Experimental research on pinned connections in aluminium truss girders

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Aluminium truss girders are widely used in the entertainment industry. The loads on these girders, representing systems for sound and lighting, are standardised in uniform loads and/or concentrated loads. Focusing on larger spans, standard connections, i.e. welded joints between chords and braces and mechanical fasteners between girder sections, may limit the design strength of these girders. In this publication the experimental research on pinned girder section connections, which allow for an easy assembly and disassembly of the truss girders, is described and discussed. The experiments have been carried out using two different boundary conditions as well as two different securing methods. The results show a design strength which is not limited by the shear and bearing mechanism of the pinned connection. Failure is induced by cracking of a centerpoint, which is applied for easy welding procedures.

Key words: aluminium truss girders, pinned connections

1 Introduction

Aluminium trusses are widely used in the entertainment industry. The advantage of using aluminium truss elements is the light weight product, which allows for easy assembly and disassembly. Aluminium trusses started out as temporarily adjustable beams to which sound and lighting systems for concerts and theatre shows could easily be attached. Nowadays complete stages are erected, entirely built up from truss elements.
In a study on larger spans of aluminium trusses [1], optimal truss dimensions were determined for trusses spanning 30 meters loaded by 1 kN per meter truss length. Diameters and thicknesses of braces and chords, as well as height of the truss elements, were optimized for minimum weight using optimal transport sizes of the truss elements as

a design criterion. However, larger truss spans indicate for more heavily loaded connections. In the considered truss girders two types of connections can be distinguished: a conically pinned connection between two or three meter length truss elements, and welded connections in the K- and N-joints between braces and chords. Both connections were investigated further. This paper focuses on the first type of connections (Fig. 1 and Fig. 2).

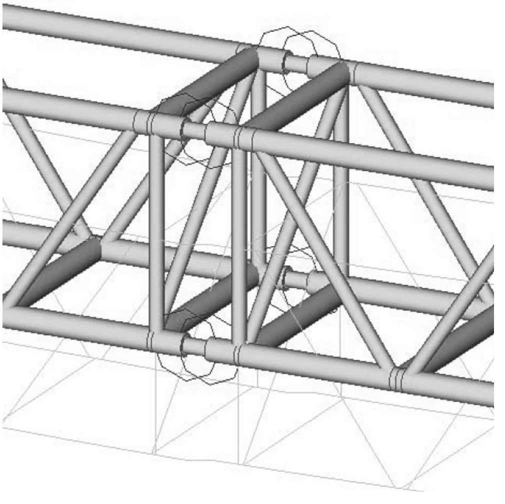

Figure 1. Connection of an aluminium truss girder

2 Type of connection

Figure 2 shows an exploded view of the conically pinned connection. A hollow connector i.e. the female connector (A) is welded to the chord ends of the truss element (C). When the trusses are assembled a conical cylinder secured with conical pins (D) provides for the connection. Because both the inner cylinder i.e. the male connector (B) as well as the securing pins (D) are conical, there is no play in the connection when it is assembled. Securing the pins with cotters (Fig. 5) allows for fast assembly and disassembly. The forces in the pinned connection are transferred by shear and bearing.

The female connector is made of an EN-AW 6082 T6 alloy, the male connector is made of an EN-AW 2007 T3 alloy and the conical pins are made of steel St 52 (S355). Material properties of the aluminium parts were determined by tensile tests according to [5] and [6]. Tensile test results were compared with standards [5]. The material tests are described in more detail in [3]. The tables 1 and 2 summarize the results for both the 6082 T6 and 2007

T3 alloy. The characteristic value is determined in accordance with annex D of [7], the calculation is included in [3].

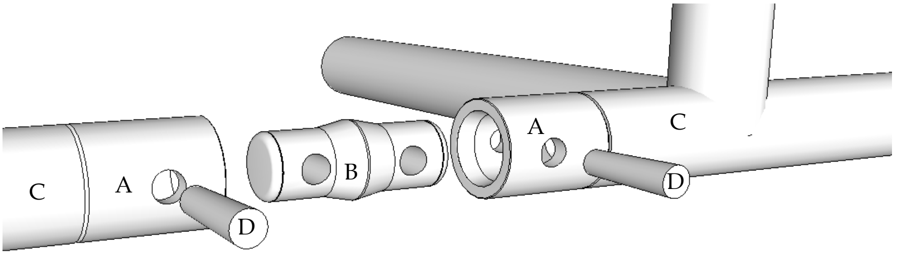

Figure 2. Conically pinned connection

Table 1. Summary of tensile test results for the 6082 T6 alloy

Parameter	Sample mean	Sample standard deviation	Characteristic value
E [N/mm²]	70 272	315	69 443
$f_{0.2}$ [N/mm²]	314	6.1	297
f_t [N/mm²]	339	6.0	324

Table 2. Summary of tensile test results for the 2007 T3 alloy

Parameter	Sample mean	Sample standard deviation	Characteristic value
E [N/mm²]	77 088	3 233	68 585
$f_{0.2}$ [N/mm²]	342	6.5	325
f_t [N/mm²]	472	5.0	459

3 Testing arrangement

The figures 3 and 4 show a schematic view and a photograph of the testing arrangement. Calculations (see annex B in [2]) have shown that the shear capacity of the conical pin will determine the connection strength. For this reason all tests are carried out for tension loading; compression loading will not lead to shear in the pins. The male connectors are supplied by internal threads for M24 bars, which will transfer the tension load centrically into the connection.

