FINITE ELEMENT ANALYSIS OF LAP JOINTS
in Steel Tubular Towers

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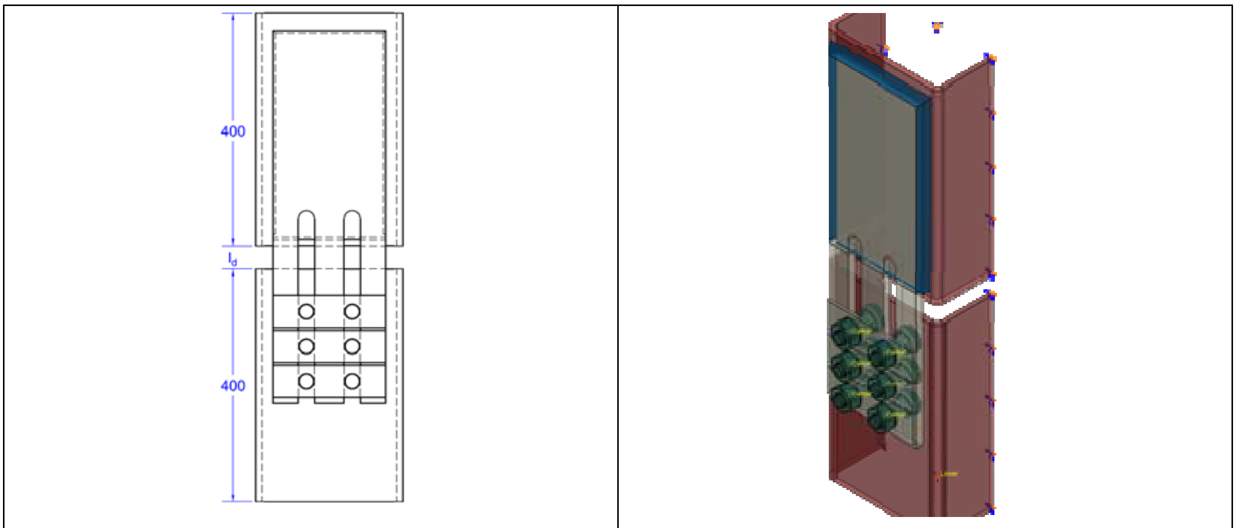
KEYWORDS: Friction connection, Finite element analysis, Loss of pretension, Long open slotted hole, Finger plate buckling.

ABSTRACT

For the connection of segments in tubular steel towers, some recently published literature promotes the use of friction connections as shown in Fig. 1 instead of the common flange connections [1]. Such friction connections consist of normal clearance holes with preinstalled bolts in one segment and long open slotted holes in the other segment. To facilitate assembly, the two segments differ in diameter. This allows for a certain deformability of the connection. The resistance of such a friction connection can simply follow the design rules of the European Standard EN1993-1-8 for friction connections with pretensioned bolts [2]. To investigate the behavior of the so called “fingers”, as which the steel plates between the long open slotted holes are designated, the following tests are going to be conducted: Two quadratic hollow sections of steel grade S355 will be connected with long open friction connections with 6 M24 bolts of grade 10.9 on two of their four sides, varying in distance l_d between the QHS 250x250x10, compare Fig. 1.



a) Front view with dimensions   b) 3-dimensional view modelled in FEA

Fig. 1. Test specimen for finger length tests at LTU

The finger plates are welded to the QHS-profiles with an additional filler plate underneath. This filler plate shall ensure a gap of 4 mm on each side of the column between the fingers and the lower column to which the fingers will be attached. These gaps represent the difference in diameter in the wind tower application and facilitate the assembling process. The tests will be performed in two steps: Firstly, tightening the bolts and secondly loading the specimen in compression until failure. The specimens will have a length l_d of 40 mm, 60 mm or 80 mm.

To predict the outcome of the tests a finite element model has been built up with the commercial software Abaqus, using the Explicit dynamic solver [5]. Taking advantage of symmetry conditions, only one half of the specimen, see Fig. 1 b), is modelled in order to save computing time [6].

