Experimental testing of bow ties in shear

Dr. Gabriele Granello

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Abstract

In the first part of this paper, the main results from a series of experiments focused on the shear performance of bow ties are presented. Five specimens were tested to evaluate their capacity and stiffness. Specimens showed a main failure mode: a combination between shear and tensile failure in the narrowest section of the bow tie. In the second part, experimental results are compared with the failure capacity predicted by using Eurocode 5 [2].

1 Experimental testing

1.1 Experimental setup

Five specimens, made of three mock columns connected by four bow ties (two per face), were tested in a shear by using an hydraulic actuator (Figure 1). Two specimens were made of Metsa plywood (Metsa plywood) and one specimen was made of Sterling OSB (Sterling OSB).

Depending on how the shear keys were oriented on the plywood panel during fabrication, they may have either four or two lamellae parallel to the shear plane (Fig 2). To distinguish between the two cases, the following notation is used:

- $PLY \updownarrow$, to indicate the shear key with four lamellae with grain parallel to the shear plane.
- $PLY \leftrightarrow$, to indicate the shear key with two lamellae with grain parallel to the shear plane.

Below each of the shear keys, a potentiometer was placed to measure the displacement parallel to the shear plane.

Two different loading protocols were used:

1. monotonic load (for both plywood and OSB), to identify the maximum connection capacity per shear plane.
2. load-unload-reload protocol (only for OSB) according to BS EN 26891-1991 [1], to identify any difference between initial and unload-reload stiffness.

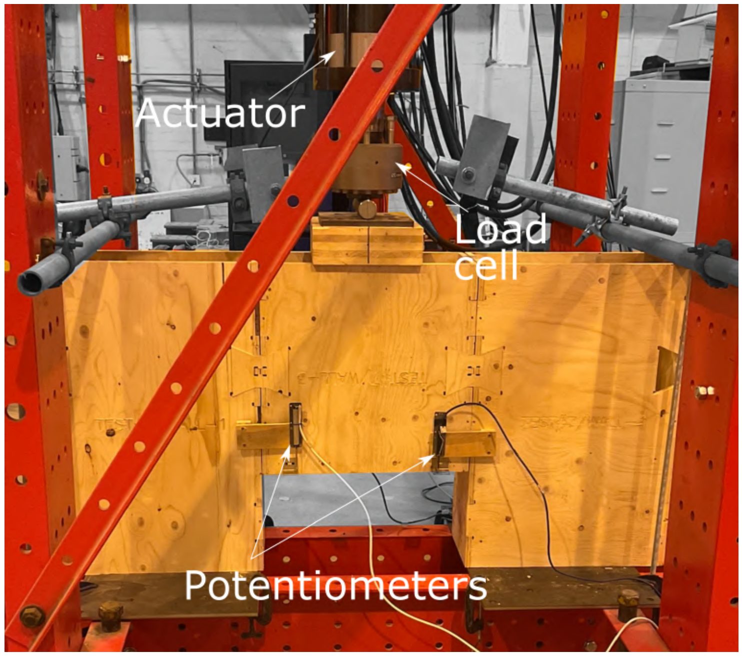
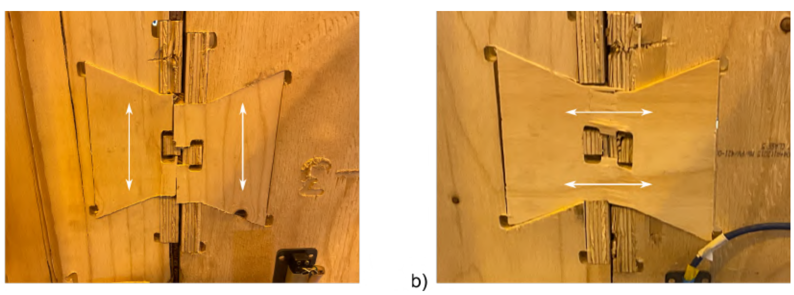


Figure 1: Experimental setup to test the shear connectors.



a) b)

Figure 2: Two possible grain orientations: a) 4 lamellae with grain parallel to the shear plane, 2) 2 lamellae with grain perpendicular to the shear plane.

