BEHAVIOUR OF A FRICTION CONNECTION USING TCB IN LONG SLOTTED HOLES

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Abstract

With constantly increasing demand for renewable energies the cost optimization of steel towers supporting multi-mega-watt wind turbines becomes important. Luleå University of Technology currently coordinate European research project (RFCS), including partners from 5 countries, which aim is to ensure the high competitiveness of the next generation of steel towers produced in Europe.
One innovation investigated within this project is the use of friction grip connection with long slotted holes to connect the steel tower sections. This paper presents a part of ongoing experimental program and result of three segment tests performed with weathering steel plates and M20 Tension Control Bolts. Experimental results are compared to the prediction according to European structural code EN 1993-1-8 Furthermore a three dimensional numerical model was used to describe behaviour of the connection with a long slotted hole together and a thick cover plate
FE-analysis of the preliminary experiments was used to endorse conclusions from the experiments.

Keywords: bolted connection, friction connection, weathering steel, slotted hole, Tension Control Bolt.

1. Introduction

Results presented here are part of the on-going RFCS (Research Fund for Coal and Steel), HISTWIN, where partners from 5 countries working on various topics. The partners are:

- Luleå University of Technology, Sweden,
- Rheinisch-Westfälische Technische Hochschule Aachen, Germany
- Germanischer Lloyd WindEnergie (GL-Wind), St
- Aristotle University of Thessaloniki (AUTH)- Greece
- Repower Portugal Equipamentos Eólicos SA, Portugal
- University of Coimbra, Portugal
- Ruukki, Finland

Experimental and numerical study of a non-standardized High Strength Friction Grip connection presented here is a part of the authors' contribution to the project.

Towers for wind turbines are most frequently made of tubular sections assembled by ring-flanges placed on the inner side of tube tower. Design of the tower is governed by rather low fatigue resistance of the connection that imposes limit on stresses in the tube and impairs the efficiency of the whole structure. High Strength Friction Grip connection with long slotted hole is expected to have better fatigue performance and thus improve competitiveness of the towers.

2. Innovative Friction Connections for Wind towers

High Strength Friction Grip connections are not so prone to fatigue issues as the flange–ring connection is. They have higher stiffness [1] and good energy dissipation properties [2]. Their implementation in towers, using Tension Control Bolts (TCB) probably leads that design of shell resistance become governing.

For the easier execution of a tube tower, the use of open slotted holes on one plate instead of the normal holes, and using fasteners tightened from the inside of the tower further improved efficiency of the tower.

The performances of such connection are assessed in the paper analysing the preliminary test results of three specimens with weathering steel plates and M20 TCB. A due attention is paid to special installation requirements which follow implementation of TCB. The main idea of the assembling using TCB is showed in **Error! Reference source not found.**. The scale and number of bolts are altered from the real case situation in the towers for wind turbines for the sake of clarity. The open slotted holes are used for the lower tower section instead of the normal clearance holes. The fasteners are safely pre-installed in the normal clearance holes of the upper tube section. The latter is then lifted and slide down in the position and than TCB (or Huck Bolts) can be tightened from the tower's inside.

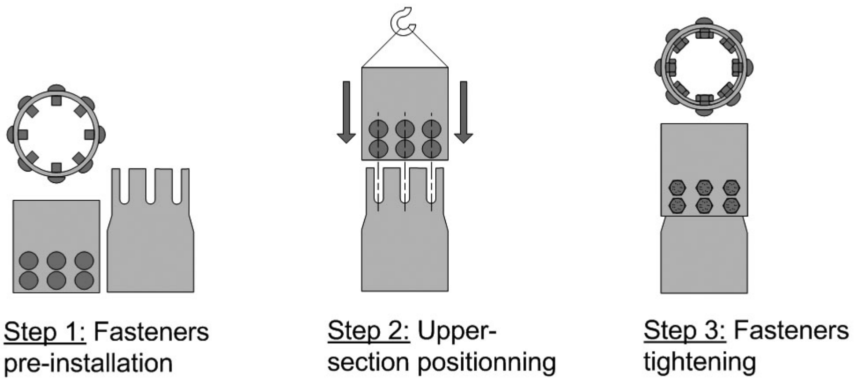

Fig. 1. Innovative High Strength Friction Grip connection – Principle of assembling

One of the HISTWIN project objectives is to evaluate feasibility and performances of the innovative connection presented above. An extensive series of tests is planned. Static segment tests will be performed to investigate the effects of plate thickness, material and surface properties (weathering steel with and without oxidation coating, zinc coated carbon steel) as well as fastener type (Hexagonal bolts and Tension Control Bolts of different sizes). Due attention will be given to a shape of the group and length of the slotted holes. Additionally the effects of the creep and fatigue will be investigated within the project.

