# Study of the Lateral Strength of Timber Joints with Inclined Self-Tapping Screws

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**Abstract**

Over the last decade, the use of self-tapping screws with continuous thread for timber to timber joints has been increased considerably. This paper presents a comparative analysis of theoretical and experimental results obtained for the shear strength of timber joints with inclined screws. With the purpose of optimizing the strength of the joints, the screws were inclined with respect to the direction of the wood fiber. The applicability of the theory of Johansen modified by Bejtka was verified to predict the behavior of these connections for Chilean wood species. The withdrawal capacities of the screws were also obtained to account for their influence on the shear strength of the joints. The comparison between the theoretical and experimental values showed the advantages of the inclination. Generally, it can be concluded that for Radiata Pine the optimal inclination of the screw is of about 30 degrees.

**Key words:** Theory of Johansen, withdrawal strength, radiate pine, self-tapping screws, shear strength

## Introduction

Currently wood based structural design for elements and joints in Chile requires the application of allowable stress method. This means that the use of wood strength feature has to be limited just within its elastic and lineal range. Such design constraint, which has been duly established under Chilean Standard NCh 1198.of91, is quite conservative regarding joint design. Consequently, those sizes required by these elements are the ones that generally control pieces scantling and, thus, make construction total cost increase. This present research work has studied shear joint ultimate strength in Chilean wood (Radiata Pine), by making use of self-tapping screws, with continuous thread. The research work has been carried out from both a theoretical and experimental point of view, so Johansen's theory (1949) is likely to be validated. In turn, this theory was modified by Bejtka *et. al.* in the year 2002. By doing so, screws withdrawal strength can be included in the system when they are slanted mounted with respect to wood fiber.

## Materials and Methods.

### Theoretical Statement.

Regarding the theoretical point of view, Johansen statement (1949) - modified by Bejtka *et. al.* in 2002 - was applied in order to predict wood shear ultimate strength in those pieces that are jointed by inclined self-tapping screws.
Generally speaking, Johansen's theory (1949) states that shear ultimate strength among wood pieces is given by the minimum achieved value from a series of equations that represent three different expected failure modes. The load-carrying capacity for failure mode 1 is limited by the embedding strength of one or two timber members. For failure modes 2 and 3, the load-carrying capacity is limited by the embedding strength of the timber members and the bending capacity of the fastener. In failure mode 2 one plastic hinge and in failure mode 3 two plastic hinges per shear plane and fastener occur. Figure 1 shows a schematic display of these failure modes.

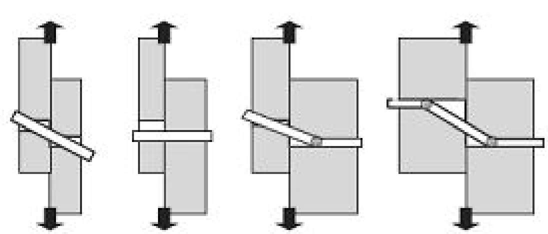

*Figure 1: Expected failure modes in shear joints, according to Johansen (1949)*

Figure 2 shows the forces and stresses in a timber-to-timber connection with an inclined screw for Johansen´s failure mode 3.

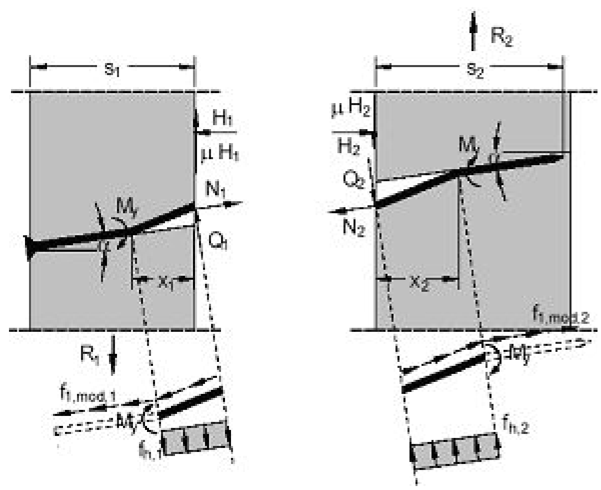


*Figure 2: Forces and stresses for Johansen´s failure mode 3*

Below are shown the most relevant parameters that are applied in stating Johansen theory (1949), which was modified by Bejtka *et. al.* (2002).