1.2 Failure load

Experimental results in terms of force-displacement per shear plane are reported in Figure 3. Note that the force per shear plane is taken as half of the force measured at the actuator, while the displacement is taken as the average between the two potentiometers measuring opposite faces of the same shear plane.

Figure 3 shows that the peak force for the $PLY \updownarrow$ specimens was 11.2 kN using the monotonic loading protocol and 10.8 kN using the cylic protocol. The peak force for the $PLY \leftrightarrow$ specimens was 12.6 kN using the monotonic loading protocol and 13.5 kN using the cyclic protocol. The OSB specimens failed at a peak force of 16.6 kN

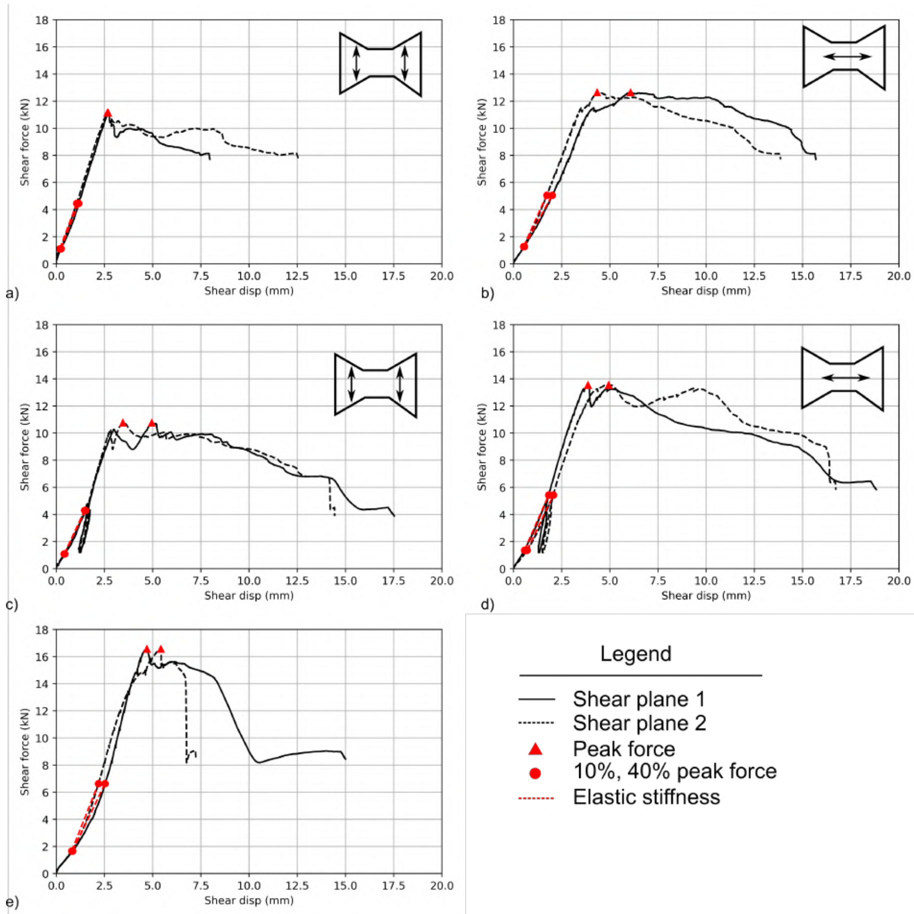


Figure 3: Force-displacement experimental results obtained for each shear plane: a), c) monotonic and cyclic test on plywood specimens with 4 lamellae which grain is parallel to the shear plane; b), d) monotonic and cyclic test on plywood specimens with 2 lamellae in which the grain is parallel to the shear plane; e) monotonic test on OSB specimens.

using a monotonic loading protocol.

1.3 Failure mode

No damage was observed in the main elements: failure was only observed in the shear keys themselves. Pictures of the observed failure modes are reported in Figure 4.

Fig. 4 shows that the lamellae with grain parallel to the plane in the plywood specimens exhibit a clear shear failure. Conversely, the lamellae with grain perpendicular to the shear plane are subjected to what seems to be a tensile failure.

