WHITE PAPER

# SUPPLEMENTARY CONSIDERATIONS FOR THE CONVENTIONAL YIELD MODEL

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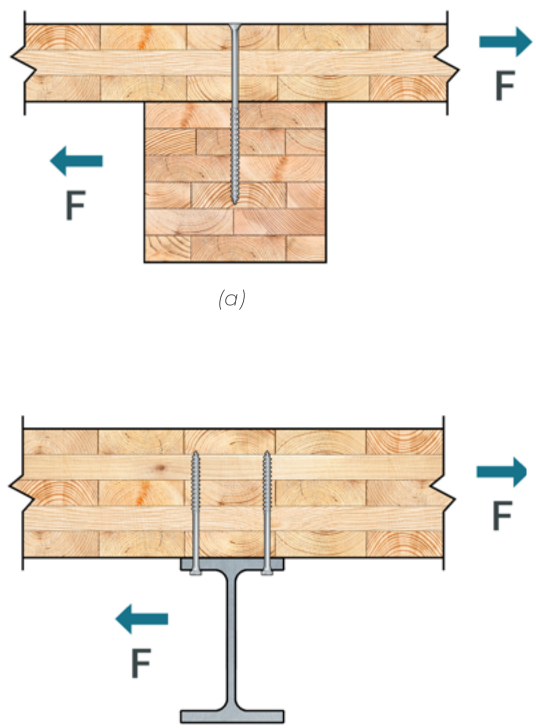
# EXECUTIVE SUMMARY

Johansen's yield model—a widely adopted design model for determining reference lateral design values for wood member connections in heavy timber and mass timber construction—is mandated for use by regulatory authorities in both Europe and North America. However, its origins in tests conducted with earlier-generation wood materials and fastening technology pose limitations to its contemporary employment. Notably, the model does not adequately address the susceptibility of certain wood species and engineered wood products to splitting, nor does it consider the influence of connection geometry. Consequently, the estimates it provides may not consistently align with actual performance in modern mass timber applications. This drawback underscores the necessity for remedial considerations in practice.

# INTRODUCTION

Shear connections facilitated by dowel-type fasteners form an integral part of modern mass timber structures. Notable examples include wood-to-wood and steel-to-wood connections, as shown in Figure 1. These joints are indispensable for transferring lateral forces, ultimately ensuring structural stability. As such, accurate determination of their reference lateral design values and yield mechanisms becomes an essential undertaking.




*(b)*

*Figure 1. Typical Shear Connections*
*(a) Wood-to-Wood Connection*
*(b) Steel-to-Wood Connection*

## *Johansen's Yield Model*

Regulatory authorities in both Europe and North America currently require the use of the yield model developed by Johansen in the 1940s [1] for calculating reference lateral design values for wood connections in shear. Despite some adaptations to consider factors such as group action and reduced penetration, Johansen's model has largely remained unaltered since its inception, notably in terms of its assumption that all fasteners possess yielding capabilities.

Comprising a set of empirical equations, Johansen's model incorporates the attributes of both wood members and fasteners into the calculation of lateral resistance for a connection and the estimation of the fastener behavior, forming the foundation for classifying connection performance. In terms of the wood components, wood density (directly related to embedment strength), side-member thickness, and fiber orientation constitute the factors influencing the connection's capacity.

When it comes to the fasteners, three factors—diameter, embedment depth, and bending yield strength—play pivotal roles in determining lateral resistance. For instance, under consistent conditions such as boundary constraints, an increase in diameter necessitates a greater force for the fasteners to yield due to their heightened stiffness. Consequently, larger-diameter fasteners generally lead to a stronger connection. However, high load-bearing capacity should not be pursued at the expense of sacrificing the desired mechanism, which, in most cases, involves provisions for ductile performance. Excessive stiffness may induce various modes of wood failure, including plug shear, row shear, and group tear-out, as a result of the substantial force imposed on the wood members by groups of fasteners. Therefore, it is imperative to strike a balance between stiffness and ductility, which fundamentally hinges on an understanding of the mechanical properties and capabilities of the fasteners.

## *PADDOCKS FORMULA 1*

*Montreal, QC*



*Photo Courtesy of FABG Architecture*

## *Limitation*

While Johansen's model is widely mandated, its direct application to modern mass timber construction may produce less desirable performance. This limitation stems from its original development and calibration, which were based on timber materials and fastening technology available at the time.