The experimental results will be carefully evaluated and interpreted using Finite Element simulations. The calibrated model will be further used to perform parametric studies and develop engineering models for design purposes.

Finally, a full scale feasibility test of the tower will be performed to assess the installation process and determine required tolerances and detailing.

3. Testing programme

Results of three preliminary tests that foresee the extensive series to come are show here.

3.1 Specimens

The tensile tests were performed on specimens which configuration and dimensions are shown in Fig. 1. The connected plates had a thickness of 8mm and were made of weathering steel COR-TEN B of grade S355 produced by Ruukki.

To achieve a surface quality of class A according to EN1090 [3], the plates were grit-blasted with steel grit of size G70 to a quality Sa2.5 (according to Swedish Visual Standard) i.e. near white metal. All dust was removed and the plates cleaned with acetone. The plates were assembled shortly afterwards therefore no rust was present. The surfaces were very rough to the touch.

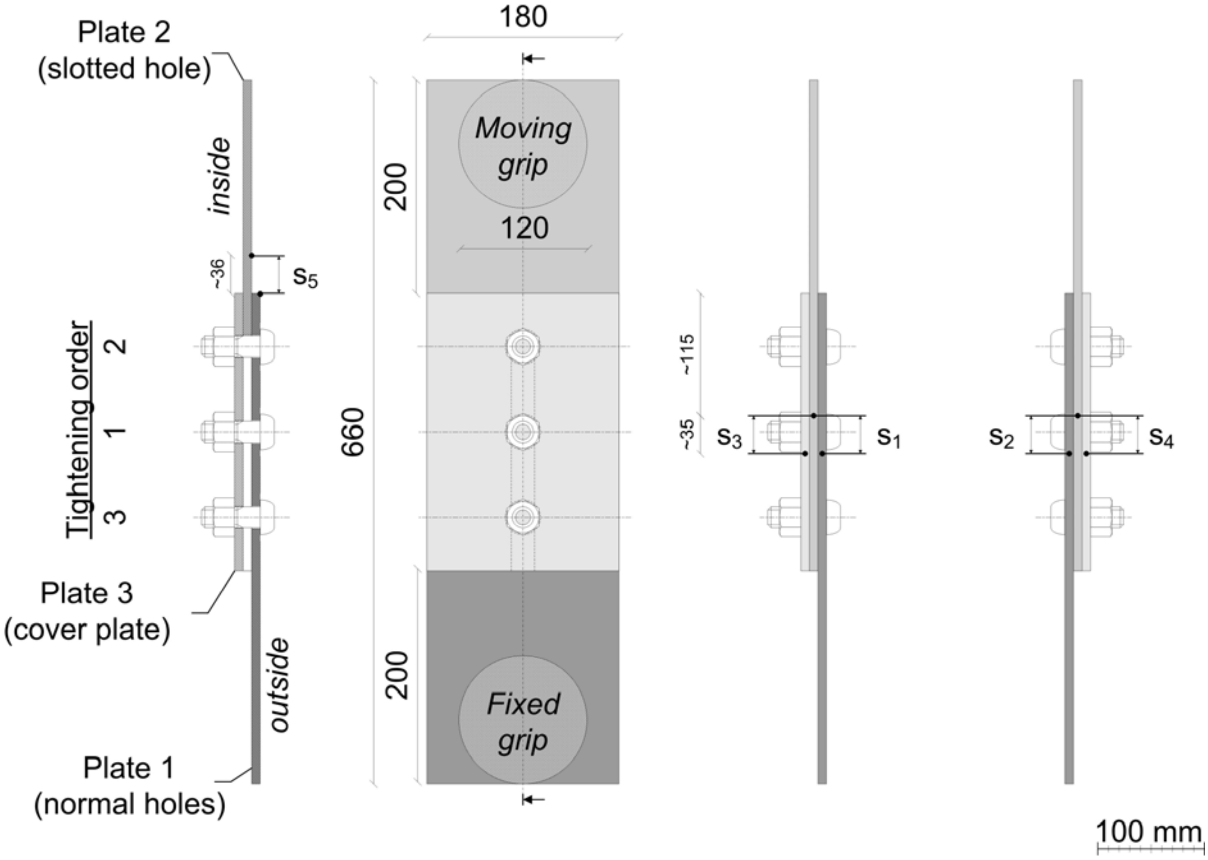

Fig. 1. Specimen dimensions

The clamping force was provided by a row of three M20 TCBs of grade S10T (equivalent to grade 10.9 [4]) produced by TCB Limited in England (Fig. 2). These fasteners are a special type of high strength, high ductility, friction grip bolts initially developed in Japan. They are particularly interesting for this application since their tightening process is carried out entirely at the nut end. For this purpose a special wrench is used which inner socket holds the spline while the nut is turned by an outer socket. By reaction the tightening torque is applied to the spline which shears off at the calibrated break neck when a sufficient level of pretension is reached.

The bolts were mounted in normal clearance holes 22mm diameter on the side of the bolt head and in the long and open slotted holes of the same size in the load direction on the nut side. According to the producer's installation instruction, no washer was used under the head. A single cover plate replaced the usual washers under the nuts is used in order to have a more uniformly distributed contact. Since the friction between nut and washer has a significant impact on the tightening torque the cover plate material was chosen so it provides similar contact properties. Hardened steel Raex400 produced by Ruukki has hardness of HBW 360-420, equivalent to that of the standard washers, H_RC 35-45. The holes had a diameter of 21mm. The installation guide recommends smearing the nut face with tallow to reduce friction. In default, lithium based molybdenum grease (Castrol MS3) was used. The thread was not lubricated.