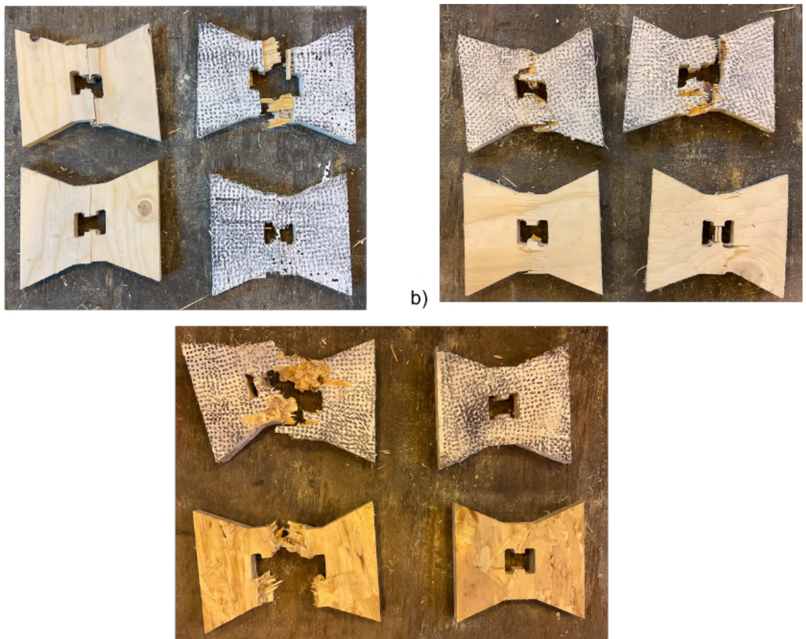


Figure 4: Observed failure modes in the: a) $PLY \updownarrow$ specimens, b) $PLY \leftrightarrow$ specimens.

The deformed shape at failure of specimen $PLY \updownarrow$ tested with monotonic load is shown in Figure 5a. Note that the amount the displacements was increased by a factor of 10 to provide a better visualization.

The shear key element is subjected to a combination of shear deformation and tensile deformation. This is because the bow tie is forced to progressively rotate while the vertical displacement increases: the bow ties is in fact constrained to follow the displacements imposed by the surrounding blocks. The two deformation mechanisms are graphically represented in Figure 5b.

The stiffness k_s of shear connections is calculated using equation 1:

$$k_s = \frac{F_{40\%} - F_{10\%}}{d_{40\%} - d_{10\%}} \tag{1}$$

where $F_{40\%}, F_{10\%}$ represent 40% and 10% of the maximum force (Fig. 3). $d_{40\%}, d_{10\%}$ represent the values of differential in-plane displacement where such force occurs.

The slip modulus k_s ranges between 5.3 kN/mm and 5.7 kN/mm for $PLY \updownarrow$, while it ranges between 6.0 kN/mm and 6.5 kN/mm for $PLY \updownarrow$. Therefore, orienting the connection having four lamellae perpendicular to the shear plane can provide slightly higher stiffness than having four lamellae parallel to the shear plane. This seems counter intuitive. However, this depends on the different deformation contributions given by the two mechanisms described in Figure 5b. If the main stiffness contribution comes from the tensile elongation of the specimen rather that the shear one, then having four lamellae with grain parallel to such elongation will provide higher stiffness. Given

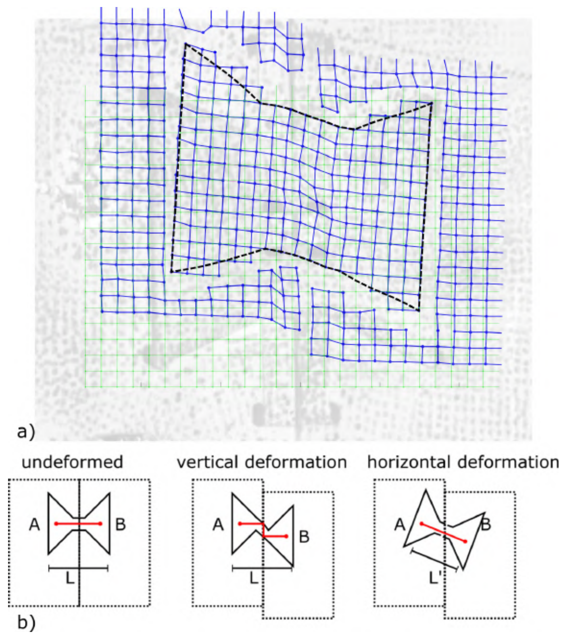


Figure 5: Deformed shape of the shear keys: a) captured by using DIC analysis and b) conceptual behaviour.

the fact the gaps exist between the bow tie and the surrounding, the second mechanism is believed to be more facilitated.