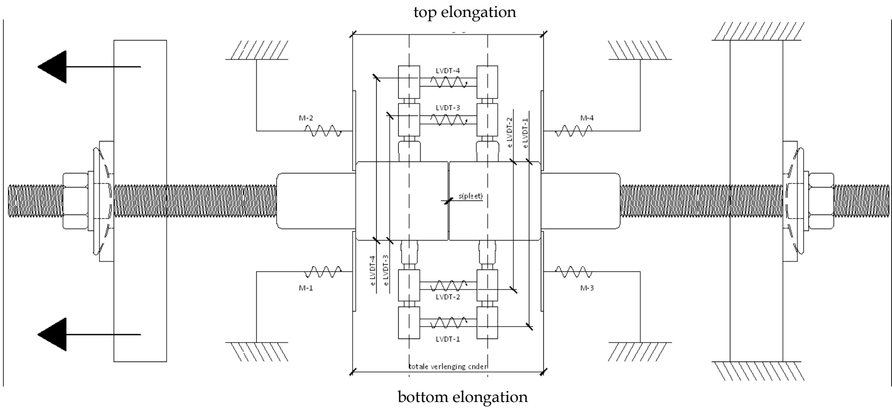

Figure 3. Schematic view of testing arrangement (specimen hinged in test bench)

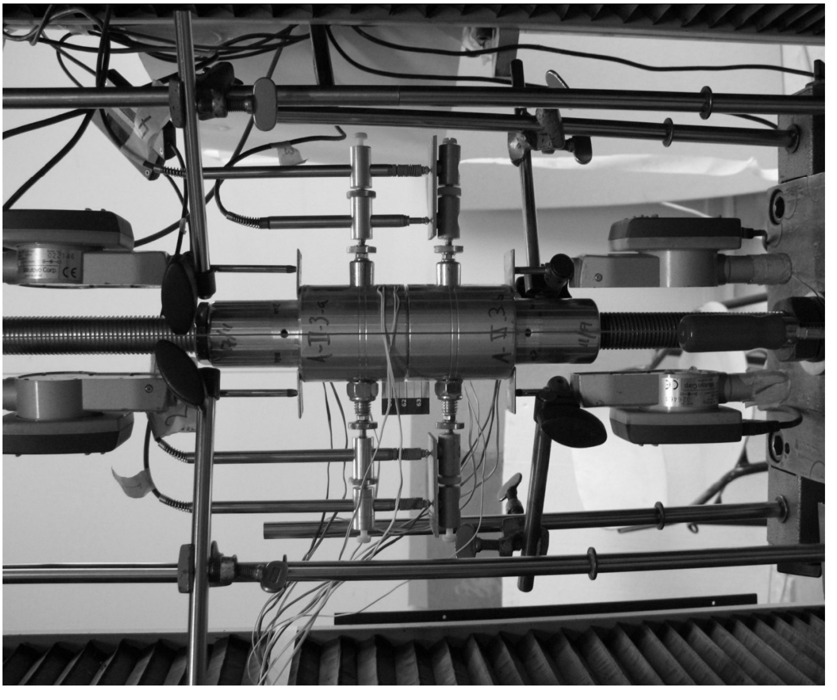

Figure 4. Photograph of test set-up (rotated 90 degrees, specimen hinged in test bench)