Tightening occurred in following order: central bolt and than the bottom and top bolt, (Fig. 1). In the contrary to recommendations, the fasteners were not snug tightened first but fully preloaded at once. Consequences of this procedure are discussed later. After pretensioning, the specimens were left overnight before testing to allow approximately 12 hours for relaxation of the bolts.

3.2 Measurements

The applied tensile load was monitored by the testing machine load cell and a displacement of the hydraulic pistons was recorded as a measure of the total elongation.

The bolt forces were continuously measured after the tightening and throughout testing in order to have complete control of the existing level of pretension, load relaxation and variation and distribution of the clamping forces during traction of the specimens. For this purpose strain gages BTM-6C supplied by TML were installed in the shafts to monitor existing level of the axial strains. They were glued at a depth of about 28,5mm (gage centre) below the head in 2mm-diameter holes about 35mm deep (Fig. 2). Tensile tests were carried on a series of five bolts in order to calibrate the gages. Bolts were loaded in a loading cycle from 0 to 50kN and back, at the linear rate of 0.5kN/s. The behaviour was found to be linear with an average slope of 54.3N/µm/m for loads above 10kN. It can be expected that this behaviour will continue at higher loads and the coefficient of variation was very low, about 0.9%, specially in comparison to the uncertainty of the gage which is ±1%. Therefore the average slope was used as calibration coefficient for all bolts delivered in the same batch.

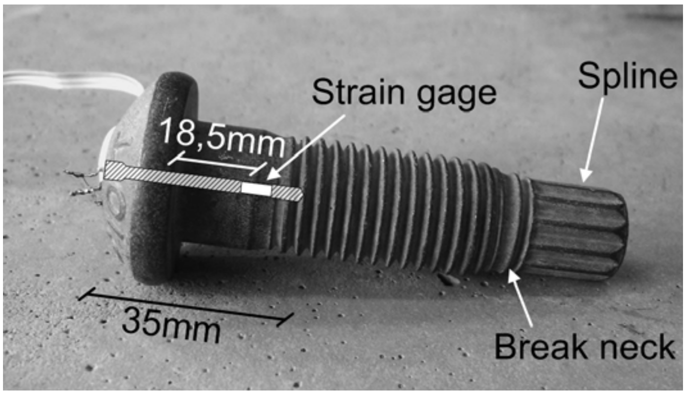

Fig. 2. Tension Control Bolt (TCB)

Relative displacements were measured with linear transducers to monitor the slip, at five different locations (Fig. 1). The slip s_1, s_2 and s_5, were between the plate 1 and plate 2, and the slip s_3 and s_4 were between the plate 1 and plate 3. Measures of s_1 and s_2, and of s_3 and s_4 were then averaged to reduced influence a possible rotation of the specimen. The transducers were calibrated for strokes up to 4mm with an accuracy of 50µm.