### *Modified withdrawal capacity ($f_{1, mod, i}$):*

This parameter reflects a given screw withdrawal capacity, when it is simultaneously moved sideward; this means, on a perpendicular fashion with respect to its axis. In practical terms, it may be achieved as the mean value of the withdrawal capacity that has been distributed all along the screw penetration. Bejtka *et. al.*'s recommendations (2002) have been taken into account in this research work. These recommendations suggest that the screw minimum withdrawal capacity (at pieces interface where the greatest sideward movement takes place) is about 70% of the removal capacity without sideward movement ($f_{1, i}$). Besides, a parabolic-type variation was assumed between these two limit values, in other words, between the joint interface and the screw plastic hinge.

### *Embedment strength ($f_{h, i}$)*

In order to compute this parameter, the equation given by the 1998of91 NCh standard was applied. This is shown in Equation 1:

$$f_h = \frac{0{,}00065 \cdot \rho_{12,k} \cdot (100 - d)}{2{,}75 \cdot sen^2\theta + \cos^2\theta} \qquad (1)$$

where:

$\rho_{12,\,k}$ = forest species typical normal density ($kg/m^3$)
d = screw diameter (mm)
$\theta$ = Strength – fiber dis-angling.

***Bending capacity of the screw ($M_y$).***

This parameter depends on screw's steel made-up or constitutive features, and should be achieved on an experimental way. On an alternative manner, according to Smith *et. al.* (2002), it is possible to have it stated by applying what is read in Equation 2:

$$M_y = \frac{(\sigma_u + \sigma_y)}{1{,}1} \cdot \frac{d^3}{12} \qquad (2)$$

where:

$\sigma_u$ = ultimate tensile strength at the screw ($N/mm^2$)
$\sigma_y$ = yield stress at the screw ($/mm^2$)
d = screw diameter (mm)

Once the above mentioned parameters have been defined, the theoretical ultimate shear strength in the case of a shear joint by means of inclined self-tapping screws can be established from those equations suggested by Bejtka *et. al.* (2002).

**Experimental Statement**

With the purpose of experimentally certifying the application of the Bejtka *et. al.* modified theory (2002) regarding joints with self-tapping screws in the case of Radiata Pine species, two types of tests were performed:

***Screw withdrawal tests*:**

This experiment consisted on the carrying out of seven screw withdrawal tests at different penetration depths. Wood to be used in these experiments was Radiata Pine, having a 12-percent-moisture content, 40 x 70 mm scantlings, a C16 mechanical grading, and a 475 $kg/m^3$ density. The self-tapping screw has a 6 mm diameter, a 75-mm-length, and features a SAE 1020 type steel.

Withdrawal load measured by the testing machine is changed to the $f_{1,\,i}$ parameter, through the following reading:

$$f_{1,i} = \frac{F_{\max}}{l_e \cdot d \cdot \pi} \qquad (4)$$

where:

$F_{max}$: Withdrawal force as measured by the testing machine (N).

$l_e$: Screw penetration depth (mm)
d: Screw diameter (mm).

By experimentally achieving this parameter, the modified $f_{l, mod, I}$ withdrawal parameter can be approximately computed for each piece and for each failure mode, as suggested by Bejtka *et. al.* (2002). Figure 3 shows the setting up of this test.

***Simple shear test in timber-to-timber joints*:**

This experiment consisted on the carrying out of nine simple shear tests, where the self-tapping screw slant angle was modified from 0º to 30º and to 45º. Tests samples consisted on three 40 mm x 140 mm pieces joint by two self-tapping screws for each shear plane. Minimum spacing or gaps at edges and between screws were done as recommended by the 1198of91 NCh standard. Wood species to be used in the tests was radiate Pine, with a 12-percent moisture content, a C16 mechanical grading and a typical 475 kg/m$^3$ density. The self-tapping screw had a 6-mm-diameter, a 75-mm-length and made of SAE 1020 type steel.