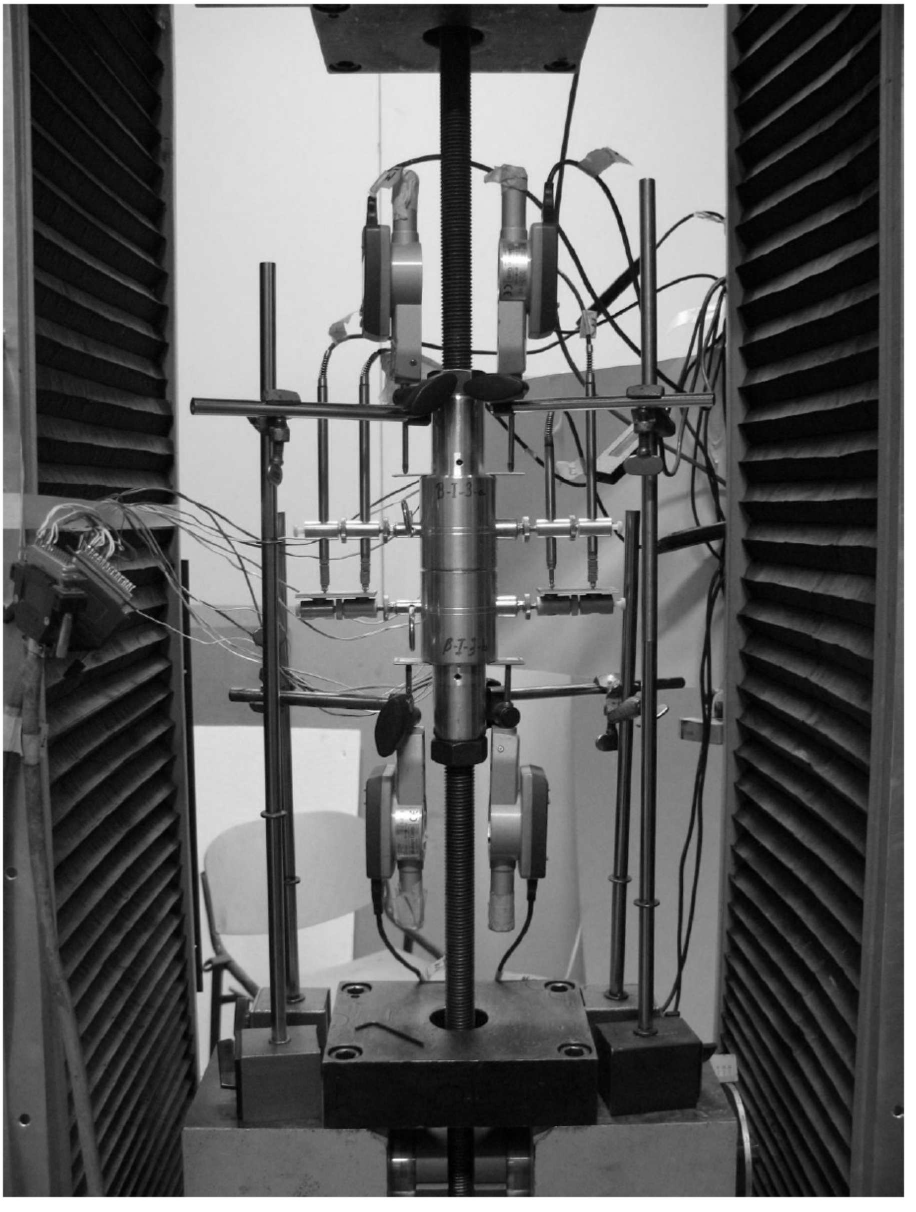

Figure 5. Photograph of test set-up (specimen clamped in test bench)

The tests to be carried out consist of four series of three tests (Table 3) investigating the following influence of parameters:

1) the way the pins are secured: cotters(I) or nuts (II), see Figures 6 and 7)

2) the boundary conditions in the testing arrangement: spherically hinged (A) as in figures 3 and 4, or threaded bars clamped in the test bench (B) as in figure 5

Table 3. Notation of tests specimens

Code	Description
A-I	Hinged in test bench, pins secured with otters
A-II	Hinged in test bench, pins secured with nuts
B-I	Fixed in clamps of test bench, pins secured with cotters
B-II	Fixed in clamps of test bench, pins secured with nuts

Figure 6. Conical pins secured with cotters

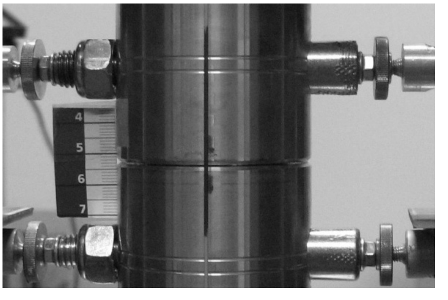

Figure 7. Conical pins secured with nuts

The first parameter (i.e. the way the pins are secured) affects the behaviour of the connection. When the pins are secured with cotters the pins can deform more easily because they are not effectively prevented from being pulled inwards. When the pins are secured with nuts the pins may be more difficult to deform, and the nuts can support the pins against rotation.
No requirements exist on the assembly method of the pins. In practice the truss fitters force the conical pin into its hole using a hammer. This was simulated in the experiments. Also no requirements exist on the tightening of the nuts. The nuts have a plastic ring at the inside to avoid loosening of the nuts by vibrations. To overcome the resistance of this plastic ring a moment of 4 Nm should be applied. The nuts were fastened with a moment of 10 Nm.

The second parameter (i.e. the boundary conditions in the testing arrangement) refers to the connection in practice, where the female connector is welded to the main tube. The main tube is supported by horizontal, vertical and diagonal members, which makes rotation of the connection in practice nearly impossible.

