Experimental testing of bow ties in tension

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Abstract

In the first part of this paper, the main results from a series of experiments focused on the tensile performance of bow ties are presented. Eleven specimens using two different geometries were tested to evaluate their capacity and stiffness. Specimens showed a main failure mode: a combination between shear and compression failure in the contact area between the bow tie and the surrounding panel. In the second part, an analytical model to calculate the capacity according to Eurocode 5 [1] is provided. Results show that the model overestimates by around 30% the capacity observed in the experiments due to the deformation of the panel surrounding the bow tie: such deformation in fact reduces the contact area between the elements.

1 Experimental testing

1.1 Experimental setup

To test the tensile behaviour of the bow tie joints, a tensile test was performed at the University of Edinburgh and at the University of Strathclyde [2]. Two different geometries (labelled A and B) were investigated, and they are reported in Figure 1.

This series of experiments consists of:

1. Three specimens of type A (single bow tie)
2. Four specimens of type B (single bow tie)
3. Four specimens of type B (three bow ties)

Specimens were made of 18 mm thick Metsa plywood (Metsa plywood), and the main grain direction is reported in Figure 2).

The experimental setup (Figure 2) consists of two timber panels connected by:

1. one bow tie (geometry A);
2. one or three bow ties (geometry B).

The specimens were subjected to tensile force until failure. A monotonic load protocol was used to identify the maximum connection tensile capacity. Two potentiometers were installed to measure the gap opening between the panels, and a load cell was installed to measure the force.

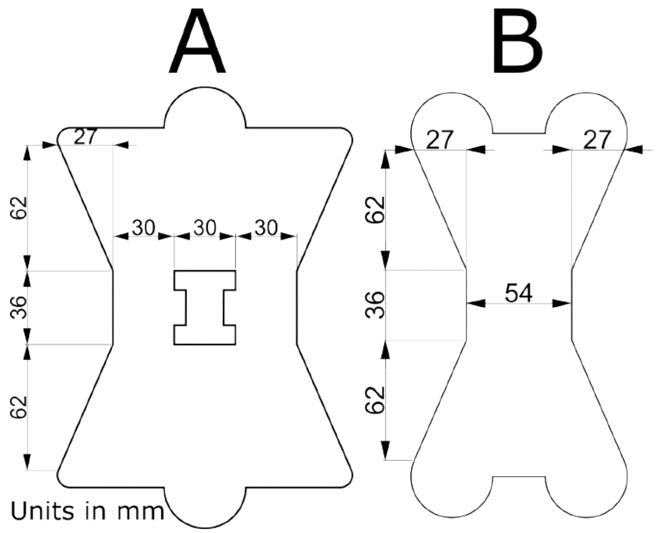

Figure 1: Geometry of the specimens.

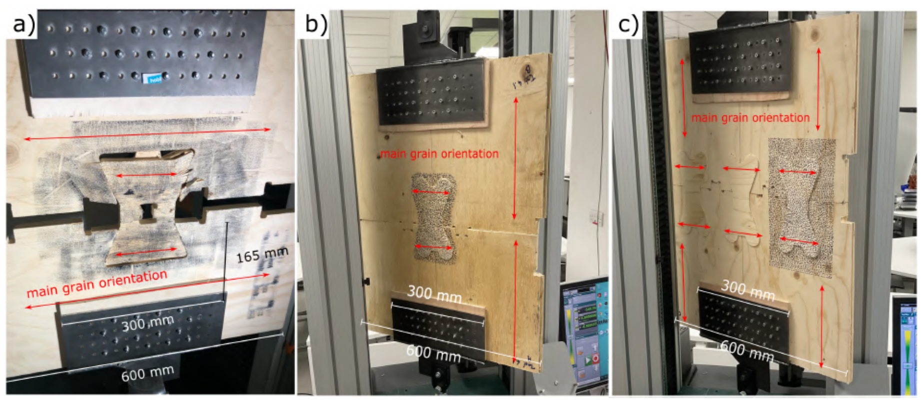

Figure 2: Experimental setup to test the bow ties in tension.