The specimens were maintained by the hydraulic grips of the tensile test machine and pulled with stroke control at the constant rate of 5µm/s. The measurement frequency was 5Hz.

4. Experimental Results

4.1 Bolt Forces

The average bolt pretension, 10s after pretensioning, was 194,2kN with a rather low variation coefficient, 2.7%.

However, as already mentioned, the fasteners were fully preloaded at once and not snug tightened first. This mishap lead to bolt forces not as homogeneously distributed as they could have been. Indeed when a new bolt is tightened the additional clamping force slightly reduces the reaction of the plates on the already tightened bolts thus reducing their pretension. The phenomenon is greatest at the central bolt which pretension decreases in average by about 4,4%.

The pretension loss between 10s and 12hrs after tightening is less than 9% for the central bolts and 4% for the outer bolts, and all had a pretension higher than required by Eurocode 3 [5]. Taking only the outer bolts into consideration the design force according to [6] becomes 177,8kN which is more than 3% higher than the design force of Eurocode 3 Part 1-8 [5].

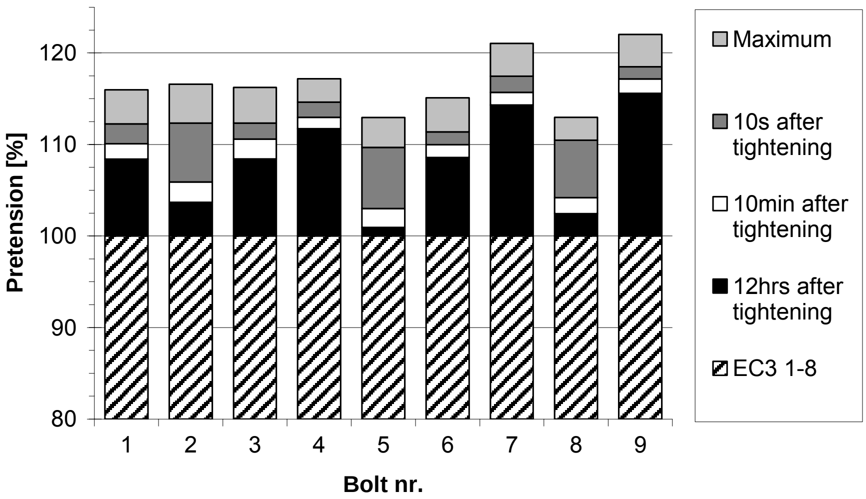

Fig. 3. Bolts Pretensions

4.2 Connection Behaviour in Tension

Results from one specimen are discussed in the paper, as shown in Fig. 4 and Fig. 5, which are representative to all performed tests.

Although the specimen behaviour is first linear the load displacement curve shows some nonlinearity before the slip load (1) is reached. The linear relative slip is very small (microslip) due to local deformations of the plates at location where the contact pressure is low. The tensile load is still transferred by friction between the plates up to the ultimate load (2) where friction is overcome and the two plates show the relative slip (macroslip). The drop in the transferred load can be explained by a lower cinematic friction coefficient and a small lost of the clamping force due to the abrupt introduction of bending in the bolts. The cover plate (Plate 3) is attached to the Plate 2 which indicates that the friction under the nuts is lower than that with the underlying plate. This is reasonable since the nuts were greased prior to tightening. Macroslip then proceeds until the clearance between holes in the cover plate and bolt shafts is closed and accordingly the bearing occurs (3) which leads to an increase in the tensile load since the Plate 1 additionally has to overcome the friction with the cover plate that is now maintained by the bolts which heads “stick” on the fixed plate. The consequent increase in bolt bending leads to a faster decrease of the axial force of the outer bolts. The load then drops slightly when the static friction under the bolts heads is overcome. Now the bolt heads slip relatively to the fixed plate until the shafts are fully bearing (5).

The test is designed so the failure mode of the connection was ductile (Fig. 4). The friction between the bolt heads and nuts is low enough so that the transmitted shear force becomes too small to produce bearing or shear failure. The maximum load drop of about 20% may be principally due to change from static to cinematic friction already noticeable at low velocity [7].