In the tests the effect of the truss on the connection can be eliminated by taking into account the right end condition in the testing arrangement. A spherically hinged end condition implies that in the test rotations can occur, due to the asymmetric transfer of loads caused by the conical form of the pin. The fixed clamps end condition more or less restricts these rotations. So, with this second parameter the influence of the truss on the connection properties is investigated.

4 Measurements

The tests should give information on the elastic load-deformation behaviour as well as on failure loads, failure modes and deformations.

The measured data are:

- total elongation of the connection (M1 to M4 in Figure 3)
- gap between female connectors (Fig. 8)
- rotation of the pin ends (Fig. 9)
- strains in male and female connectors (Fig. 10)

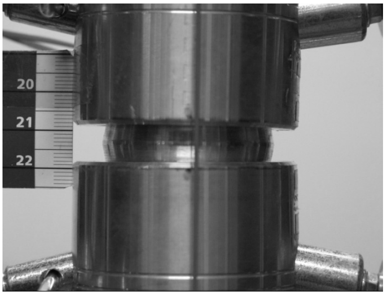

Figure 8. Measurement of the gap between the female connectors

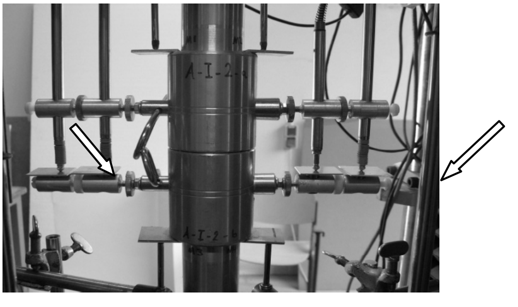

Figure 9. Measurement of the rotation of the pin ends

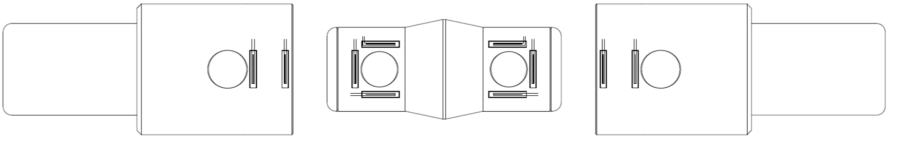

Figure 10. Strain gauge locations

The total elongation of the connection is monitored using four devices, which measure the longitudinal displacement of thin plates that are adhesively bonded to the female parts of the connector. These devices are shown in figure 3 as M1 to M4. As illustrated in figure 8 the connection rotates, and this is the reason why four measurements are needed instead of two. The devices M1 and M2 measure the displacement on the loading side of the test bench, the devices M3 and M4 on the other side. The elongation ΔL of the connection is calculated as the average of M1 minus M3 (i.e. top elongation in Fig.10) and M2 minus M4 (i.e. bottom elongation in Fig.10). The gap between both female connectors is an important measurement that may indicate what happens inside the connection. In the first two specimens the gap was measured using a feeler gauge. However, this was not very accurate in the elasto-plastic range. For the other specimens the gap was photographed and measured manually (Fig. 8). The accuracy of the latter method was at least the same as the measurements of the first method in the elastic range.

The rotation of the conical pins needs to be measured in a rather complex way, because the pins can not be reached easily after the connection has been assembled. Therefore the pins are lenghtened and two elongation gauges are mounted near each pin end (see figure 9). The angle of rotation is calculated using both elongation measurements at each side and the distance between both elongation gauges. The calculations are worked out in [4].

All previous parameters can be obtained by measurements outside the connection. However, this is not the case for the behaviour of the male part of the connection. To be able to gain information on the male part behaviour, strain gauges are adhesively bonded to the connector before assembly (Fig. 10). Not all specimens are supplied with strain gauges: only the third specimen of each series will give information on the behaviour of the male connector. The main objective of the strain gauge measurements is to determine where and when elastic deformations end and elasto-plastic deformations start. The strain gauges in load direction, next to the hole in the male connector, give information on the load-elongation traject of the male connector. When bearing of the female connector is responsible for the start of elasto-plastic deformations, this should be measured by the strain gauges next to the hole of the female connector. And finally, when curvature of the pins introduces large bearing stresses and local deformations in the male connector, this can be measured by the strain gauge transversely placed behind the hole in the male connector.

5 Test results

A typical load-deformation graph is shown in Figure 11. The graph consists of two branches: an elastic deformation, which ends at a load of circa 54 kN, and an elasto-plastic deformation for loads higher than 54 kN. The ultimate load is 128 kN (for the specimen shown in the graph).