1.2 Failure mode

Specimens using geometry A showed failure at the contact zone between the bow tie and the panel (Figure 3). It appears that the failure mechanism was a combination between compression and shear stress.

Specimens using geometry B in single configuration also showed a similar failure mode in the contact zone. Specimens 3 and 4 also showed some cracks in the panel which appears to be a shear failure.

Specimens using geometry B in triple configuration mainly showed a failure on the external panel (Figure 5; specifically, the external portion of the panel in contact with one of the two lateral bow ties. This part of the panel can be seen as a small

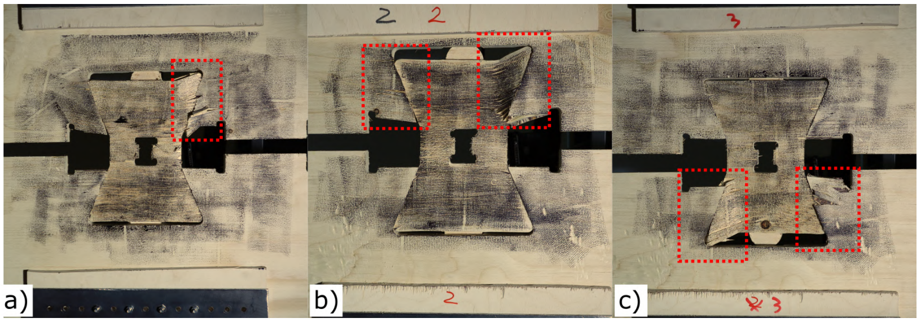

Figure 3: Observed failure modes in a) specimen 1, b) specimen 2 and c) specimen 3.

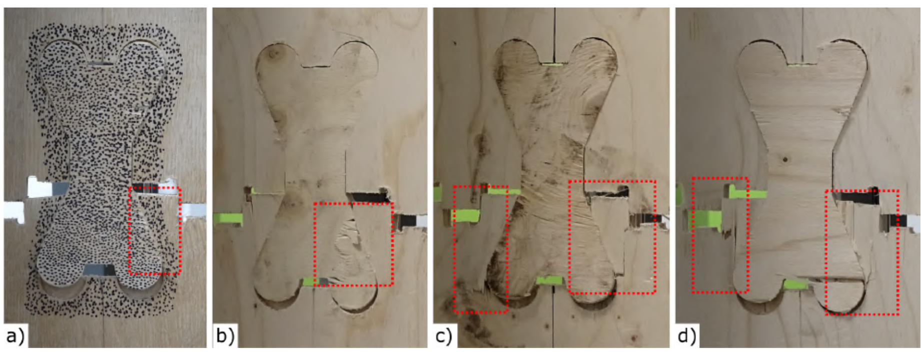

Figure 4: Observed failure modes in a) specimen 1, b) specimen 2, c) specimen 3 and d) specimen 4.

cantilever working in bending. Specimens c and d also showed a failure in the contact zone between the bow tie and the panel.