Conventional fasteners, such as lag bolts as well as tight-fit pins and bolts, typically have a bending yield strength of approximately 300–500 MPa. In contrast, self-tapping screws (STSs), favored in contemporary mass timber projects, exhibit an over threefold increase in bending yield strength, measuring around 1,000 MPa.

The high bending yield strength of STSs is closely linked to the exacting demands of modern timber construction. When driving these screws into wood members without predrilled holes, a substantial turning force is requisite, resulting in high insertion moments. Additionally, the exploitation of the favorable withdrawal action in inclined fasteners necessitates higher tensile strength. These conditions collectively call for screws with exceptional bending and tensile performance. Manufacturers achieve this by employing high-hardness steel, in conjunction with a case-hardening process that allows for varying levels of hardness in the screw's case and core.

As the required hardness approaches the critical limit, the steel becomes more susceptible to embrittlement. Consequently, more advanced quality-control (QC) testing becomes essential to prevent the exceedance of critical hardness boundaries. The rigorous QC measures, in turn, result in minimal variation in strength performance, which can be comparatively more accurately predicted.

Conversely, conventional fasteners are fabricated from softer steel and undergo considerably less stringent QC measures during manufacturing. The latter may lead to a larger variation in bending yield strength and hardness. As a result, the yielding behavior of these fasteners, and their ability to deform under loading, are subject to appreciably more uncertainty, warranting larger safety factors.

The discrepancy in bending yield strength also gives rise to a difference in the onset of yielding behavior between conventional and modern fasteners. These disparities are, however, unaccounted for in Johansen's model.

## *Splitting Considerations*

Certain wood species, such as Douglas-fir and larch, exhibit a natural propensity for splitting owing to their fiber composition. Premature splitting in connections made from these woods is likely to impede the realization of their full lateral resistance potential, as indicated by Johansen's model.

While the presence of cross laminations in cross-laminated timber (CLT) panels is expected to theoretically mitigate the splitting issue, strap testing conducted with an MTS extensometer at the University of Northern British Columbia has revealed distinctive deformation behavior and sensitivity to alternative failure modes under high loads. This unexpected phenomenon can be attributed to the inaccurate capacity estimate provided by Johansen's model. Specifically, the estimated mechanism develops at a load higher than expected, leading to a shift in connection performance from yielding to a combination of failure modes (i.e., plug shear, rolling shear, and splitting, as shown in Figure 2), which are characterized by inductile and brittle behavior.

*Figure 2. Rolling and Plug Shear and Splitting Failure Observed in a CLT Panel Subjected to Splitting Force Component*

The concern surrounding splitting becomes especially significant in scenarios involving a vertically generated force component perpendicular to the grain direction. For simplicity's sake, a connection configuration featuring a steel-plate attachment secured through a single fastener is used as an example for illustration, as shown in Figure 3.