To achieve a most realistic model, bolts and nuts are modeled in a very detailed way, showing even the threads. This allows for a pretensioning of the bolts by tightening the nuts, which is a finite element method developed by Pavlović et al. [7].

CONCLUSIONS

From the above described finite element analysis including the parameter study of various distances l_d the following conclusions can be drawn:

1. Using the turn-of-the-nut-method in the FEA allows for taking into account the group effect during tightening of the bolts.
2. None of the specimens reaches its plastic resistance.
3. All specimens fail due to buckling of the middle finger.
4. Slenderness of the fingers does not dramatically influence the buckling behavior of the modeled specimens.
5. Only half of the system is modeled taking into account vertical symmetry conditions, which possibly raise the buckling resistance as they prevent buckling in the sides of the QHS-profiles without finger plates.
6. When the results from the laboratory experiments are available, the above described finite element models will be validated accordingly so that further studies with even more realistic results can be achieved. Additionally, the results from this study will be compared to results from hand calculation models.

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INTRODUCTION

For the connection of segments in tubular steel towers, some recently published literature promotes the use of friction connections as shown in Fig. 1 instead of the common flange connections [1]. As major drawbacks of the common flange connections, the low fatigue resistance and complex design are listed as well as time consuming production, assembling at the construction site and laborious maintenance.
All this shall be eliminated by the use of friction connections, which consist of normal clearance holes with preinstalled bolts in one segment and long open slotted holes in the other segment. To facilitate assembly, the two segments differ in diameter. This allows for a certain deformability of the connection.

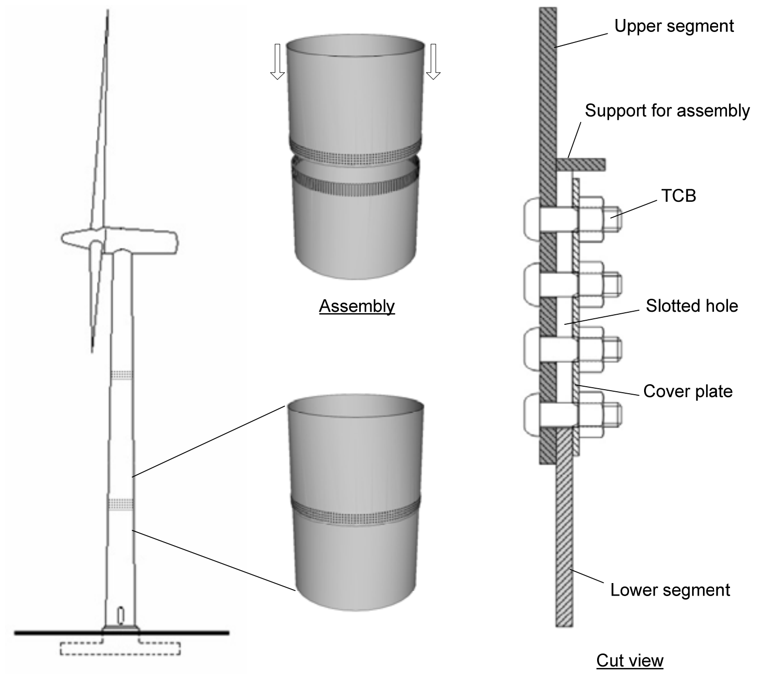


Fig. 1. Concept of a friction connection in tubular towers for wind turbines [1]

The resistance of such a friction connection can simply follow the design rules of the European Standard EN1993-1-8 for friction connections with pretensioned bolts [2]:

$$F_{s,Rd} = \frac{k_s \cdot n \cdot \mu}{\gamma_{M3}} \cdot F_{p,C} \qquad (1)$$