It is advisable to state that these are deformation-controlled tests, featuring a relative displacement with respect to the central piece not larger than 15 mm. Figure 3 shows the tests experimental setting up.

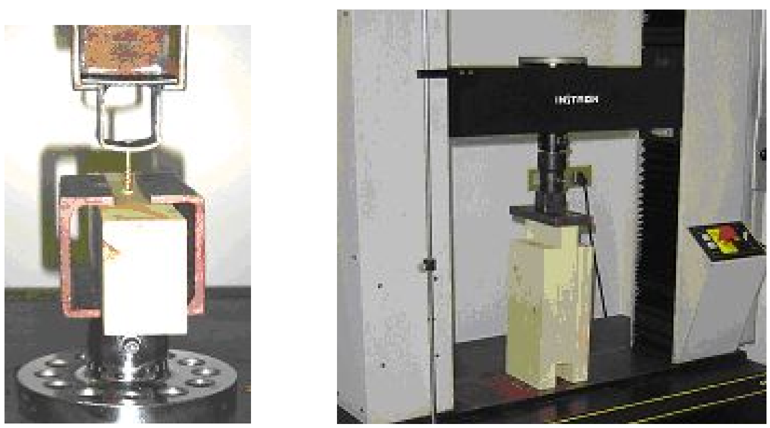

*Figure 3: Withdrawal and shear tests experimental setting up.*

## Results and Discussion

Outcomes achieved in this research work can be sorted in three large groups: stating of normal withdrawal capacity ($f_{l, i}$), stating of the modified removal capacity ($f_{l,mod,i}$) and stating of the shear ultimate capacity ($R_{VM}$).

It was found out of this seven tests series that average maximum withdrawal capacity amounted to 17.32 N/mm$^2$, which matches up a 2.4 mm axial displacement of the screw.

If compared to those results achieved by Bejtka *et. al.* (2002) for the case of wood species having the same density, it can be observed that withdrawal capacity in the case of radiate Pine turns out to be 10% lower. Besides, if compared those axial displacements where the greatest strengths take place, it can be seen that axial displacement is a 30% greater in the case of Radiata Pine.

By making use of the information obtained in the screw withdrawal tests, it is possible to theoretically compute withdrawal capacity distribution at the screws penetration length for each piece. Regarding each failure mode, distances between the screw plastic hinge and the joint interface (called $x_1$ and $x_2$) for each piece may be analytically stated. Finally, with both distances, the distribution of the modified withdrawal strength can be calculated. Table 1 displays the results achieved for the various failure modes, taking an $\alpha = 0^o$ slant into consideration.

When comparing distances $x_1$ and $x_2$ with the experimental evidence obtained from the checking of the screws after the shear tests, it may be observed that how acute the theoretical model is, thus achieving comparative differences lower than 10%. When comparing the $f_{l,\ mod}$ values with those ones obtained by Bejtka *et. al.* (2002), for wood featuring the same densities, it may be seen that Radiata Pine removal modified strength is 10% lower. By analyzing those values obtained from $f_{l,\ mod}$, the ultimate shear strength may be calculated on a theoretical manner (for an approximate 15 mm displacement), according to equations suggested by Bejtka *et. al.* (2002).

| Modo falla | $x_1$(mm) | $x_2$(mm) | $f_{1,mod,i}$ (N/mm$^2$) | $f_{1,mod,j}$ (N/mm$^2$) |
|---|---|---|---|---|
| 1a,l | 0 | 0 | 12.20 | 17.32 |
| 1a,r | 0 | 0 | 17.32 | 12.20 |
| 1b | 34.03 | 21.33 | 15.05 | 14.93 |
| 2ª | 35,14 | 19.47 | 14.65 | 15.23 |
| 2b | 16.96 | 29.73 | 16.60 | 15.36 |
| 3 | 16.38 | 16.38 | 16.53 | 15.73 |

*Table 1: Modified withdrawal strengths for α = 0º*

Regarding shear strength we may conclude that, in the case of an approximate 15 mm displacement, the greatest shear strength has been given by the 30º slant. This value is 53% greater than for a 0º slant, and 35% greater than a 45º slant. Thus, an advantage from the maximum strength point of view when slanting the screw can be made evident, since the screw removal strength has been included to the system.