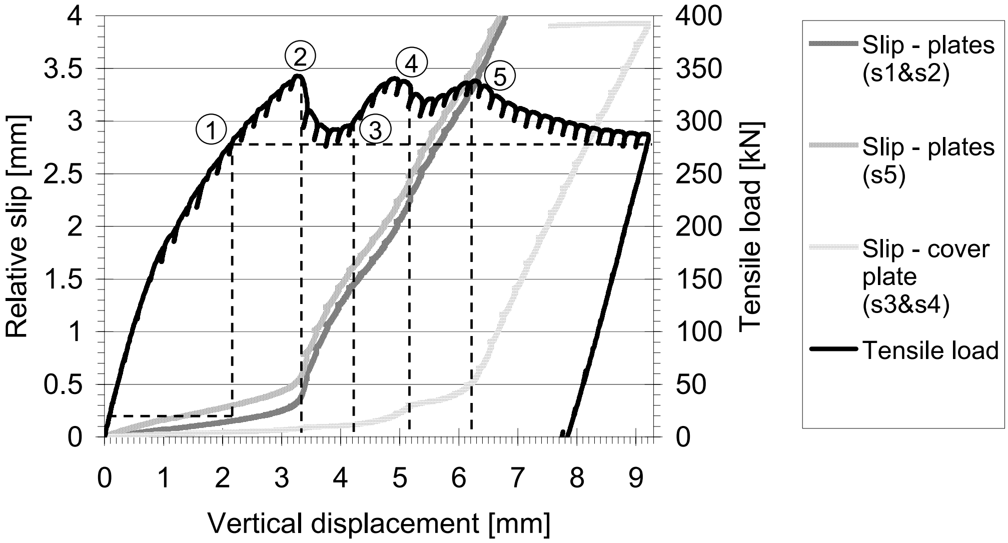

Fig. 4. Slip behaviour

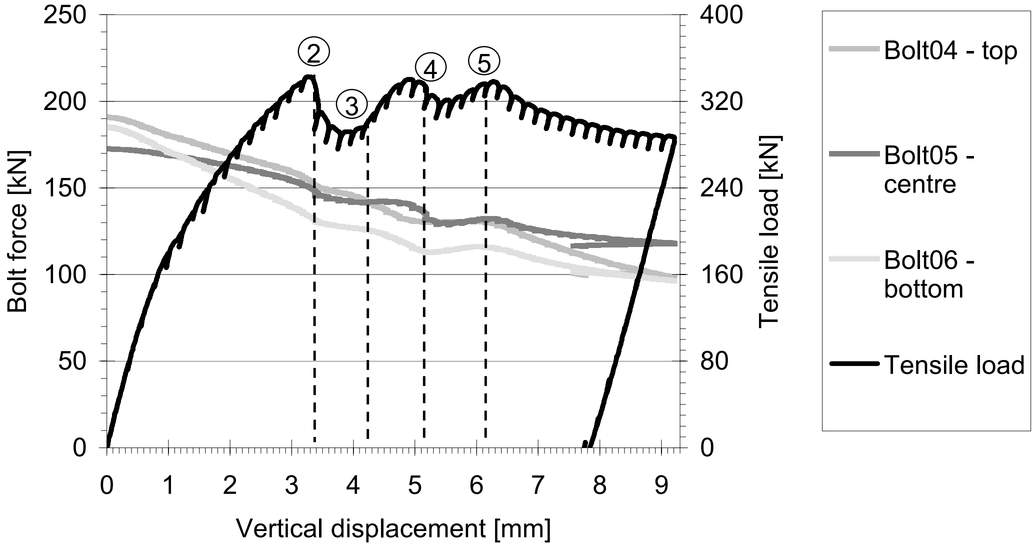

Fig. 5. Bolt Forces behaviour

4.3 Connection Resistance

The failure load of friction connections is most often taken as the ultimate load which is acceptable considering that the failure is ductile. In that case, the average resistance of the three specimens is 344,1kN.

The failure load may also be taken as a load at the certain slip, for example, the load at slip of 0,15mm, according to [3]. The average resistance is then lower by about 16% but ensures safer design preventing the macroslip. However, the numerical value given here shall be considered with care since measurement errors due to the transducers accuracy being about 0,05mm may significantly flaw the determination of the slip load.