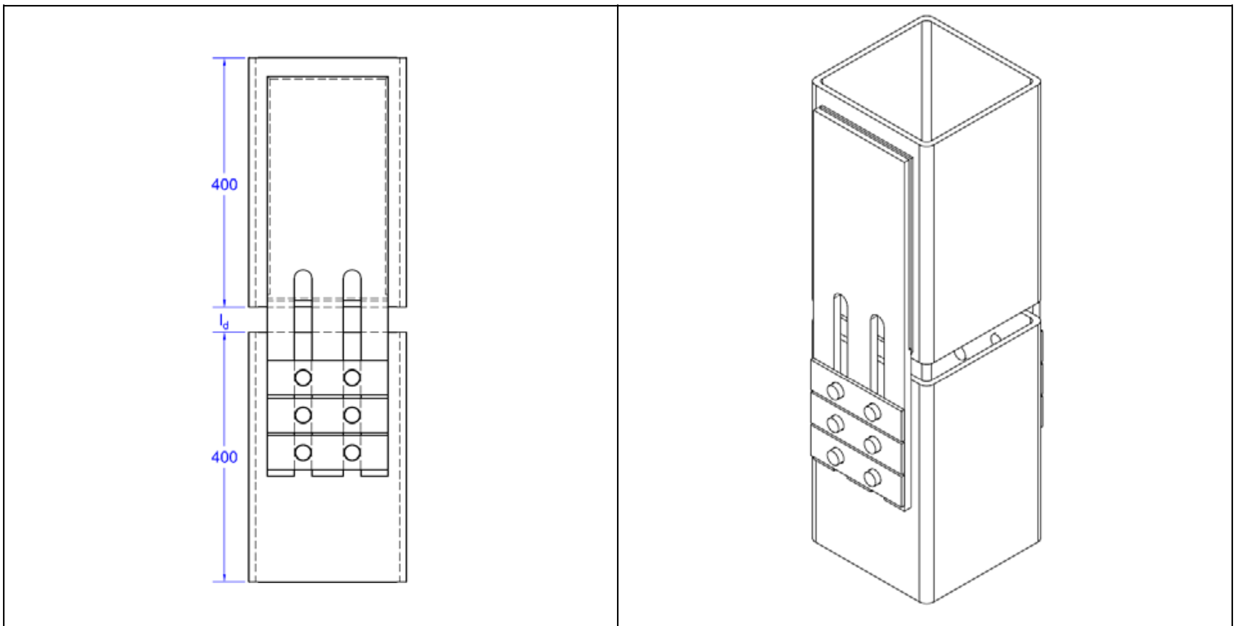
where k_s is a coefficient taking into account the type of hole
n is the number of friction surfaces

μ is the slip factor
γ_{M3} is the partial coefficient
$F_{p,C}$ is the preloading force.

That this concept works well has been proven in various tests [3] [4]. However, geometrical details of the segment part with long open slotted holes are not fully ascertained yet. Therefore, a finite element analysis has been carried out and experimental tests are planned to be undertaken at Luleå University of Technology during spring 2014.

1 TESTING PROGRAMME

To investigate the behavior of the so called "fingers", as which the steel plates between the long open slotted holes are designated, a test series consisting of 6 single tests is planned. Two quadratic hollow sections of steel grade S355 will be connected with long open friction connections with 6 M24 bolts of grade 10.9 on two of their four sides, varying in distance l_d between the QHS 250x250x10, compare Fig. 2. Instead of normal washers cover plates will be used. This does not only accelerate the assembling process but also distributes the pretension forces of the bolts equally within the friction connection.



a) Front view with dimensions b) 3-dimensional view

Fig. 2. Test specimen for finger length tests at LTU

The finger plates are welded to the QHS-profiles with an additional filler plate underneath. This filler plate shall ensure a gap of 4 mm on each side of the column between the fingers and the lower column to which the fingers will be attached. These gaps represent the difference in diameter in the wind tower application and facilitate the assembling process.