Figure 4 shows the mean trend of shear tests for 0º, 30º and 45º slant.

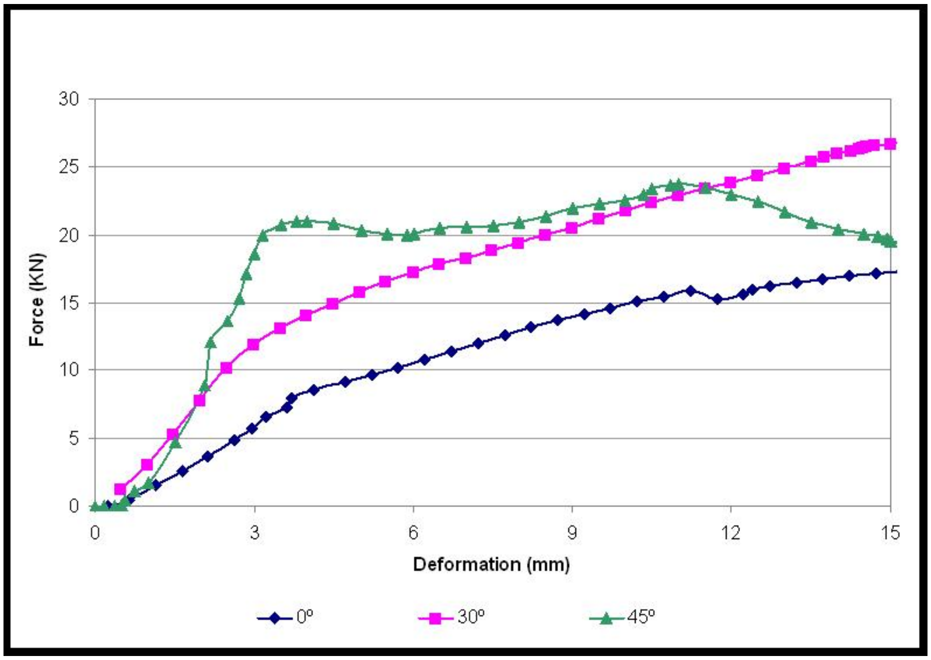


*Figure 4: Experimental shear strength for screws having various slants.*

When comparing those outcomes obtained for both a 30º and 45º slants, it can be seen that the latter represents a great initial stiffness, due to the outstanding initial joint work between wood and screw. However, when embedment strength is exceeded, the screw keeps working just under a tensile basis, close to its yield stress. Besides, it can be observed that in the case of service load and displacement values below to 11 mm, the 45º slant provides greater strength than the 30º one.

Figure 5 shows a comparison between the experimental and theoretical results of the shear ultimate strength, in the case of various slants.

