Comparison of Slender Dowel-Type Fasteners for Slotted-in Steel Plate Connections under Monotonic and Cyclic Loading

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Summary

The objective of this study was to investigate the monotonic and cyclic behavior of different kinds of slender dowel-type fasteners. To accomplish this, four types of fasteners were tested in a series of 73 monotonic and cyclic tests using either one or two slotted-in steel plates in PARALLAM®, a Parallel Strand Lumber (PSL) product. The fastener types were a) plain shank steel dowel of 6.35 mm diameter, b) steel dowel of 6.35 mm diameter with threads, nuts and washers on either end, and c) two types of a new commercially available self-drilling dowel of 7 and 5 mm diameter which feature a threaded end on one side and a cutting bit on the other (SFS WS-T5 and -T7).

In addition to the test regimen, the monotonic and cyclic behaviors of the fasteners were successfully modeled using a finite element program based on the theory of an elasto-plastic beam on a nonlinear foundation that included provisions for fastener head restraint, hole tolerances and fastener material fatigue.

Keywords: dowel-type, fastener, psl, cyclic loading, finite-element analysis

1. Introduction

Among mechanical timber connections, dowels (steel pins) and bolts are very practical and thus popular fasteners. This is because connections are relatively easy to produce, they use only inexpensive standardized and readily available parts and they are able to transmit high loads over a relatively small connection area.

The mechanical behavior of a bolted or doweled connection is very complex and its general understanding and strength prediction as it is expressed in standards varies widely. To design dowel or bolt connections, current structural timber codes typically rely on the European Yield Model (EYM) to determine fastener strength. This mechanical model solely allows for the estimation of capacities through comparison of various failure modes. However, for extreme loading cases such as encountered in an earthquake, the complete response of a connection must be fully known to enable the assessment of the reliability of a structure or its parts. Due to the ductile nature of failure of slender dowel-type fasteners, their behavior under load is mainly influenced by the fastener geometry and its material.

Objectives of this study were thus to a) investigate the influence of different head geometries on the monotonic and cyclic behavior of dowel-type fasteners, b) compare a new type of fastener, the self-drilling SFS WS, to fasteners made from plain mild steel stock with regard to behavior under monotonic and cyclic load conditions, c) To modify an existing finite element-based software to include head restraint effects, hole tolerances and fastener material fatigue, and finally to d) predict the monotonic and cyclic strength and behavior of dowel-type fasteners with single and multiple slotted-in steel plates.

2. Experiments

Four types of fasteners (Figure 1) were investigated in four test series (D, E, F and G):

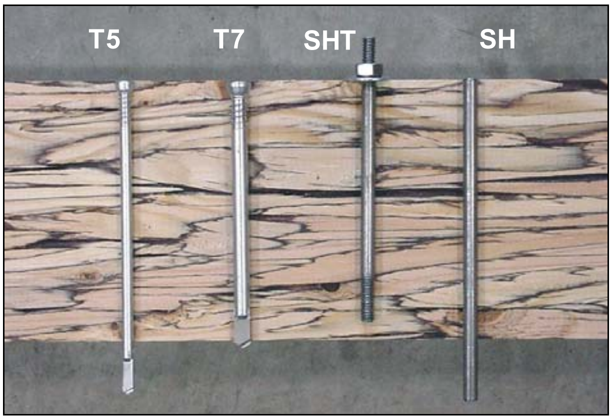

Figure 1 – Investigated Fastener Types

1) A straight, plain-shank dowel of 6.35 mm diameter ("SH"). These fasteners were cut to varying lengths from 6.10 m hot-rolled mild steel bar stock. 2) A matched dowel where both ends were manually threaded over a length of 15-20 mm allowing the attachment of washers and nuts ("SHT"). 3) The SFS WS-T7 steel dowel ("T7") which features a drill tip that allows for insertion into a wood-steel-wood connection without pre-drilling. It also features a head as well as a short threaded portion below the head. The diameter of this fastener is 7 mm and it is available in a range of lengths. According to the manufacturer's data, it is produced from cold rolled steel with a minimal tensile ultimate strength of 550 MPa. The drill-tip length is 11.8 mm. 4) The SFS WS-T5 ("T5"), which is similar to the T7-version. It features a diameter of 5 mm, a minimum 800 MPa steel strength and a drill-tip length of 13.8 mm.