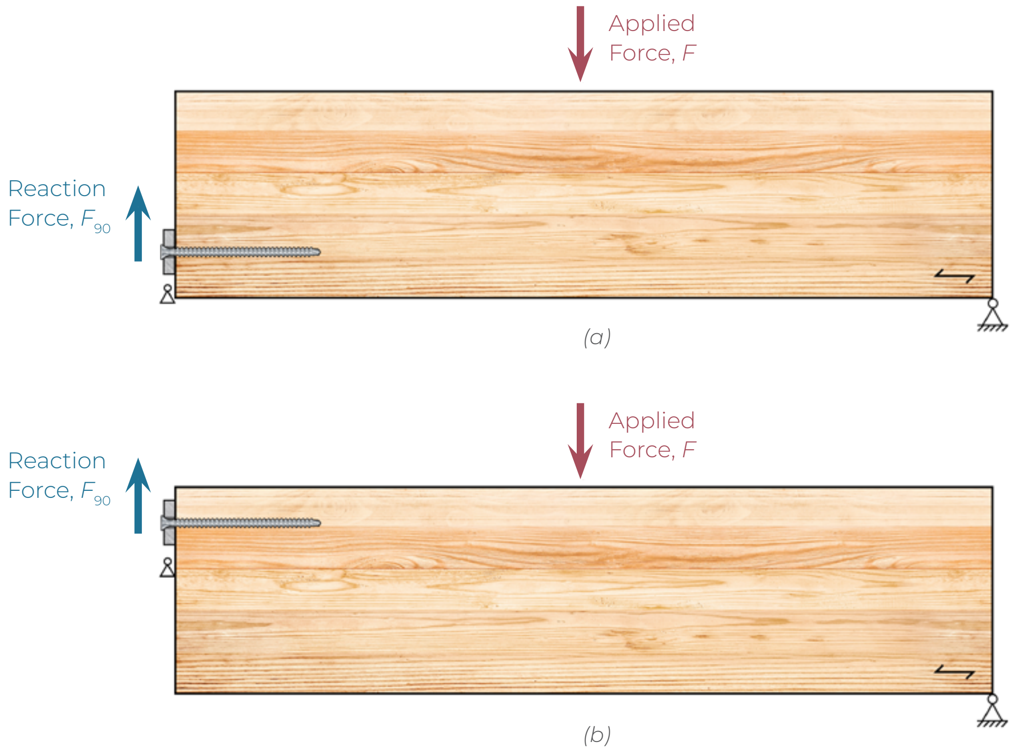



*Figure 3. Connections with Different Fastener Placements*
*(a) Distant from the Loaded Edge*
*(b) Close to the Loaded Edge*

Johansen's model would produce identical reference lateral design values for the simplified connections depicted in Figure 3(a) and (b) due to the absence of geometrical considerations. However, these estimates deviate from reality. The stress transmitted from the steel plate appreciably influences the anchoring effect of the wood member and, consequently, the connection's capacity.

In simpler terms, both cases depicted in Figure 3(a) and (b) involve compression above the fastener and tension below it. In this context, compression is less concerning as it serves to close any existing cracks. In comparison, perpendicular-to-grain tension poses a substantial risk to the structural integrity of the wood member, potentially giving rise to a sizable crack along the fastener. This defect can be simplified as a detachment of the lower portion, exposing the fastener and greatly compromising the lateral resistance of the connection, which ultimately may lead to brittle failure.

## Geometric Considerations

The two cases, however, differ in terms of the risk of a weakened lateral resistance capacity. While the reaction force at the steel plate, denoted as $F_{90}$, remains consistent in both cases (equivalent to half of the external force applied at the center of the upper surface of the beam, denoted as $F$, i.e., $F_{90} = F/2$), its vertical splitting componenet along the fastener, denoted as $F_{t,90}$, varies. Using the equation given by Ehlbeck et al. [2, 3], $F_{t,90}$ can be determined as follows:

$$F_{t,90} = \left[1 - 3\left(\frac{h_e}{h}\right)^2 + 2\left(\frac{h_e}{h}\right)^3\right] F_{90} \quad (1)$$

where $h_e$ is the distance between the fastener and the loaded edge and $h$ is the height of the beam. The relationship elucidated by Equation (1) is apparent: as the fastener is positioned closer to the loaded edge, the splitting tension at the fastener increases, consequently elevating the risk of splitting. Figure 4 provides a visual representation of the relationship between $h_e/h$ and $F_{t,90}$, expressed as a percentage of $F_{90}$.

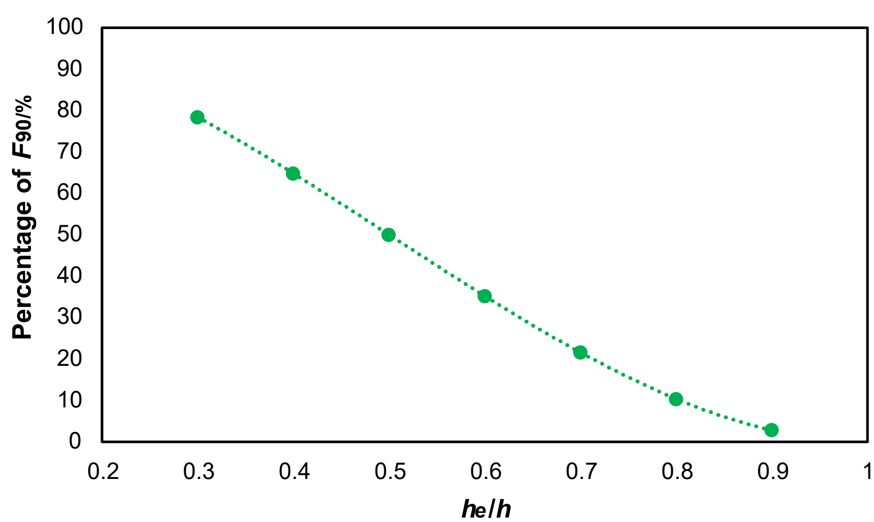



*Figure 4. Impact of $h_e$ / h on Stress Transferred into Wood Member*

It is generally accepted that no mitigation measures are necessary at $h_e/h > 0.70$. For $h_e/h$ ratios falling within the range of 0.20–0.70, it is advisable to verify the tensile strength of the wood member in the direction perpendicular to the grain. However, fastener placement resulting in a $h_e/h$ of $< 0.20$ should be avoided [3, 4]. Of note, as of the date of this article's publication, this so-called "70% rule" is reportedly under regulatory review for potential revisions.