The tests will be performed in two steps: Firstly, tightening the bolts and secondly loading the specimen in compression until failure. All the time deformation of the fingers and pretension forces in the bolts will be monitored. Due to the tightening of the bolts the gap between finger plate and lower column will be closed. This leads to an eccentricity, which has to be taken into account for the analysis of the finger buckling.

The three specimens will have a length l_d of 40 mm, 60 mm or 80 mm. Of all three tests one replicate will be performed to improve the reliability of the results.

2 FINITE ELEMENT ANALYSIS

To predict the outcome of the tests a finite element model has been built up with the commercial software Abaqus, using the Explicit dynamic solver [5]. Taking advantage of symmetry conditions, only one half of the specimen, see Fig. 3, is modelled in order to save computing time [6].

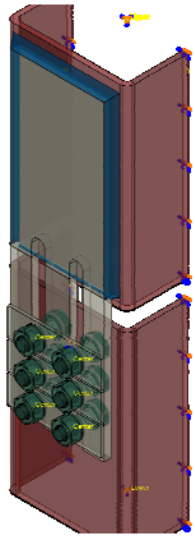


Fig. 3. Finite element model [6]

To achieve a most realistic model, bolts and nuts are modeled in a very detailed way, showing even the threads. This allows for a pretensioning of the bolts by tightening the nuts, which is a finite element method developed by Pavlović et al. [7]. The analysis itself is divided into 3 steps: First, the holes in the lower profile are tightened. This shall resemble the fact that bolts and hole clearance actually have the same diameter to prevent the bolts in the real tests from falling out. Then the bolts are tightened one after the other and finally a compression force is applied on top of the specimen.

3 RESULTS

The analysis has been performed for not only the distances l_d = 40 mm, 60 mm and 80 mm which are planned for the tests, but also for lengths l_d = 100 mm and 120 mm to see if longer fingers have a different influence on the compression resistance than shorter ones.
Due to the fact that the bolts have not been tightened simultaneously but one after the other, the pretension force in the bolts differs from bolt to bolt. By this the so called group effect, which has been observed in previous tests at Luleå University of Technology, is taken into account [8], [9]. This also leads to the result that the system does not fail “perfectly”, which would be buckling of the middle finger with the longest buckling length first followed by a simultaneous failure of the two outer fingers. However, here the two outer fingers fail one after the other, which is more realistic.
Fig. 4 shows the final buckling failure of specimen 4 with a distance l_d = 40 mm between the two QHS-profiles. Here, all the three fingers have buckled and the differences in buckling length of the fingers are clearly visible.

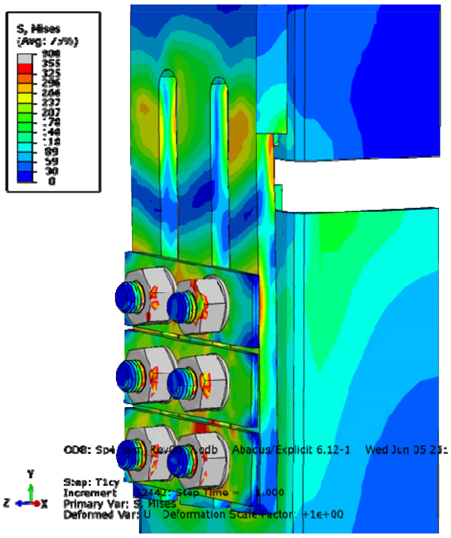


Fig. 4. Buckling failure in Specimen 4 with l_d = 40 mm [6]

3.1 Cross-section resistance

According to EN1993-1-1, the plastic capacity of the finger plates is 1448 kN [10]. None of the modeled specimens has reached this capacity, see Table 1.

Table 1. Ultimate failure loads per specimen

	Specimen 4	Specimen 5	Specimen 6	Specimen 7	Specimen 8
l_d [mm]	40	60	80	100	120
F_{pl} [kN]	1448	1448	1448	1448	1448
F_{max} [kN]	1428,2	1411,6	1375,6	1342,9	1366,4

The maximum failure load is characterized by buckling of the middle finger. When this took place, the strength of the specimens reduces creepingly until the two outer fingers buckle.