All tested connections used PARALLAM®, a Parallel Strand Lumber (PSL) product manufactured by Trus Joist, A Weyerhaeuser Business to evaluate the performance of slender dowel connections in an advanced structural wood composite. Two cross-sectional sizes were selected for this test program: 133 × 110 mm and 89 × 110 mm. Steel plates were 6.35 mm in thickness.

Figure 2 illustrates the specimen geometries. The test matrix, shown in Table 1 shows the test configurations for all 73 specimens.

It was generally observed during manufacture that the SFS WS fasteners penetrated wood and steel without problem. Nevertheless, pressure had to be exerted to enable the drilling process. In the largest specimens (series F), the fasteners drilled through 119 mm of PSL and 12.7 mm of mild steel.

All monotonic fastener tests were conducted under ramp loading at a constant displacement of 1.27 mm/min. The cyclic tests were conducted according to the CEN-Protocol as outlined in prEN 12 512 [1]. This protocol bases the applied displacement cycles on the yield displacement ν_y. Speed of loading was kept at a low level to eliminate rate-of-loading issues. However, overall test duration required a higher speed than what was applied in the monotonic tests. Speeds varied thus from 3.2 to 12.8 mm/min.

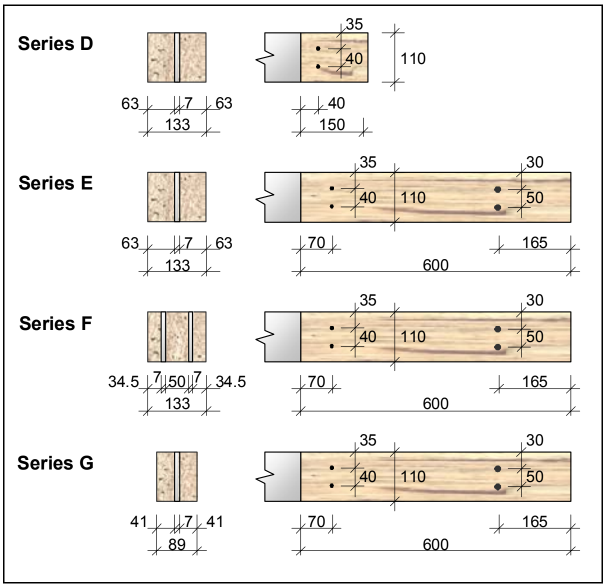

Figure 2 – Specimen Dimensions

During **monotonic** testing, all fasteners without head restraint (SH, T7 and T5) deformed towards the inside of the specimens. Fasteners with head restraint (SHT, T7-1X3 and T5-73) showed no movement. Embedding of the washers was observed in the SHT tests.

Under load, all SH specimens showed a width increase at the fastener location (spreading) while all SHT specimens experienced a width reduction (clamping).

Table 1 – Series D, E, F and G Test Program (Number of Specimens):

Test Series	**Fastener Type**							
	SH		**SHT**		**SFS WS-T5**		**SFS WS-T7**	
	M	**C**	**M**	**C**	**M**	**C**	**M**	**C**
D 1)	5	--	5	--	5 2)	--	5 2) 5 (T7-113)	--
E	5	5	2	2	--	--	2 (T7-113)	2 (T7-113)
F	5	2	2	2	--	--	2 (T7-133)	2 (T7-133)
G	5	2	2	2	2 (T5-73)	2 (T5-73)	--	--

M = Monotonic loading (series D – compressive, series E, F, G – tensile) C = Cyclic loading
1) Monotonic compressive loading only 2) Cut to specimen width (head and drill tip removed)

The T7-1X3 and T5-73 specimens also showed a width increase (smaller than the SH specimens). The magnitude of width change was higher in specimens with thinner outer parts (Series F and G).

Deformed fastener shapes can be seen in Figure 3.

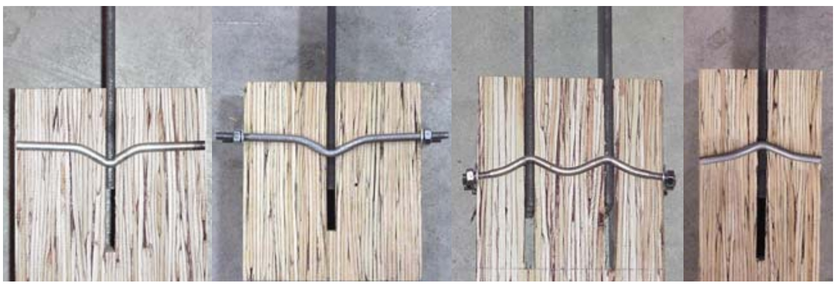

Figure 3 – Deformed Fasteners (Series D, E, F and G)

The load-displacement behavior of fasteners without head restraint typically featured a maximum load plateau (Figure 4). Fasteners with head restraint had a continuous post-yielding load increase resulting in a tangential stiffness. This behavior was more pronounced in the SHT specimens than in the T7-1X3 specimens.