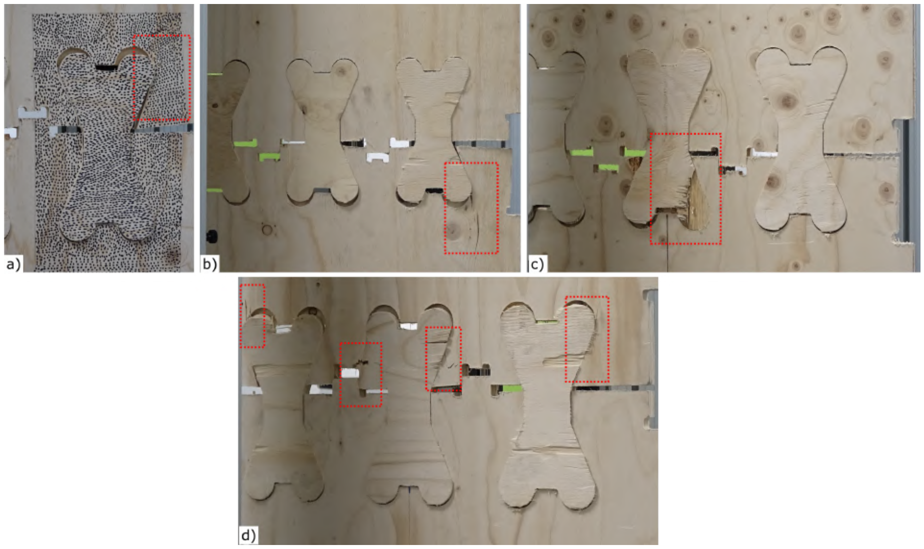

Figure 5: Observed failure modes in a) specimen 1, b) specimen 2, c) specimen 3 and d) specimen 4.

1.3 Failure load

Specimens using geometry A showed a maximum force between 8.4 kN & 9.0 kN, and a slip modulus between 1.37 kN/mm & 1.57 kN/mm.

The slip modulus k_s 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, and $d_{40\%}, d_{10\%}$ represent the values of differential in-plane displacement where such force occurs.

Specimens using geometry B in single configuration showed a maximum force between 7.4 kN & 8.8 kN, and a slip modulus between 1.44 kN/mm & 1.67 kN/mm.

Specimens using geometry B in single triple showed a maximum force between 19.2 kN & 24.1 kN, and a slip modulus between 4.43 kN/mm & 5.83 kN/mm.

Data in terms of force-displacement are reported in Figure 6, while results are summarized in Table 1.

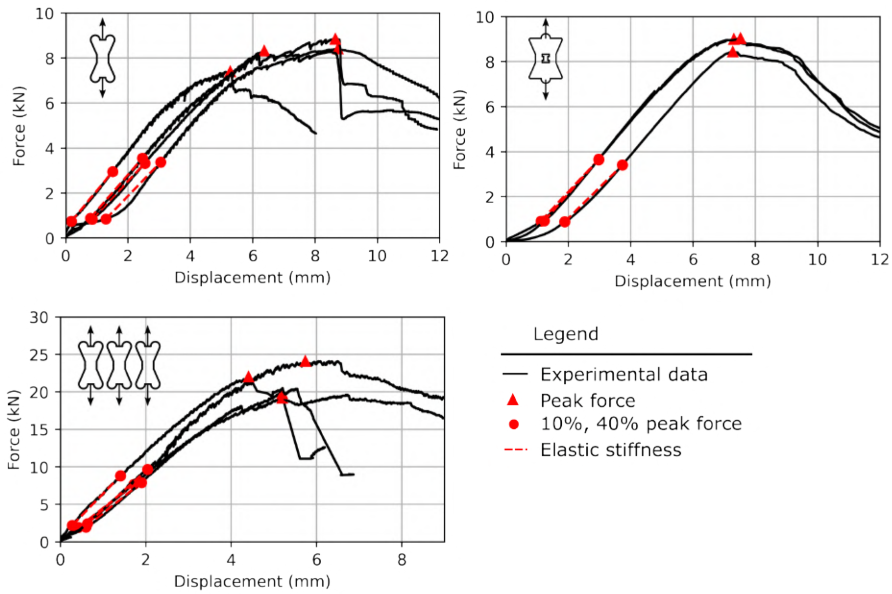

Figure 6: Force-displacement experimental results obtained for each test: a) geometry A single bow tie, b) geometry B single bow tie, c) geometry B three bow ties

Table 1: Experimental results where F_{max} is the connection capacity, and k_s is the slip modulus.