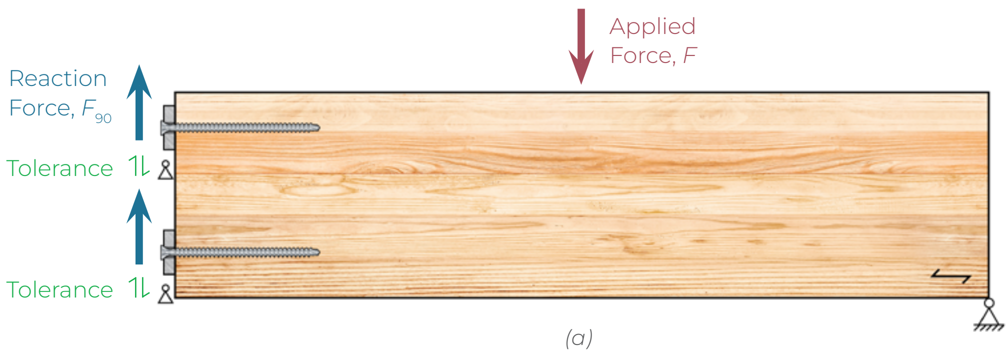
# REMEDIATION

Although generally discouraged, there may be instances where placing fasteners in close proximity to the stressed edge in beam-to-post connections becomes necessary. This is especially true when employing a sacrificial wood char layer as a protective measure for steel fasteners against fires. Ideally, fasteners should be positioned as far as possible from the loaded edge, as established previously. However, due to the natural upward propagation of fires, low placement subjects fasteners to a significantly higher risk of fire exposure, likely weakening their structural and functional integrity. The most intuitive solution is to raise the fasteners, but this can lead to splitting issues. Considerations for seismic drift, implemented to prevent unbalanced loading, present another instance of this placement dilemma. Consequently, it is imperative to develop remedial measures for connection configurations involving fastener placement close to the loaded edge.

A further examination of Equation (1) identifies $F_{90}$ as another factor affecting the perpendicular-to-grain tensile stress at the fastener. Therefore, a reduction in $F_{90}$ emerges as a viable strategy for diminishing the splitting force acting on the portion of the wood member below the fastener. While the concept of employing two (or more) fasteners in a vertical arrangement, as demonstrated in Figure 5(a), may initially seem promising in achieving this objective, practical implementation proves challenging in real-world scenarios. This is because its success pivots on both fasteners reacting simultaneously. Any deviation from synchronized response poses a risk of connection failure.

For instance, if the top fastener reacts faster due to tolerance issues, it will bear the entire load, potentially giving rise to the formation of a crack along its length and compromising its load-bearing capacity to an unpredictable extent. The inherent uncertainty surrounding the remaining capacity of the top fastener markedly affects the load-sharing responsibility of the bottom fastener, thereby resulting in extraordinary difficulties in ensuring sound connection behavior.

Arguably, ductile systems can redistribute loads more effectively than stiff systems. However, if load distribution precipitates splitting, this assumption no longer holds true.



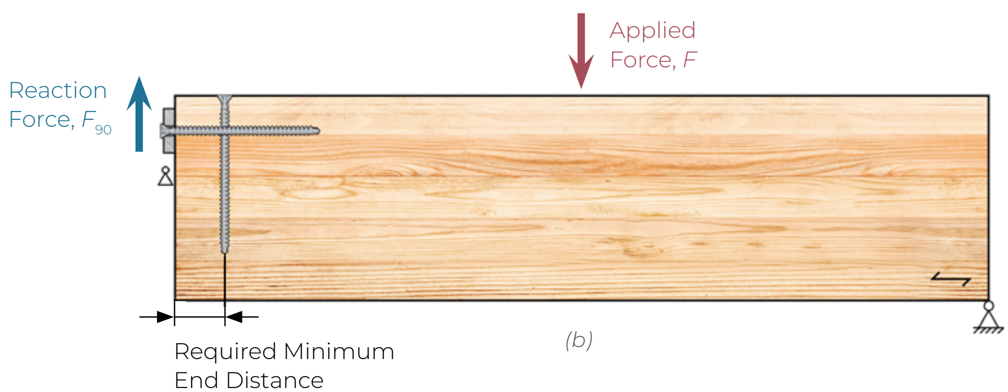




*Figure 5. Remedial Solutions*
*(a) Vertical Arrangement of Multiple Fasteners*
*(b) Insertion of a Fastener Perpendicular to the Grain Direction and Close to the Beam End*