All series F tests showed a continuous post-yielding load increase due to the two-plate arrangement and a resulting additional strength component in the center portion of the fasteners.

Due to the fastener length and possible friction effects, the D_T5 specimens also showed a continuous load increase. In contrast, the G_T5-73 fastener leveled at a maximum load, which can be explained by negligible head fixity and the short length of the fastener.

Stiffness was highest in the T7 and T7-1X3 tests. This was followed by the SH and SHT tests. Lowest stiffness values were shown by the T5 and T5-73 specimens.

Strength and stiffness were found to be lower in the tensile specimens of series E than the compressive specimens in series D. This was more pronounced in the SHT and T7-113 specimens than in the SH and T7 specimens, respectively.

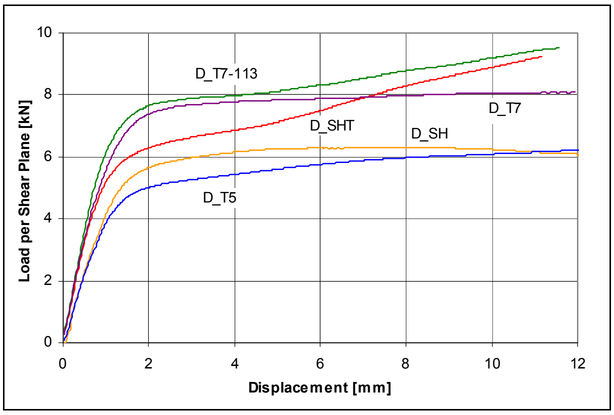

Figure 4 – Average Load-Displacement Curves for Series D Monotonic Tests

All **cyclic** tests experienced an initial slack, which was due to the test set-up (and hole tolerances in the SH and SHT specimens). This led to an uneven loading during the first positive and negative cycles.

Under load, the SH fasteners were first drawn towards the inside of the specimen (as was observed in the monotonic tests). At higher displacements, yielding of the steel resulted in permanent elongation of the fasteners and a push-out during the unloading phase of the load reversal. In the SHT tests, washers and nuts first pressed onto the wood and later loosened and pushed outward. All T7-1X3 or T5-73 specimens showed little or no outside movement.

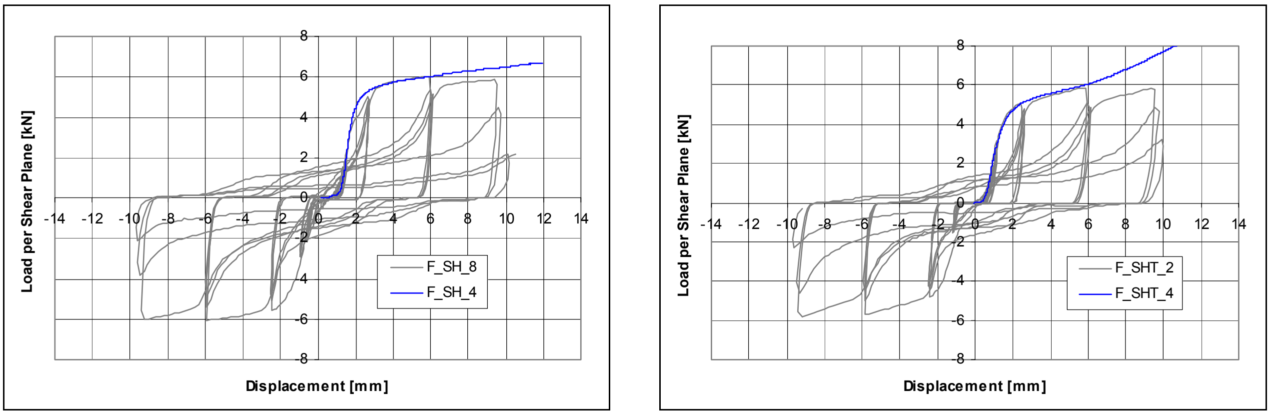

Figure 5 – Typical F_SH and F_SHT Cyclic and Monotonic Load-Displacement Curves

All cyclic tests experienced a fatigue yielding of the fasteners after approximately 8-9 mm displacement in series E and F and approximately 7 mm displacement in series G. This failure typically started during higher cycles at 6 to 8 times the yield displacement.

