Flange connection vs. friction connection in towers for wind turbines

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ABSTRACT: The paper deals with connections used to assemble sections of tubular steel towers supporting wind turbines. The design of current ring flange connections is briefly presented. An alternative option for the assembling connection is to use single overlapping friction connection. This is introduced in on-going research project "HISTWIN- High-Strength Steel Tower for Wind Turbine, 2006-2009". The main characteristic of the friction connection is long open slotted holes. Design example for equivalent design load at ultimate load of the friction connection is compared to the flange solution on a particular example of REpower Tower MM92. The benefits of the new connection in terms of design simplicity, fatigue strength and material costs are discussed.

1 INTRODUCTION

Nowadays the demand in renewable energies increases more and more. One of these renewable energies is wind. During the last decades wind farms have been built all over the world, especially in Europe. Since the average wind speed rose due to the global climate change, gaining electric power out of wind energy became excessively interesting.

Each wind energy plant consists of rotor, nacelle, tower, foundation and transformer. The turbines rest on various kinds of towers: concrete-, steel- or hybrid-towers. Steel-towers can be divided into lattice and tubular towers. The latter are the most common solution for onshore wind farms, as they combine aesthetical, economical and safety reasons.

To advance the competitiveness of wind-energy costs have to be reduced. According to Sahin (2004) the capital cost for constructing a power plant and coupling it into the grid accounts for 75-90% of the total costs. Within this amount of costs for the construction arise expenses of about 15-20% for the tower itself (WWEA 2008).

The cost reduction can be realized by improving the relationship between the produced electric energy and the costs per converter. Constructing higher towers to reach zones of higher wind speeds is one possible solution.

A European Project called HISTWIN focuses on tubular steel towers. Herein the attention is turned to the optimization of the tower geometry and innovative solutions for the assembly joints. One of the details which HISTWIN focuses on is the flange connection of the individual tower sections. Ongoing investigations check if the flange connection can be replaced by a friction connection with long slotted holes. The advantage of this are the big cost savings related to the production and the assembling of the tower. In addition to this friction connections are less sensitive to fatigue.

In this paper friction connections in towers for wind energy plants are presented. A design method is proposed and compared to the design of conventional ring flange connections. A typical example is given and benefits in terms of fatigue strength, design simplicity and cost savings are discussed.

2 DESIGN OF BOLTED RING FLANGE CONNECTIONS

2.1 *General*

Currently the sections of tubular steel towers are assembled with bolted ring flange connections. Steel rings are welded at both tube ends and connected by high strength bolts.
For design purpose it is assumed that the resistance of the three dimensional bolted ring flange connection can be described by the resistance of a segment with a single bolt and a width equivalent to the arc length between bolts holes. The segment is considered to be loaded in tension.
Seidel (2001a) proved the correctness of this assumption with help of numerical analyzes of the whole system.
The required design checks are the following:

- Resistance at ULS
- Fatigue strength
- Resistance at the SLS

For comparison with the friction connection, only the resistance at ULS and fatigue strength will be considered. They are assumed to be design driving. The other design checks were obviously verified and met for the considered examples as the tower is currently in operation.