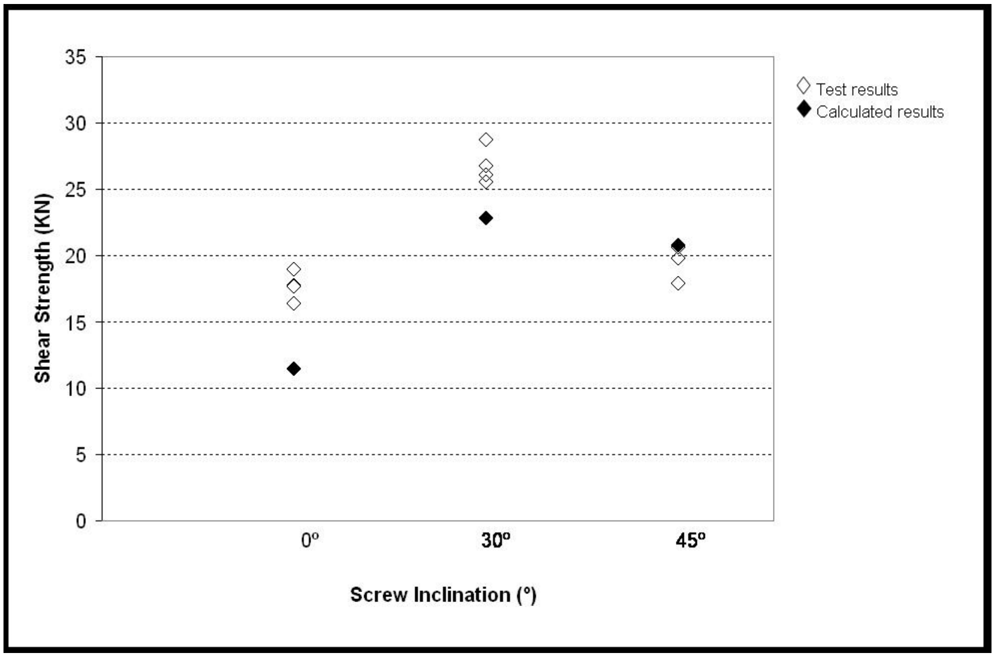


*Figure 5: Comparison of shear strength theoretical and experimental results.*

From the figure above we may see that average differences between theoretical and experimental values range between 35%, 15% and 5%, in the case of 0º, 30º and 45º slants, respectively. Nevertheless, when checking the screws after the tests, the actual failure modes could be observed, as shown in Figure 6.

When making the suitable corrections to the theoretical strength, to make them be compatible with the experimental failure modes, differences between theoretical and experimental values ranging between 13%, 3% and 5% can be found, for 0º, 30º and 45º slants.

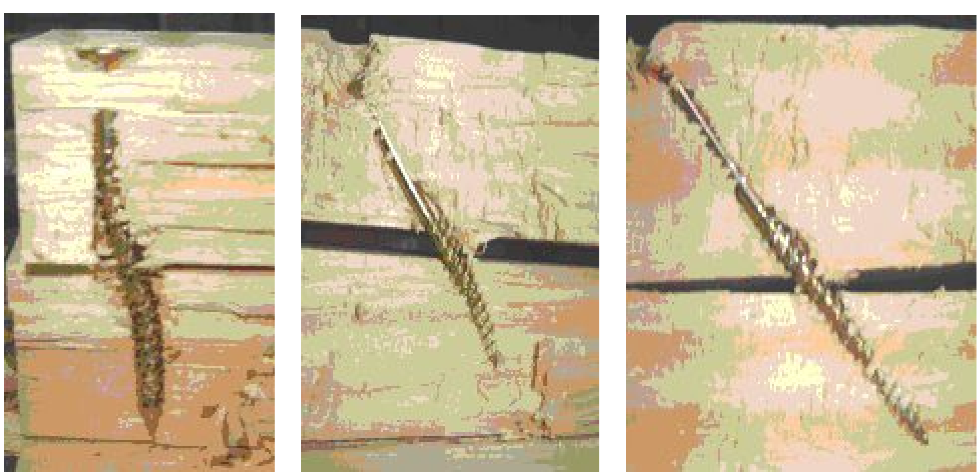

*Figure 6: Reviewing screw failure modes for α = 0º, 30º and 45º.*

## Conclusions.

Johansen's theory (1949) modified by Bejtka *et. al.* (2002) is quite suitable for assessing Radiata Pine joints ultimate strength, with inclined self-tapping screws, thus achieving results that are related to safety issues regarding experimental tests. It turns out to be essential for the proper application of theoretical equations to experimentally assess the strengths parameters regarding screw withdrawal in Radiata Pine, because shear strength is quite sensible to this parameter when screws are inclined.

The assumed withdrawal capacity parabolic distribution in those wood embedment areas turned out to be satisfactory. However, the withdrawal minimum capacity number has to be experimentally adjusted in the interface (0.7 $f_{l,i}$), since such recommendation is a conservative one.

From the experimental point of view, it has been made evident that screw slanting is favorable for shear joint ultimate strength with respect to non-slanted strengths. In fact, strengths being 53% and 35% higher, in the case of screws featuring 30º and 45º slants, respectively.

Wood based shear joint design through slanted self-tapping screws features a number of comparative advantages if compared to the traditional mechanical joint means, because not only wood embedment capacity can be developed, but also the withdrawal capacity. This fact should imply cheaper, more efficient and safer designs.

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