According to Eurocode 3 Part 1-8 [5], for friction surfaces of class A (μ=0,5) and pretension of 70% the bolts ultimate load, the characteristic resistance is only 162,1kN, less than 50% of the experimental ultimate load. It then appears that the friction coefficient allowed for surfaces of class A is not satisfying when designing with weathering steel. Indeed its friction coefficient is already reported, higher than 0,5 [8]. Even if more realistic friction coefficients as well as the actual bolt forces are used, the resistance is too conservative what indicates that the additional reduction factor for long slotted holes oriented in load transfer direction may be excessively low. This assumption is subject to a numerical investigation presented further.

5. Finite Element Analysis

5.1 Model Description

Due to the symmetry of the set-up, only one half of the specimen is modelled with three dimensional solid elements (Abaqus 3D8R). The material has Young's modulus of 200GPa and Poisson coefficient of 0,3. Bolts and cover plate are elastic whereas the connected plates have a yield stress of 355MPa.

By default the interaction at the interface between parts in contact is solved by a pure master/slave algorithm, i.e. the nodes on one surface (slave) cannot penetrate the segments that make up the other surface (master). The default "Hard" contact formulation where a pressure is transmitted only when the elements are in contact was used wherever solutions were easily obtained. However at some interfaces numerical problems were overcome with a "soft" contact formulation where the contact-pressure/clearance relationship was taken as exponential with a maximum pressure of 250Mpa at contact and zero pressure at 0,05mm clearance.

Simple Coulomb friction models were used at all contacts. The friction coefficients are reported in Table 1. Additionally distinction was made between interfaces where relative sliding may occur and where it was not expected. In the former case a finite sliding formulation was used (contact pairs are redefined at each increment) and in the latter a small sliding formulation (contact pairs are defined only once).

Master surface	Slave surface	Contact formulation	Friction formulation	Friction coefficient
Bolt head	Upper plate (normal holes)	“hard”	Small sliding	0,3
Nut face	Cover plate	“hard”	Finite sliding	0,2
Cover plate	Lower plate (slotted hole)	“soft” (exponential)	Finite sliding	0,5
Lower plate (slotted hole)	Upper plate (normal holes)	“soft” (exponential)	Finite sliding	0,68

Table 1. Contact definitions

The simulation is divided in two steps;

1. The bolts are preloaded by defining an internal section of the shank and applying compressive strains to the underlying layer of elements. This induces tensile stresses in the other shank sections, and, maintaining the initial strains throughout further steps, the bolt force can vary with external solicitations thus realistically modelling the fastener behaviour.
2. A vertical displacement of the lower plate is applied.

5.2 Comparison between experimental and numerical results

A good agreement between the load-slip curves (Fig. 6) was obtained with initial bolt forces corresponding to the measurements of specimen 2 and a friction coefficient 0,68 suggested by the experimental results, see [8].

Calculated slip load and ultimate load fitted within 4% of the experimental results.