2.2 *Static resistance at ULS*

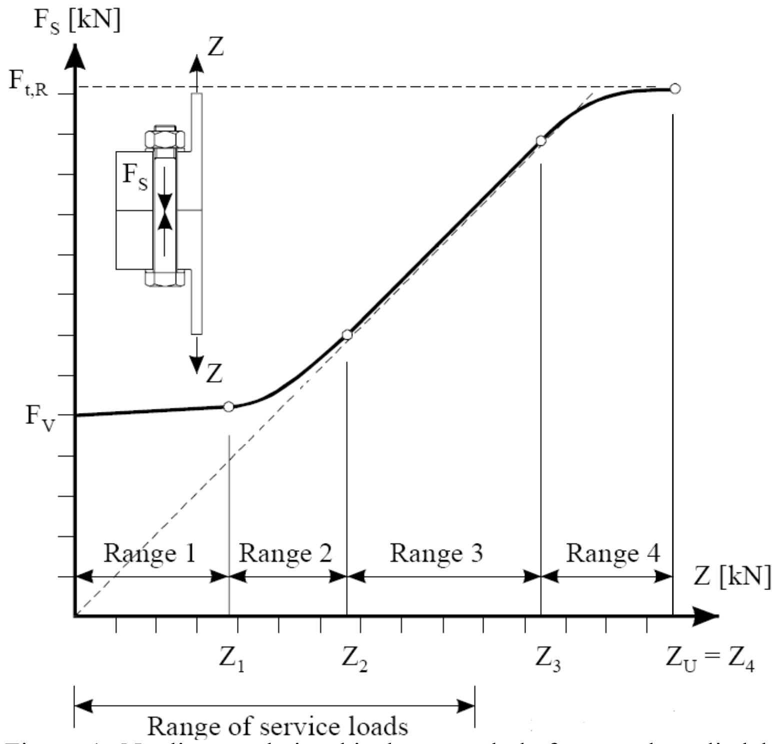
The static resistance of a flange connection at ULS is determined by the failure of the bolts or of the flange. The design is usually performed using the plastic-hinge method developed by Petersen and presented in (Seidel 2001a).
The flange is considered as a beam and failure modes are defined with plastic hinges developing at different locations. Initially three failure modes were defined by Petersen. They correspond to bolt failure, plastic hinge in the shell and plastic hinge in the shell and in the flange.
Seidel accounted for the distribution of bolt forces and defined two failure modes with plastic hinges in the flange at the bolt axis and at the middle of the washer respectively.
The resistance models corresponding to the different failure modes are extensively presented in (Husson 2008, Seidel 2001a).

2.3 *Fatigue resistance*

Fatigue failure of flange connections occurs by failure of the bolts. The resistance of the bolt as component is however not sufficient to determine alone the resistance of the connection. Indeed the solicitations are dependent on the geometry and pretension.
The design verification is performed according to EN1993-1-9 by ensuring that the Palmgren-Miner damage accumulation is lower than unity:

$$D_d = \sum \frac{n_i}{N_i} \leq 1 \qquad (1)$$

The relationship between tension in the shell and stress variations in the bolts is nonlinear. This behavior is illustrated in Figure 1 where the service and fatigue loads are typically within range 1 to 3. The simplification of the fatigue load spectra to a Damage Equivalent Load (DEL) can not be used for such nonlinear systems. Instead the fatigue loads must be defined as Rainflow or Marcov matrices which include information on the load range occurrence and amplitude but also on its average. Based on a model of the relationship between tensile load Z and bolt force F_S the stress ranges can be derived and the corresponding damages are extracted from appropriate Wöhler curve.
Different models have been developed to approximate the relationship between tensile load and bolt force. They are extensively described by Seidel (2001a) who also proposed an improved method.



Range 1:
Approx. linear curve, stresses between flanges are reduced while contact zone is closed

Range 2:
Successive opening of the flanges

Range 3:
Open connection with slope depending on loads and geometry

Range 4:
Plastification of bolts and/or flange until failure of the connection

Figure 1. Nonlinear relationship between bolt force and applied load in the shell (adapted from (Seidel 2001b)).