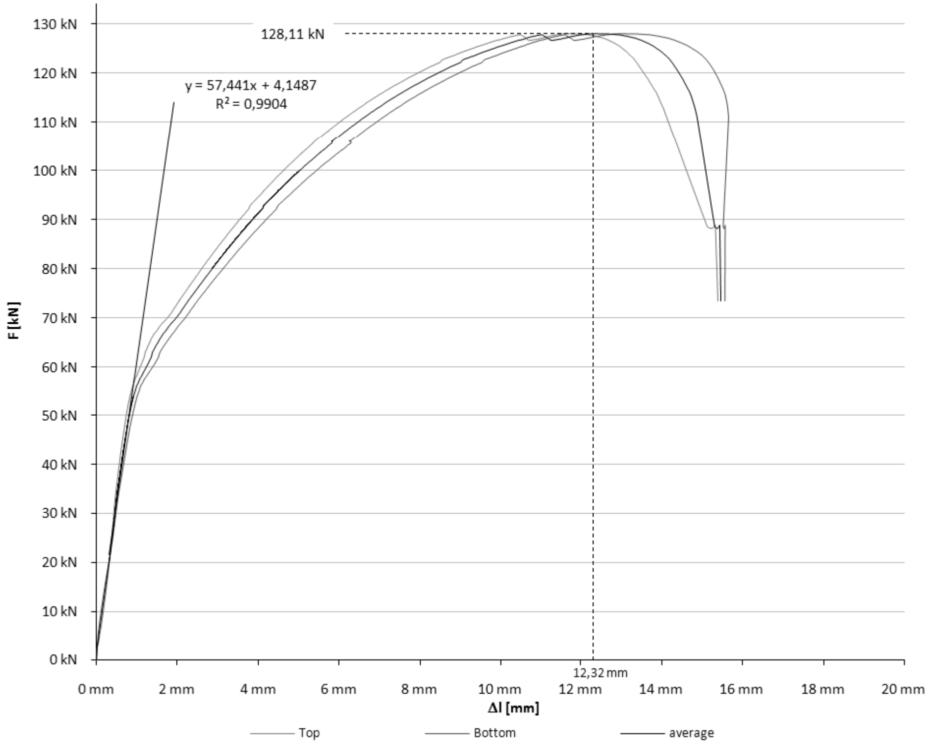

Figure 11. Load-deformation graph of test specimen A-I-3 (Elongation of connection by force F)

At the top of the curve the onset of structural failure is indicated by a small drop of the applied force. This can be explained as follows. In the front of the female connector a small centre point is located, which allows the welding robot to weld the female connector exactly to the centre of the truss chords. The centre point is directly in line with the bigger hole in the female connector, which transfers more load than the thin end, due to which larger stresses occur at that side of the female connector. The weakening of the female connector at the centre point allows the material to crack near its maximum load. This crack indeed starts at the centre point (Fig. 12) and grows with increasing deformations.

Due to the reduction of the material at the crack, less force is transferred through the connection. At a certain load the uncracked area is so small that the remaining material tears suddenly (Fig. 13).

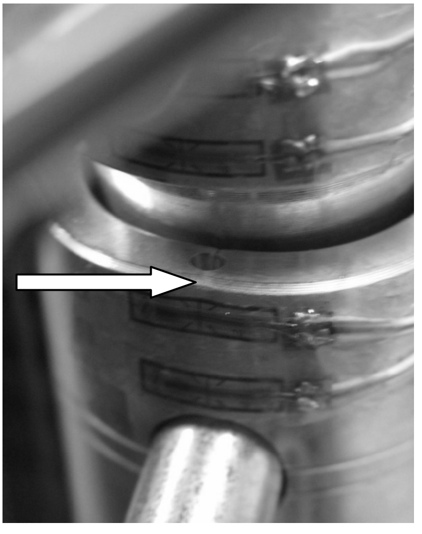

Figure 12. Start of crack at the centre point

Figure 13. Structural failure due to extended cracking at the centre point

In [2] and in [4] all load-gap graphs, load-rotation graphs and strain measurement graphs are given. The results for specimen A-I-3 are shown in the Figures 14, 15 and 16 respectively.

The progression of the gap between the connectors (Fig. 14) shows the same behaviour as the total elongation of the connection (Fig. 11). At a load of approximately 50 kN the progression of the gap increases. The rotation of the pin ends starts to increase more rapidly before the onset of elasto-plastic behaviour of the total connection (Fig. 15). However, the shape of the rotation graph suggests that rotation of the pin ends induces elasto-plastic behaviour.

The results of the strain gauge measurements confirm this. As can be seen in figure 16 all graphs, except the measurements on the bearing behaviour in the mail connector (top left graph and bottom left graph) show a much longer elastic part than the total elongation of the connection. All these curves contain two branches with a point of inflection at a load level of 100 kN to 120 kN. The top left graph and bottom left graph however show results similar to the deformation of the total connection. Especially the top left graph, where the point of inflection coincides perfectly with the point of inflection of the total elongation graph (Fig. 11) and the progression of the gap graph (Fig. 14). This indicates that increasing deformation of the conical pins is determining the start of elasto-plastic behaviour of the total connection.