The envelope of the cyclic load-displacement curve for the fasteners without head restraint (SH) was typically closest to the monotonic curve up to the point when fatigue failure initiated. Fasteners with full head restraint (SHT) and all series F fasteners showed a similar behavior during the first cycles as respective monotonic tests. At higher cycles (at or just before failure), these tests had a lower strength but retained the same tangential stiffness as the monotonic curve. This was due to the washers bearing again on the wood (and the two-plate configuration in series F). Fasteners with partial head restraint (T7-1X3 and T5-73) showed a similar but less pronounced behavior.

3. Analysis

A finite element program based on the theory of an elasto-plastic beam on a nonlinear foundation (Figure 6), which calculates the load-displacement behavior of a single dowel-type fastener [2], was modified to incorporate fastener material fatigue, fastener head restraint (spring) and hole tolerances into the computation of the monotonic and cyclic response of a connection. Wood embedment and fastener stress-strain curves are illustrated in Figure 7 and Figure 8 (see [3] for details).

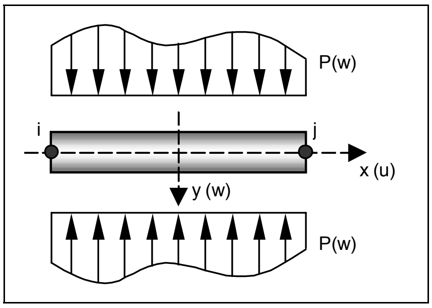

Figure 6 – FE Beam Element

Wood and steel layer embedment properties were successfully calibrated manually using compressive series D specimens. A calibration of fastener head spring stiffness using the D_SHT and D_T7-113 test results yielded a higher stiffness for the SHT-fastener than for the T7-fastener. Fastener steel properties were determined from tension testing.

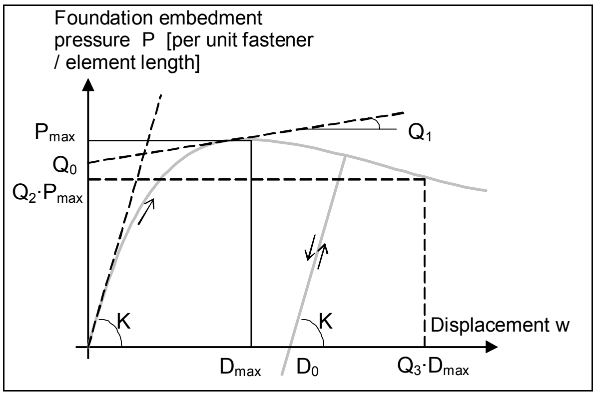

Figure 7 – Wood/Steel Plate Material Behavior

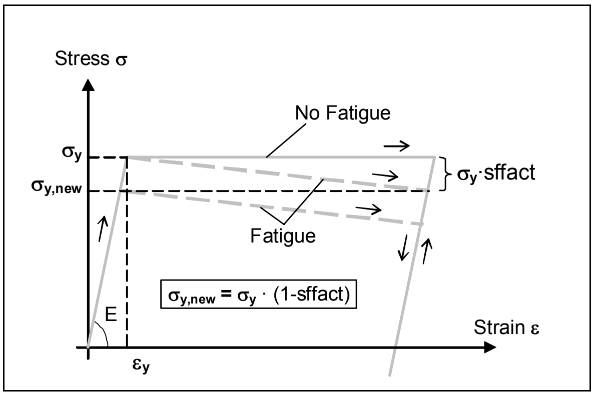

Figure 8 – Fastener Material Behavior

Monotonic calculation results for the tensile series E were largely comparable to the compressive calculated results from series D. While overall behavior of the headless fasteners (SH) was typically well predicted, strength of fasteners that featured a head (SHT, T7-1X3 and T5-73) was slightly overestimated after the yield point. Different to that were only the F_SH load-displacement curve which overestimated strength after the yield point and the G_SH curve which underestimated the yield area's strength. It appeared that the fastener head spring stiffness, which was calibrated to the compressive Series D tests, led to the higher strength levels in all tensile calculations where fasteners featured a head. This effect was marginally more pronounced in the T7 and T5 fastener calculations than in the SHT fastener calculations.