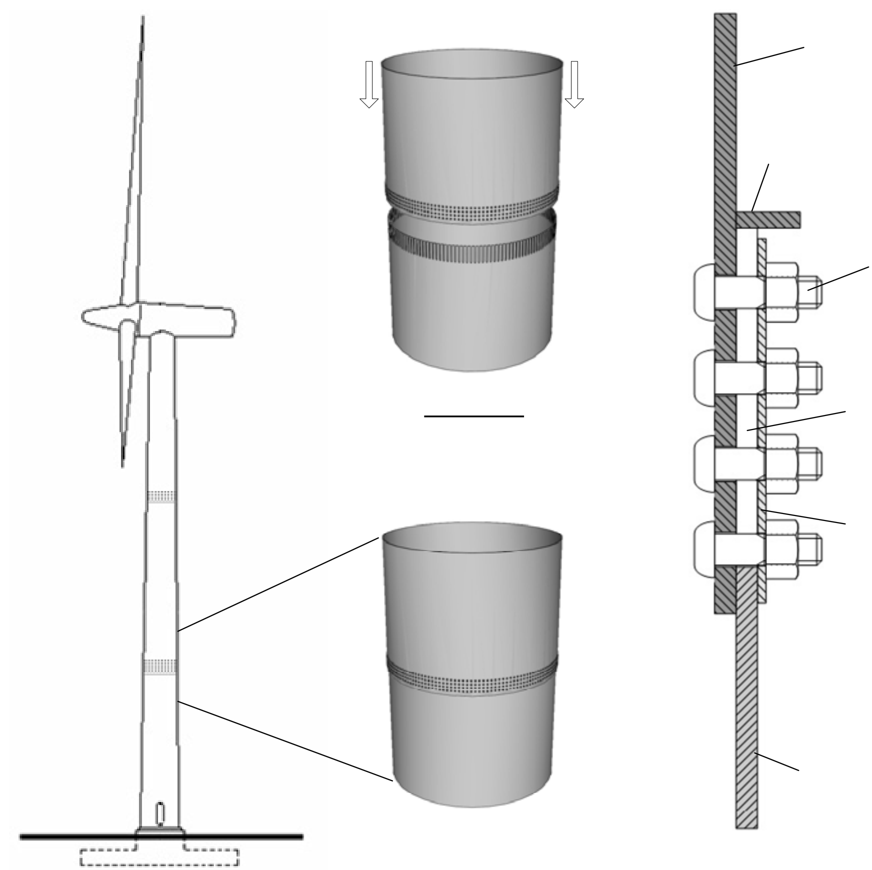


Figure 2. Principle of the proposed friction connection.

3 DESIGN OF FRICTION CONNECTIONS

3.1 *New concept*

The conventional friction connection with High Strength Bolts and normal holes is not easily applicable for the erection of tubular steel towers. For practical and safety reasons the fasteners shall be tightened from within the tower only, and the holes shape and clearance shall be adapted to facilitate alignment of the sections and installation of the fasteners. The principle of the considered solution is presented in Figure 2.

To facilitate assembly one of the tubular sections, say the lower one, has open slotted holes. The fasteners can be preinstalled in the normal holes of the other section and they can then be used for the angular alignment of the upper section while it is slid down in position. Support is provided to hold the sections during tightening. The slots offer important longitudinal tolerances and the shell bending stiffness is locally reduced. It enables good conformation between the tubes without significantly affecting the contact pressure. Instead of standard washers for each bolt, a common cover plate is used. Its purpose is to hold the bolt group together during assembly and to spread the clamping force in a more uniform manner.

Tension Control Bolts (TCBs) may be chosen to provide the clamping force. It is a special type of high strength fasteners with tightening carried out entirely at the nut end with a special electric wrench. It is available on the market in metric sizes up to M30. The mechanical properties are equivalent to those of High Strength Bolts: grade S10T may be considered as bolt grade 10.9 (Ryan 2001, Cosgrove 2004). As tightening is performed at the nut end only, no torsion is introduced in the shank (TCB 2008). This property is believed to reduce the risk of self loosening and the amount of torsional relaxation.

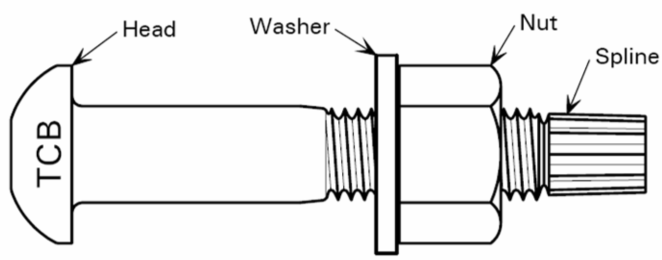


Figure 3. Tension Control Bolt, Grade S10T (Prior to pretensioning) (Cosgrove 2004).

3.2 *Design considerations and basic assumptions*

The same approach can be used as for the design of flange connections, i.e. a segment with a single row of bolts is considered.