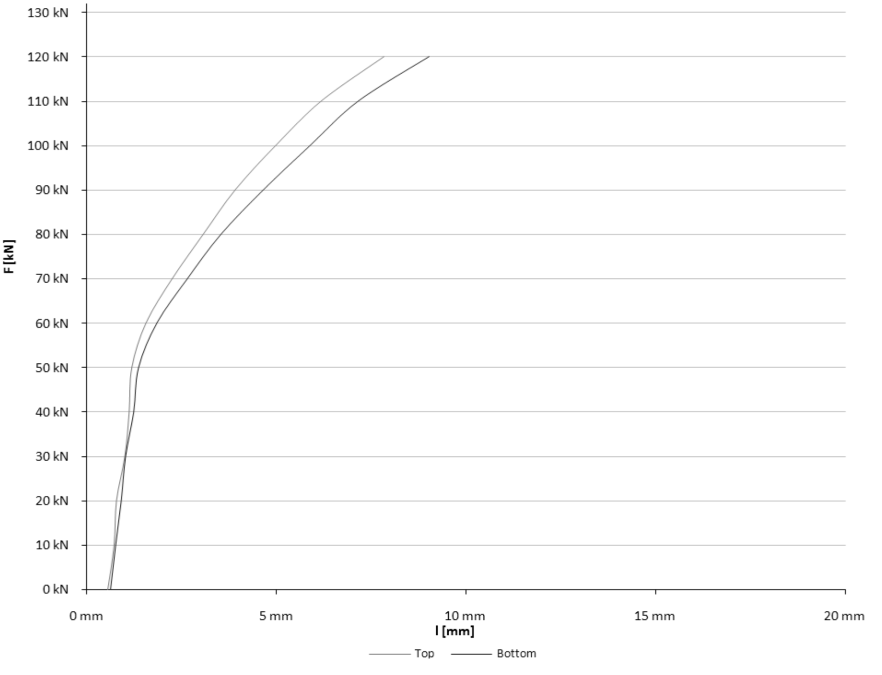

Figure 14. Progression of gap between connector parts graph for test specimen A-I-3

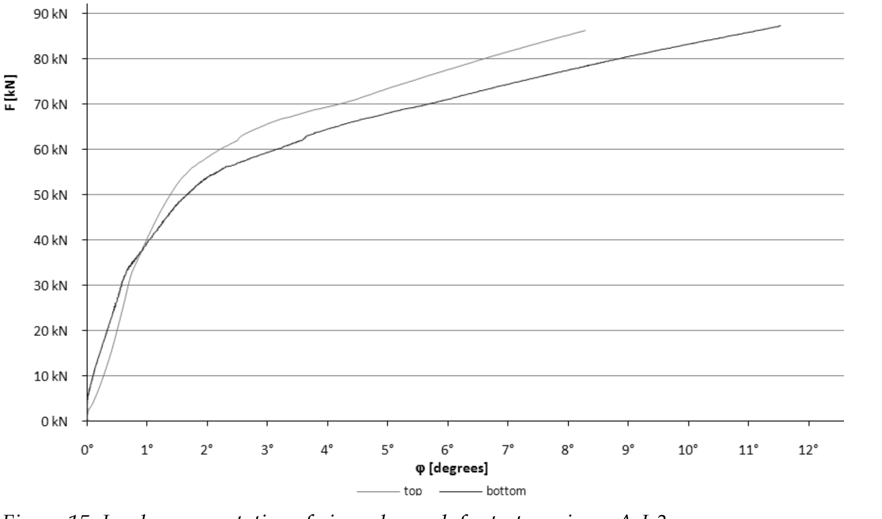

Figure 15. Load versus rotation of pin ends graph for test specimen A-I-3

A complete view of test results can be found in [4], a summary of the results is shown in Table 4.