Specimen	F_{max} (kN)	k_s (kN/mm)	Failure mode
A1	9.0	1.48	Shear-compression @ interface
A2	9.0	1.57	Shear-compression @ interface
A3	8.4	1.37	Shear-compression @ interface
B1	8.4	1.44	Shear-compression @ interface
B2	8.3	1.47	Shear-compression @ interface
B3	7.4	1.67	Shear-compression @ interface Shear @ panel
B4	8.8	1.59	Shear-compression @ interface Shear @ panel
3x B1	19.2	4.43	Bending external panel
3x B2	19.8	4.57	Bending external panel
3x B3	24.1	5.13	Bending external panel Shear-compression @ interface
3x B4	22.0	5.83	Bending external panel Shear-compression @ interface

2 Analytical model

An analytical model is developed to calculate the bow tie capacity for design purposes. Two main failure modes are considered (Figure 7): tensile failure in the middle of the bow tie F_1, and combined shear-compression failure F_2 at the contact interface between the panel and the bow tie.

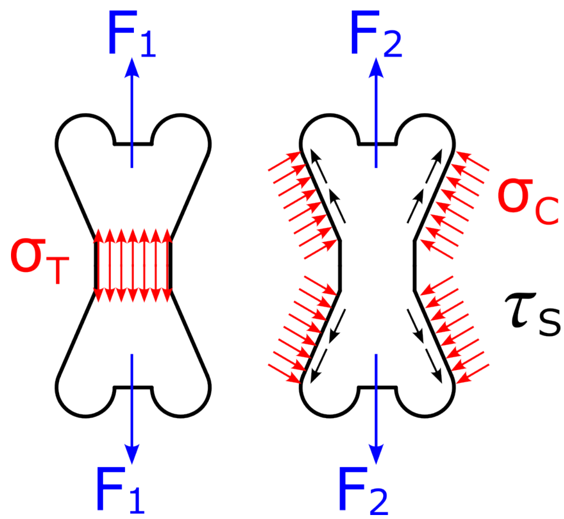

Figure 7: Conceptual model of the failure mechanisms.

Notice that the failure of the external panel observed in the geometry B triple configuration (Figure 5) is not taken into account. This is because, in a real scenario, that side of the panel is restrained. Therefore, it is believed that this failure mode is not likely to occur.

The failure F of the bow tie is taken as the minimum between F_1 and F_2, whereby:

1. F_1 corresponds to a tensile failure in the narrowest section due to tension stress σ_T.

2. F_2 corresponds to a failure in the contact zone between the bow tie and the panel, due to a combination of compression stress σ_C and shear stress τ_s.

2.1 Tensile failure

The value of F_1 can be calculated as per equation 2:

$$F_1 = A_t f_t \tag{2}$$

where A_t is the area of the bow tie in tension, and f_t is the tensile stress of the material.

2.2 Shear-compression failure

The calculation of F_2 requires an iterative algorithm (see algorithm **??**). This is because the contact area between the bow tie and panel reduces while pulling the connection (Figure 8).

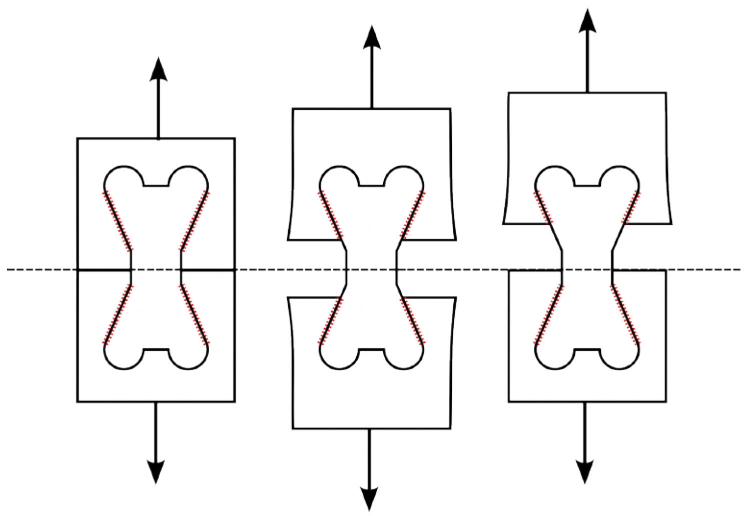

Figure 8: Reduction of the contact zone due to the slip of the bow tie.