A significantly more practical remedial measure involves inserting a fully threaded fastener perpendicular to the grain direction in close proximity to the beam end, as illustrated in Figure 5(b). Leveraging its withdrawal capacity, this technique redirects the tensile stress to this reinforcing fastener, effectively averting potential cracking along the fastener parallel to the grain. It is worth noting that the reinforcing fastener will remain under a sustained load.

Importantly, the positioning of the reinforcing fastener should be as close as possible to the point of stress initiation. However, this guideline must be balanced with the minimum end-distance requirement for the fastener, specified as a multiple of its nominal diameter, denoted as D. For example, according to the Evaluation Service Report 3178 from the International Code Council Evaluation Service, the minimum end-distance requirement stands at 7.5D for Douglas-fir and 5D for other wood species when using SWG ASSY® fully threaded screws.

This approach mirrors a longstanding reinforcement practice in concrete structures. As illustrated in Figure 6, stirrups are conventionally placed at the dapped end of a concrete beam to distribute the load developed at the notches throughout the entire structure. This established practice strongly advocates for the universal adoption of reinforcing fasteners in analogous situations within mass timber construction.

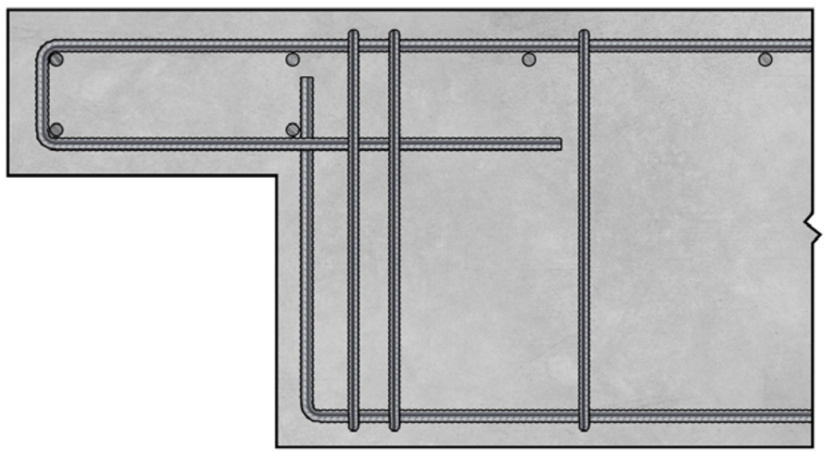


*Figure 6. Elevation View of Stirrup Reinforcement at the Dapped End of a Concrete Beam*

The specific parameters of the reinforcing fastener, such as diameter and embedment depth, can be accurately determined based on the required withdrawal capacity derived from $F_{t,90}$. Nevertheless, it is crucial to verify that the ultimate tensile strength of the fastener surpasses the withdrawal force. Should it fall short, additional fasteners may be employed to distribute the load.

Vertical fasteners, although effective in preventing crack formation as described above, have the potential to absorb heat from the charred section of the wood member during a fire event. This heat can then be transferred upwards within the wood member, potentially leading to an unintended outcome. Given this, further exploration is merited. Some initial findings have already been presented elsewhere [5].

# CONCLUSION

In summary, Johansen's yield model remains a crucial tool for determining reference lateral design values for shear connections, a requirement upheld across jurisdictions. However, its limitations in accounting for material and geometric factors can impede desired performance in contemporary mass timber structures. As such, it is essential to adopt remedial measures.

A promising approach to counter splitting issues, often encountered with fastener placement near stressed edges but unaccounted for in Johansen's model, involves integrating vertical reinforcing fasteners in close proximity to the point of stress initiation. This strategic addition not only addresses the innate material concern but also enhances the reliability of anticipated load distribution behavior, thus safeguarding against unforeseen complications.

For further information and design guidance, please contact our Technical Support Team.

# *EA OFFICE EXTENSION*

*Vancouver, BC*

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