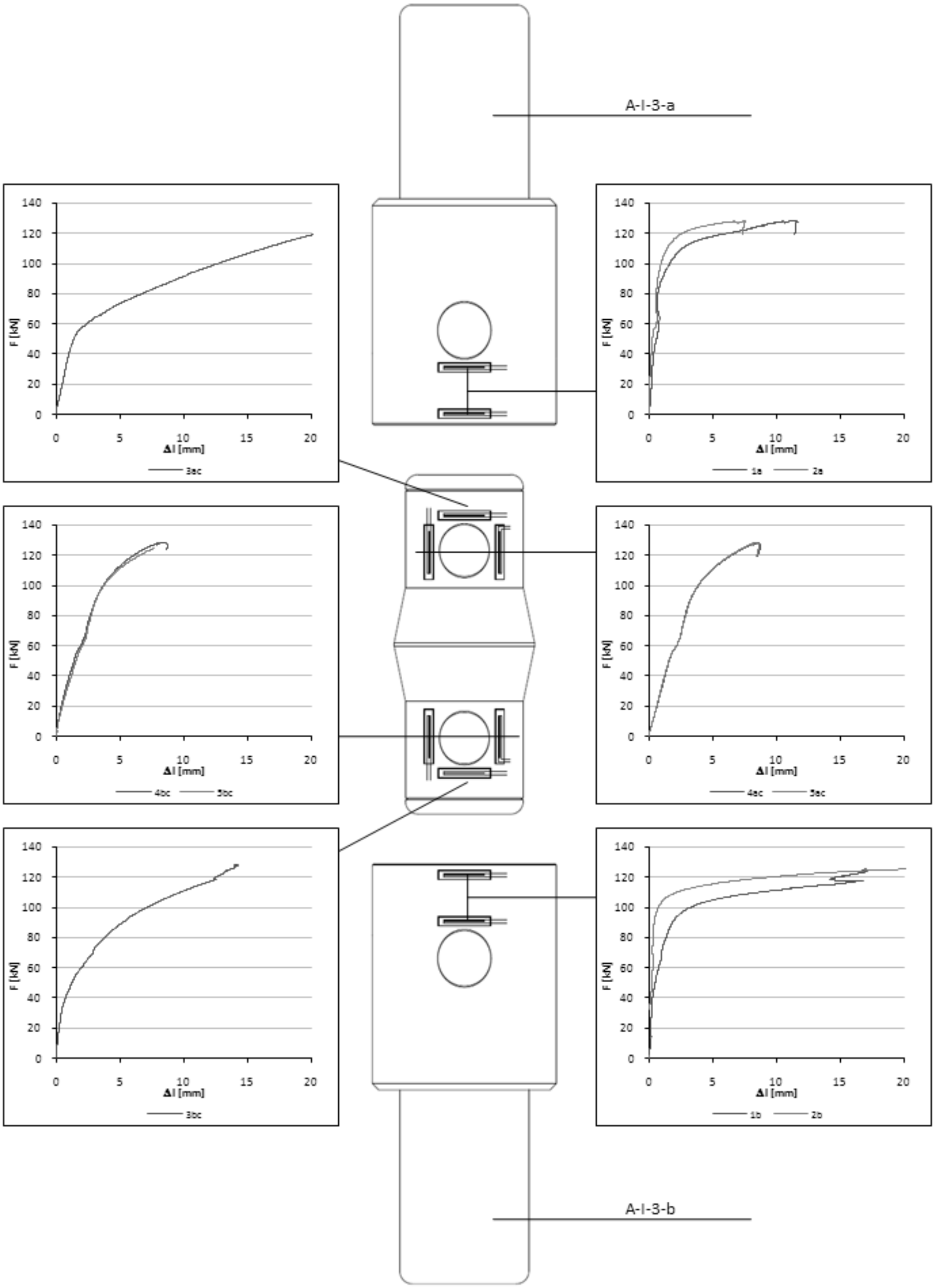

Figure 16. Results of the strain gauge measurements for test specimen A-I-3

6 Discussion

The Tables 5 to 7 show rearranged test results, i.e. elongation at structural failure, load at elastic deformation limit and relative stiffness for elastic deformation, respectively.
The mean maximum load at structural failure is 136 kN. This load was not influenced by the parameters investigated. The maximum elongation at structural failure is influenced by the way the pins are secured (Table 4). The use of nuts (Series II) results in more elongation (sample mean 14.7 mm) compared to the use of cotters (Series I, sample mean 13.1 mm).

Table 4. Overview of the test results

	F_{max}	Δl_{max}	F_{el}	'Stiffness'	Structural failure in part: *	Spigot end with max rotation:
A-I-						
1	138,67 kN	**	**	**	b	thin end
2	130,49 kN	12,31 mm	± 49 kN	53,2 kN/mm	b	thin end
3	128,11 kN	12,32 mm	± 54 kN	57,4 kN/mm	b	thin end
Sample mean	132,42 kN	12,31 mm	51,5 kN	55,3 kN/mm		
Standard deviation	5,54 kN	0,00 mm	3,5 kN	3,0 kN/mm		
A-II-						
1	133,16 kN	14,90 mm	± 46 kN	34,9 kN/mm	a	thick end
2	138,69 kN	15,94 mm	± 54 kN	36,7 kN/mm	a	thick end
3	137,37 kN	14,81 mm	± 54 kN	37,3 kN/mm	a	thick end
Sample mean	136,41 kN	15,21 mm	51,3 kN	36,3 kN/mm		
Standard deviation	2,89 kN	0,63 mm	4,6 kN	1,3 kN/mm		
B-I-						
1	135,06 kN	13,63 mm	± 41 kN	57,9 kN/mm	a	thin end
2	136,70 kN	13,26 mm	± 36 kN	73,5 kN/mm	a	thin end
3	138,38 kN	13,94 mm	± 49 kN	42,5 kN/mm	b	thin end
Sample mean	136,72 kN	13,61 mm	42,0 kN	58,0 kN/mm		
Standard deviation	1,66 kN	0,34 mm	6,6 kN	15,5 kN/mm		
B-II-						
1	134,89 kN	14,28 mm	± 40 kN	38,3 kN/mm	b	thick end
2	139,60 kN	14,99 mm	± 36 kN	39,9 kN/mm	a	thick end
3	138,09 kN	13,37 mm	± 36 kN	48,7 kN/mm	b	thick end
Sample mean	137,53 kN	14,21 mm	37,3 kN	42,3 kN/mm		
Standard deviation	2,41 kN	0,81 mm	2,3 kN	5,6 kN/mm		
Overall						
Sample mean	135,77 kN	13,98 mm	45,0 kN	47,3 kN/mm		
Standard deviation	3,59 kN	1,14 mm	7,5 kN	12,1 kN/mm		