Table 1: Experimental values of the bow ties tested in shear: F_max; maximum force per shear plane (SP), $d_{10\%}$ differential shear displacement corresponding to 10% of the maximum force, $d_{40\%}$ differential shear displacement corresponding to 40% of the maximum force, k_s shear stiffness of the connection.}

Specimen	**Load type**	F_{max} **(kN)**	$d_{10\%}$ **(mm)**		$d_{40\%}$ **(mm)**		k_s **(kN/mm)**		
			SP1	**SP2**	**SP1**	**SP2**	**SP1**	**SP2**	**average**
$PLY \updownarrow$	monotonic	11.1	0.185	0.244	1.06	1.16	5.7	5.7	5.7
	cyclic	10.8	0.409	0.431	1.47	1.52	5.3	5.3	5.3
$PLY \leftrightarrow$	monotonic	12.6	0.523	0.567	1.73	2.01	6.1	5.9	6.0
	cyclic	13.5	0.71	0.523	2.07	1.83	6.4	6.5	6.5
OSB	monotonic	16.6	0.8	0.847	2.19	2.53	7.8	7.6	7.7

1.4 Single bow tie average

The values presented in table 1 are averaged to provide a summary for a single bow tie working in shear:

1. the average shear capacity $S \updownarrow$ is equal to 5.5 kN.

2. the average shear capacity $S \leftrightarrow$ is equal to 6.5 kN.
3. the average shear capacity S_{OSB} is equal to 8.3 kN.

The average shear stiffness k_s for plywood bow ties is equal to 2.9 kN/mm.

2 Analytical model

The geometry of the bow ties is reported in Figure 6. The average shear capacities $S_{\updownarrow}$,

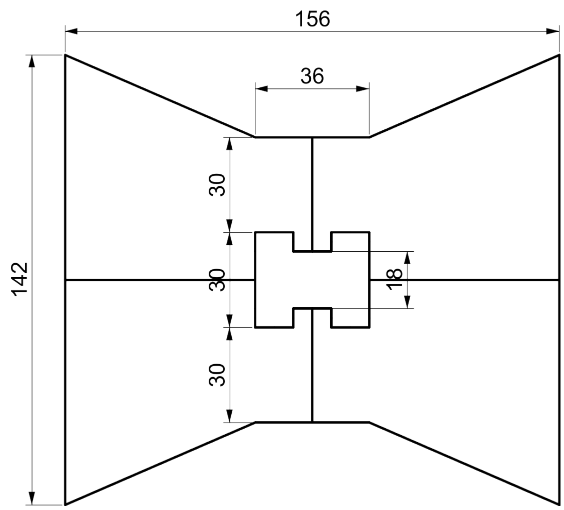


Figure 6: Geometry of the bow tie.

$S_{\leftrightarrow}$ and S_{OSB} can be calculated as:

$$\begin{cases} S_{\updownarrow} = \underbrace{A_s}_{60\cdot 18} \overbrace{f_{s,avg,\updownarrow}}^{5.3} = 5.7\ kN \\ S_{\leftrightarrow} = \underbrace{A_s}_{60\cdot 18} \overbrace{f_{s,avg,\leftrightarrow}}^{6.4} = 6.9\ kN \\ S_{OSB} = \underbrace{A_s}_{60\cdot 18} \overbrace{f_{s,avg,OSB}}^{6.8} = 7.3\ kN \end{cases}$$

It can be seen that the analytical results are consistent with the experimental data.

Acknowledgements

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greatly appreciated.

References

[1] Normalisation Comite Europeen de. *BS EN26891:1991 5 Timber structures - Joints made with mechanical fasteners - General principles for the determination of strength and deformation characteristics*. Brussels, Belgium, 1991.

[2] Normalisation Comite Europeen de. *Eurocode 5 - Design of Timber Structures. Part1-1: General rules and rules for buildings*. Brussels, Belgium, 2004.