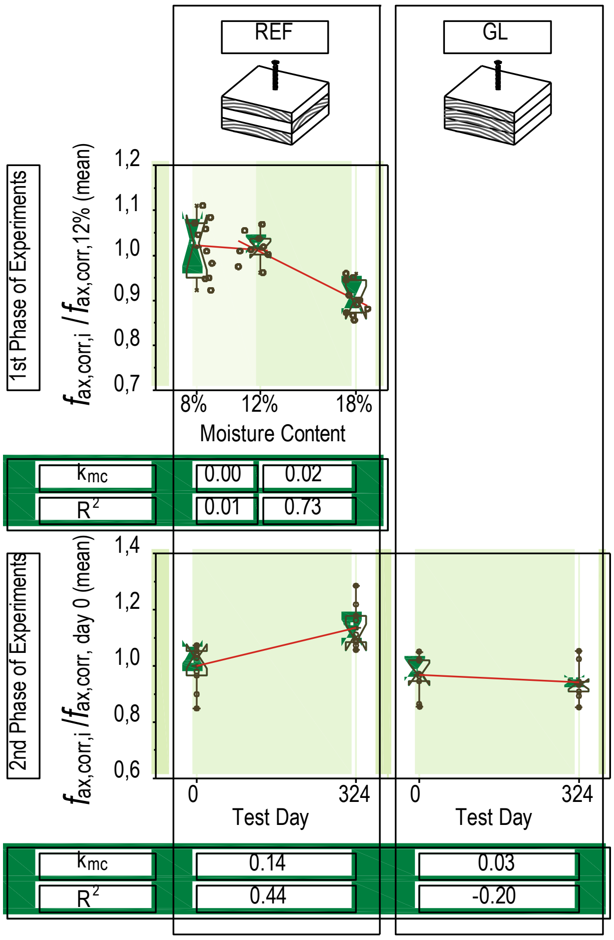


Fig. 7 - Graphs of linear regressions between different moisture levels tested on first phase of experiments and between tests performed before and after RH cycle performed during second phase of experiments for configurations with GAPs with 4mm. k_{MC} and R^2 values related with same linear regressions are presented bellow respective graphs.



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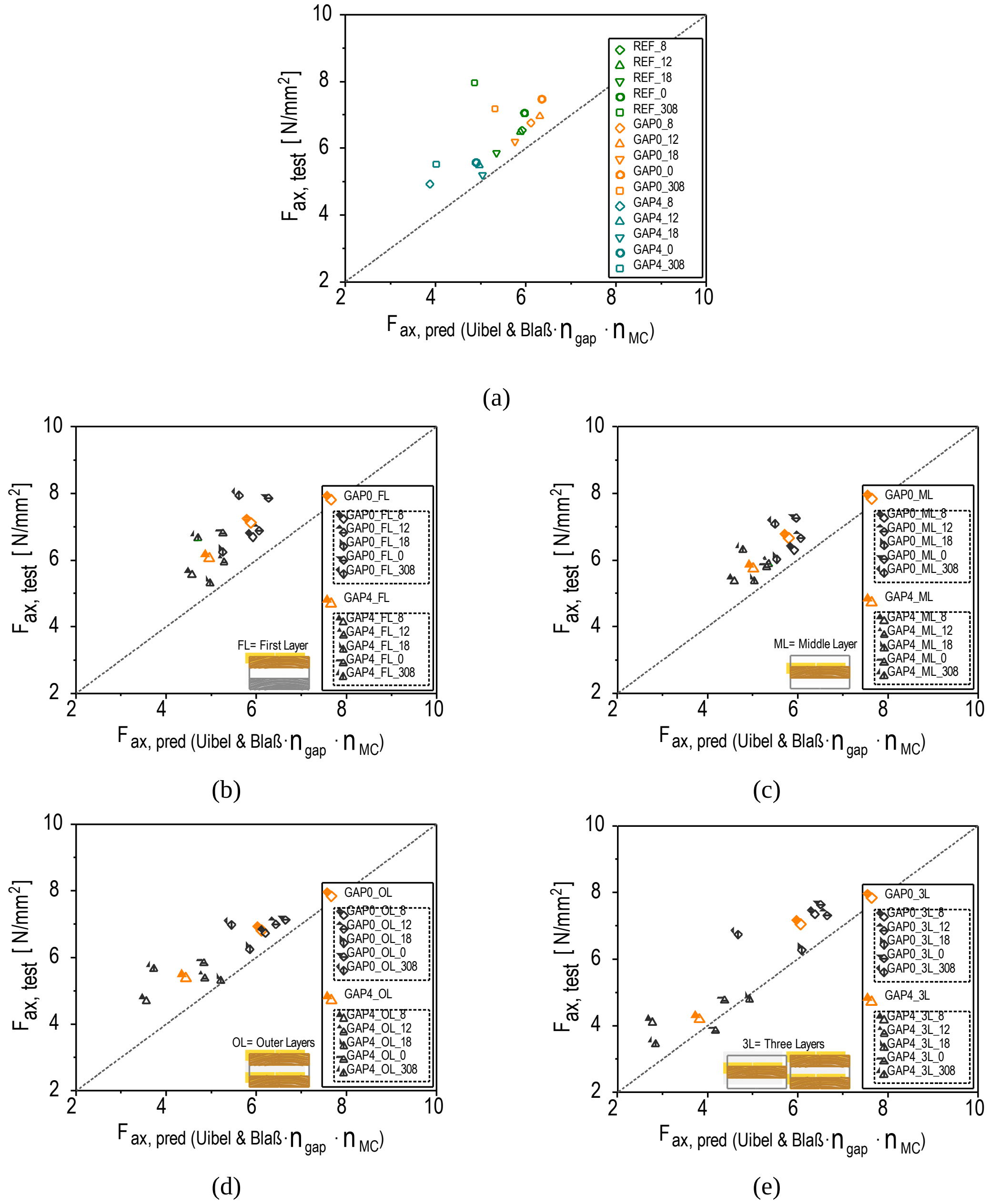

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