* a: top female connector in test bench
b: bottom female connector in test bench

** No data avaliable

The load at maximum elastic deformation is influenced by the boundary conditions in the test bench (Table 5). The clamped specimens show a mean elastic load limit of 39.7 kN, which is approximately 12 kN lower than the hinged specimens which show a mean elastic load limit of 51.4 kN. This can be explained by the additional stresses in the fixed connections resulting from the prevention of rotations, leading to a lower limit for elastic loading.
The elastic connection stiffness is dependent on the way the pins are secured. The stiffness using cotters is 56.9 kN/mm, which is considerably higher than the stiffness using nuts which is 39.3 kN/mm (Table 6).

The first important test result is the limited load for elastic deformations. However, this load should be considered in serviceability limit state, as it is not related to structural failure, but to a proper assembly and disassembly of the connections. The gap between elastic load and failure load is rather large, which means that structural failure will probably not determine the connection strength in practice.
The second important test result is the fixation of the connection having a negative effect on the maximum elastic load. In practice the female connector is always fixed to the main tube of the truss, and this fixation may be even more rigid, and thus lead to an actual maximum elastic load even lower than demonstrated in this research.
Finally it may be concluded that the deformation of the conical pins contributes most to the overall deformation of the connection. Both the measurements of the rotation of the pin ends and the strain gauges confirm this statement. To increase the elastic failure load, the flexural stiffness of the pin needs to be increased. This can be done by using a material with a modulus of elasticity higher than 210 000 N/mm^2. It is also possible to increase the moment of inertia, for example by changing the shape of the pins or by increasing the cross-sectional area of the pins.

7 Summary and conclusions

Pinned element connections in aluminium trusses are investigated experimentally [2]. Forces in the connections are transferred through shear and bearing. Because the inner cylinder and the securing pins are conical, there is no play in the connection when it is assembled. Securing the pins with cotters allows for fast assembly and disassembly. In practice also nuts are used for securing the pins. The parameters investigated in the research are the boundary conditions (hinged or fixed in clamps of the test bench) and the way the pins are secured (with cotters or with nuts). The mean maximum load at structural failure is not influenced by the parameters investigated; structural failure was induced by cracking of a welding centerpoint. The maximum elongation at structural failure is

Table 5. Maximum elongation of series I and series II

Δl_{max}	Series I	Series II
	**	14,90 mm
	12,31 mm	15,94 mm
	12,32 mm	14,81 mm
	13,63 mm	14,28 mm
	13,26 mm	14,99 mm
	13,94 mm	13,37 mm
Sample mean	13,09 mm	14,71 mm
Standard deviation	0,75 mm	0,85 mm

** No test results available

Table 6. Maximum force for elastic deformation, series A and series B

F_{el}	Series A	Series B
	**	± 41 kN
	± 49 kN	± 36 kN
	± 54 kN	± 49 kN
	± 46 kN	± 40 kN
	± 54 kN	± 36 kN
	± 54 kN	± 36 kN
Sample mean	51,40 kN	39,67 kN
Standard deviation	3,71 kN	5,09 kN

** No test results available

Table 7. Stiffness for elastic deformations, series I and series II

'Stiffness'	Series I	Series II
	**	34,9 kN/mm
	53,2 kN/mm	36,7 kN/mm
	57,4 kN/mm	37,3 kN/mm
	57,9 kN/mm	38,3 kN/mm
	73,5 kN/mm	39,9 kN/mm
	42,5 kN/mm	48,7 kN/mm
Sample mean	56,9 kN/mm	39,3 kN/mm
Standard deviation	11,2 kN/mm	4,9 kN/mm

** No test results available

influenced by the way the pins are secured: the use of nuts results in more elongation than the use of cotters.

The load at maximum elastic deformation is influenced by the boundary conditions in the test bench: clamped specimens show a lower elastic load limit than the hinged specimens. In practice the connection is more rigid than the boundary conditions in the testing arrangement. This will lead to a lower elastic load limit than the experimental results. The elastic connection stiffness is dependent on the way the pins are secured. The stiffness using cotters is considerably higher than the stiffness using nuts. To increase the elastic load limit the flexural stiffness of the pin needs to be increased.

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