As these specimens are modeled with vertical symmetry boundary conditions, it might be possible that this raises the buckling resistance.

3.2 Comparison of various finger lengths

In Fig. 5 the load displacement curves for all modeled cases can be seen. As expected, more slender specimens fail earlier. Although the specimens fail in an anticipated way, the slenderness does not influence the final resistance considerably. The maximum applied load for all the specimens reaches a value of about 1350 to 1430 kN and a final vertical displacement of about 1,5 mm.

In the beginning, the load-displacement curves show a linear behaviour until a load of ca. 600 kN. Then they become slightly non-linear until a load of about 1200 kN, when the grade of non-linearity rises and buckling of the middle finger starts.

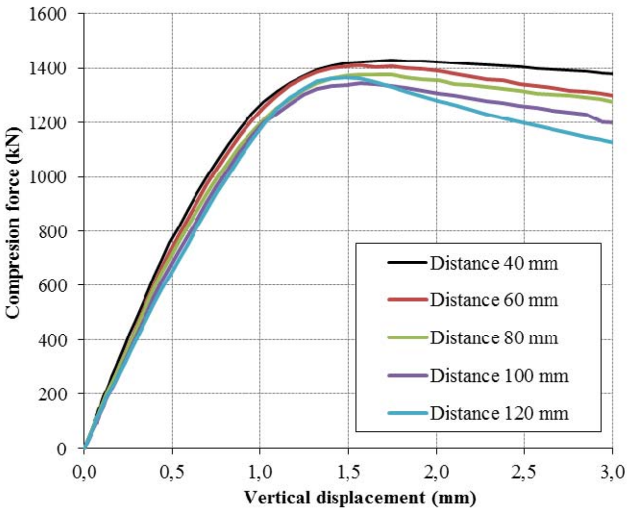


Fig. 5. Load-displacement curves depending on distance between upper and lower QHS profiles

3.3 Bolt pretension force

In these specimens M24 bolts of grade 10.9 are modeled, which each provide a pretension force of $F_{p,C} = 250$ kN according to EN 1993-1-8 [2]. The tightening of one bolt equals one step of the analysis, starting from the top row. Each bolt is tightened by turning the nut until the gap between finger plate and lower QHS-profile is closed and $F_{p,C}$ is reached. Due to pretensioning of the following bolt, the before tightened bolts loses some of its pretension force. Table 2 shows exemplarily the total losses after tightening of all bolts for specimen 4 with l_d = 40 mm. Here, A1 designates the uppermost bolt to the left and C2 the lowermost bolt to the right in the front view of Fig. 3.

Table 2. Ultimate failure loads per specimen [6]

Preloading of bolt	Bolt force (kN)					
	A1	A2	B1	B2	C1	C2
A1	245,4					
A2	231,5	265,0				
B1	215,6	248,8	251,7			
B2	215,4	244,4	235,4	254,1		
C1	214,2	243,0	220,2	238,5	236,8	
C2	213,6	241,9	221,2	233,2	223,5	260,8
Total loss (%)	12.96	8.72	12.12	8.23	5.62	0.00

Recalculating the final pretension loads in each bolt into percentages of their initial preloading forces, shows that for rows A and B the losses are of about the same range when bolt row C is tightened. From this, one might expect that for longer connections with more bolt rows the final losses will be the same.

It should be noted that in this finite element analysis, effects of primer and other surface finishing are not taken into account. In the model, the friction coefficient is set to 0,45 for all surface pairs besides bolt and nut, where a friction coefficient of 0,14 is considered.

4 CONCLUSIONS

From the above described finite element analysis including the parameter study of various distances l_d the following conclusions can be drawn:

1. Using the turn-of-the-nut-method in the FEA allows for taking into account the group effect during tightening of the bolts.
2. None of the specimens reaches its plastic resistance.
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5 ACKNOWLEDGMENTS

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