The algorithm is made of the following steps:

1. Start with arbitrary F_2, for example 1 kN.
2. Calculate the contact zone by considering a bow tie slip $s = \frac{F_2}{k}$ with k the bow tie stiffness.
3. Decompose F_2 into $F_{2,comp}$ and $F_{2,shear}$ according to the bow ties geometry.
4. Calculate the compression stress σ_C and shear stress τ_S based on the contact zone.
5. Check if the element has failed according to $\frac{\sigma_c}{f_{c,d}} + \frac{\tau_s}{f_s} = 1$. If not, increase F_2.

A spreadsheet file showing the steps of the algorithm is reported as supplemental material to this document.

2.3 Comparison between analytical and experimental results

The analytical model was used to calculate the failure load, leading to a tensile force equal to 10.9 kN. This is between 24% and 33% of the average capacity force for

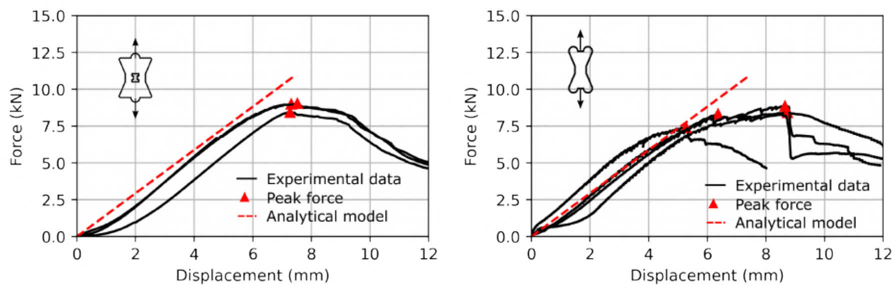

Figure 9: Comparison between experimental and analytical results.

geometry A and B, respectively. The comparison between experimental and analytical results is reported in Figure 9.

This is believed to be due to the fact that, while pulling out the bow tie, the contact zone might reduce even further due to the deformation of the panel near the bow tie (Figure 10). While the analytical model considers the elements to be rigid and fully in contact with each other, in reality the external panel deforms further reducing the contact area. This leads to an increase of stress, which is believed to to anticipate the failure.

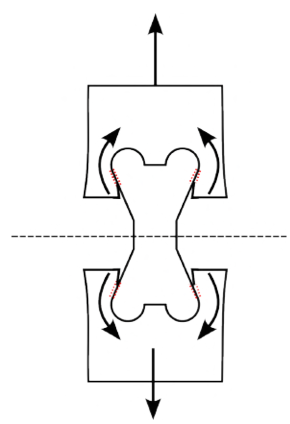

Figure 10: Deformation of the external panel further reducing the contact between the bow tie and the surrounding panel.

This effect should be mitigated in a real design scenario, because the panel will be constrained by the surrounding wall columns.

Acknowledgements

The series of experiments on geometry A was carried out at the University of Edinburgh (UoE). The contribution of Tom Reynolds and the technical staff in the structural engineering lab at UoE is greatly appreciated. The series of experiments on geometry B was carried out at the University of Strathclyde by Aidan Napier under the supervision of Marcus Perry. Their contribution as well as the one of the technical staff at UoE is greatly appreciated.

References

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

[2] Aidan Napier. "Experimental testing of plywood integral mechanical attachment joints to define tensile and stiffness characteristics". Master thesis. Department of Civil and Environmental Engineering, University of Strathclyde, 2022.