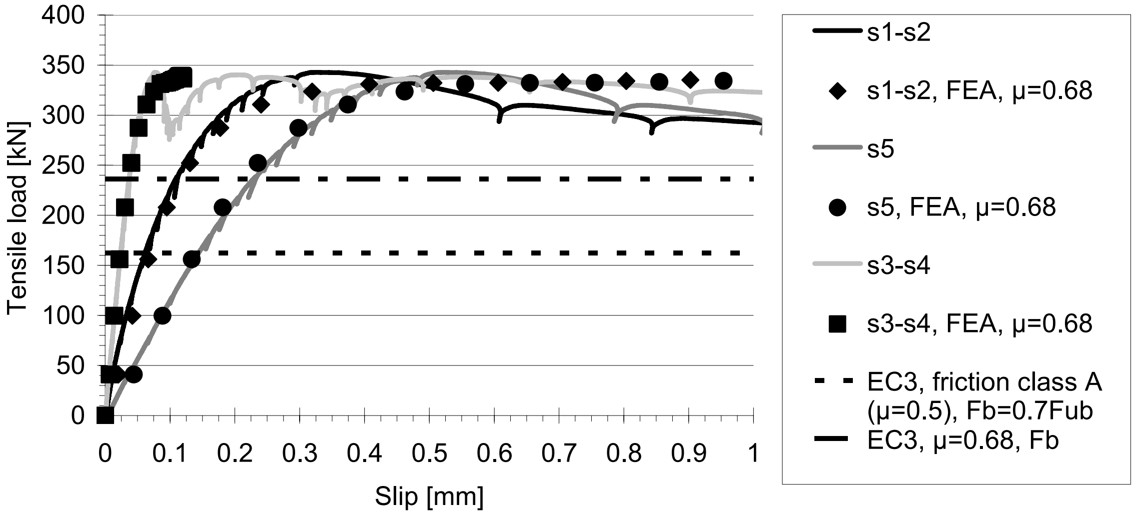

Fig. 6. Load-slip behaviour – comparison with FEA

However the pretension loss in the numerical simulation was faster and more important (ultimately up to 14% for the lower bolt). Reasons for this discrepancy shall be investigated and particular attention given to the influence of the initial position of the plates. Indeed the physical specimens were assembled with the plates pushed towards each other whereas the holes of the numerical model were strictly coincident. The normal contact formulation may also be refined in further models what was unfortunately not possible within the scope of this study.

5.3 Cover Plate

The examination of the contact pressure distribution between cover plate and slotted plates indicates that the latter is efficiently distributing the load in the axis of the whole. In the perpendicular direction however the contact pressure is negligible at distance greater than 25mm from the axis. To connect 8mm-thick plates with M20 bolts it is therefore recommended to use a 50mm-wide cover plate 60mm longer than the holes interval.

5.4 Effects of Long Slotted Hole

The same modelling technique was applied to a specimen with normal holes where the cover plate was then replaced by standard washers (diameter: 37mm, thickness: 4mm) as part of the bolt nuts. The initial pretension was set to the measured average of 185,6kN for all bolts.

The connection with normal holes sustained a higher ultimate load together with a higher stiffness and thus a better slip load (Fig. 7). The contact properties being identical the variation in behaviour is directly related to the bolt force behaviour.

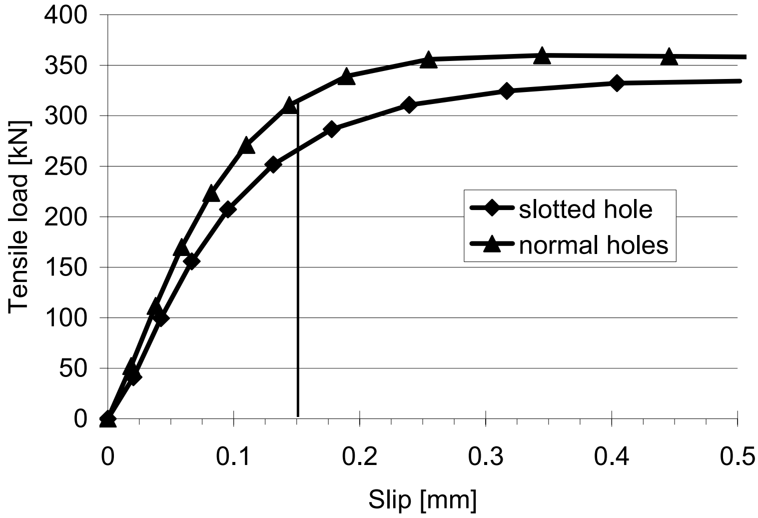

Fig. 7. Load-slip behaviour – comparison with normal holes

The loss induced by the use of a long slotted hole together with a cover plate is about 7% for the ultimate load and 15% for the slip load at 0,15mm.The reduction factor of 0,63 imposed by Eurocode 3 [5] appears to be too conservative.

6. Conclusions

Preliminary tests on the new type of friction connections showed performances very encouraging for their use in towers for wind turbines.

Tension Control Bolts appeared to be suitable and attractive for that particular application since they were very quickly and easily installed, and provided a pretension level higher than that required by Eurocode 3 Part 1-8 [5] showing a rather low scattering. The friction coefficient of weathering steel was confirmed to be higher than allowed for surface class A of Eurocode 3 Part 1-8 [5] (μ=0,5), thus leading in practice to more beneficial resistance.

Numerical analysis performed with the commercial software Abaqus 6.7 yielded results close enough to the experiments to allow the comparison to connections that would be obtained using the normal clearance holes. The numerical results showed that the resistance was in the order of 15% lower when long slotted holes in the load direction and using a thick cover plate. The preliminary test indicates that the reduction factor according to Eurocode 3 Part 1-8 [5] (ks=0,63) may be too conservative.

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