Deformed fastener shapes were generally well predicted by the calculations (Figure 9). Only a few cases exhibited the formation of additional yield hinges, which were not observed in the tested specimens. Fastener withdrawal was generally observed in similar magnitude as in the tests.

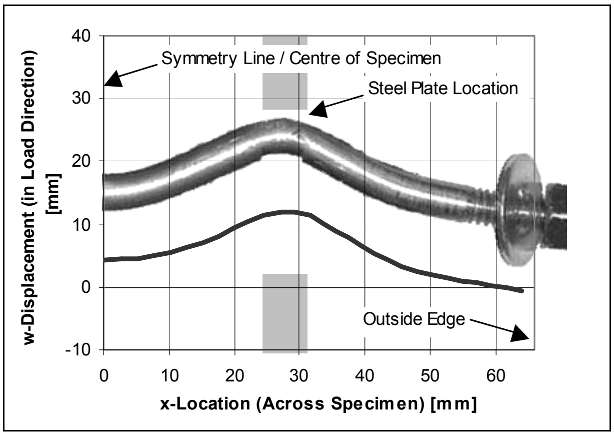

Figure 9 – Deformed F_SHT Dowel Shape Comparison (Calculated Shape in Black)

Preliminary **cyclic** finite element calculations, which applied no modifications for material fatigue and hole tolerances led to "open" hysteresis shapes that did not exhibit appropriate strength reductions between subsequent

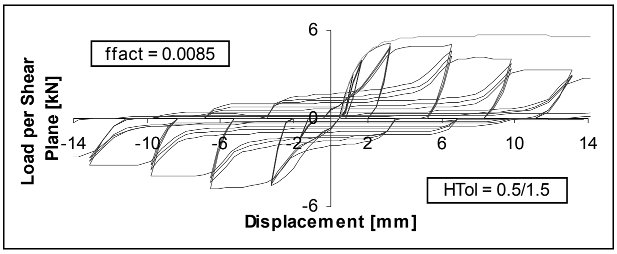

Figure 10 – E_SH Calculated Hysteresis Curve (Calculated Monotonic Curve Shown in Grey)

displacement steps. They also did not properly represent the zero displacement area ("pinching") and the residual strength during unloading of the fastener. These effects – observed in the tests – required the inclusion of material fatigue and appropriate hole tolerances.

An increase in the level of fatiguing led to an increase in the amount of strength reduction between subsequent load cycles. Ultimately, a fatigue factor of 0.0085 was chosen for most of the calculations because it yielded a good representation of the fatigue effect as well as the strength level around the zero displacement point.

All SH series hysteresis curves were generally well approximated by the finite element calculations (Figure 10).

Calculations for the SHT, T7 and T5 tests also showed good predictions of the test curves. Differences were found in the overestimation of tangent stiffness and higher strength in the ultimate hysteresis cycles of the calculated curves.

4. Conclusions

- A clamping and a strength increase in the PSL specimens were observed in fasteners that featured a head restraint. In contrast, a widening was detected at the location of the headless fasteners. The SFS WS fasteners showed the smallest specimen width change under load. Under cyclic loading, the bolt-type fastener heads did not remain in contact with the wood during the unloading portions of a cycle due to the permanent plastic elongation of the fastener. Hole tolerances also had an effect on the cyclic behavior and appeared in load-displacement curves as a zero-strength slack influencing mainly the displacement demand.
- The self-drilling SFS WS fastener proved itself as a comparable alternative to common dowels or bolts. Advantages lie in the easier manufacturing process as well as slightly improved monotonic stiffness and strength. Cyclic behavior was comparable to the bolt-type fastener.
- In FE modeling the connections, it was shown that a) the fastener head needs to be modeled by a unidirectional spring to accurately describe its behavior under reversed loading and b) the inclusion of a fatiguing material model for the fastener has a strong influence on the hysteresis shapes. Considering hole tolerances also proved necessary. Simulated load-displacement behavior (monotonic and cyclic) and deformed shapes were most accurate for the headless SH dowels. Cyclic calculations showed good agreement with the tests although it appeared that the calibrated fastener head stiffness led to overestimated loads.

5. References

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