It is assumed that the bolts forces from pretension are entirely resulting in clamping force that produces friction at the interface. Also the cross-section need not be reduced as the load is progressively transferred in the overlapping zone with double thickness.

The required design checks are the following:

- Static resistance at ULS
- Fatigue strength

3.3 *Static resistance at ULS*

The static resistance of the connection segment can be based on the design model from EN1993-1-8 and given for a single bolt as:

$$F_{S,Rd} = \frac{k_S \cdot \mu_S}{\gamma_{M3}} \cdot F_{p,C} \tag{2}$$

According to EN1993-1-8, the correction factor, k_S, should be taken as 0.63 for a connection with long slotted hole parallel to load action. However this value was found to be excessively conservative. Indeed the experimental resistance of the connections with long slotted holes and cover plates was less than 5% lower than with normal holes (Husson 2008). Moreover the different zinc rich primers currently used in the industry have a great variation of friction coefficient which can take

higher but also lower values than given in the norms. For optimum design of serial products such as wind towers it is thus recommended to obtain correction factor and friction coefficient from testing and statistical analysis.
To derive the design load acting on a segment only compressive longitudinal stresses originating from bending (tilting moment) and vertical load (self-weight) are considered. Radial and circumferential stresses can be neglected. It is furthermore assumed that the stresses are uniform over the segment width. This is similar to assuming a maximal, constant stress over the entire cross-section. Consequently, the minimal amount of bolts is given as:

$$n_{Bolts} \geq \frac{\sigma_{N,Ud} \cdot \pi \cdot d_a \cdot t}{F_{S,Rd}} \tag{3}$$

The maximal amount of rows is related to the row spacing which is determined either by the minimal bolt spacing given in EN1993-1-8 or by the clearance necessary for tightening. As the electrical wrenches used with TCBs are compact tools the row spacing is determined by the norm. The maximal amount of rows becomes:

$$n_{Rows} \leq \frac{\pi \cdot d_a}{2.4 \cdot d_H} \tag{4}$$

3.4 *Fatigue resistance*

The fatigue resistance of the connection may be estimated according to EN1993-1-9. Although a segment is an eccentrical lap joint, it actually has three dimensional constraints from the shell curvature that will prevent out-of-plane bending. For fatigue calculations it may be pesimistically regarded as a “one sided connection with pretensioned high strength bolts” with a detail category 90. In fact on-going experimental results indicate a much higher resistance (Rebelo et al. 2009).
In accordance with the recommendations from Germanischer Lloyd Guideline (2004) the endurance limit at 10^8 cycles is disregarded. A single Wöhler slope with m=4 may be used as it is current practice for the design of steel towers (Krutschina 2007). This significantly simplifies the fatigue calculations. The fatigue strength at $2 \cdot 10^8$ cycles becomes:

$$\Delta\sigma_N = 90 \cdot \left(\frac{2 \cdot 10^6}{2 \cdot 10^8} \right)^{1/4} \approx 28.5\, MPa \tag{5}$$

The considered system is linear and Damage Equivalent Loads can be used. As for the static design load only damages from longitudinal stresses are considered. Furthermore the component from rotor thrust can reasonably be neglected and only stresses from tilting moment are used for the design calculations.
As the stresses are calculated using the gross cross-section, the fatigue strength will not be influenced by the number of bolts or bolts rows. It will rather be governed by the shell thickness.

4 DESIGN EXAMPLE

4.1 *Bolted ring flange connections*

Two bolted ring flange connections designed for the intermediate assemblies of an 80m-high tower are considered. Their dimensions and properties are shown in Figures 4-5. The extreme design section loads relevant for static and fatigue design checks are given in Table 1. Partial safety factors of 1.35 and 1.00 are already included for static and fatigue loads respectively which are provided by the turbine producer.
Based on this information the design ratios for the static resistances at ULS are 0.67 and 0.53 for flange 1 and flange 2 respectively. The details of the derivation can be found in (Husson 2008).
Unfortunately the design load spectra required for fatigue assessment were not available. Given the important provisions of the static resistance it is however likely that the fatigue strength is design driving.

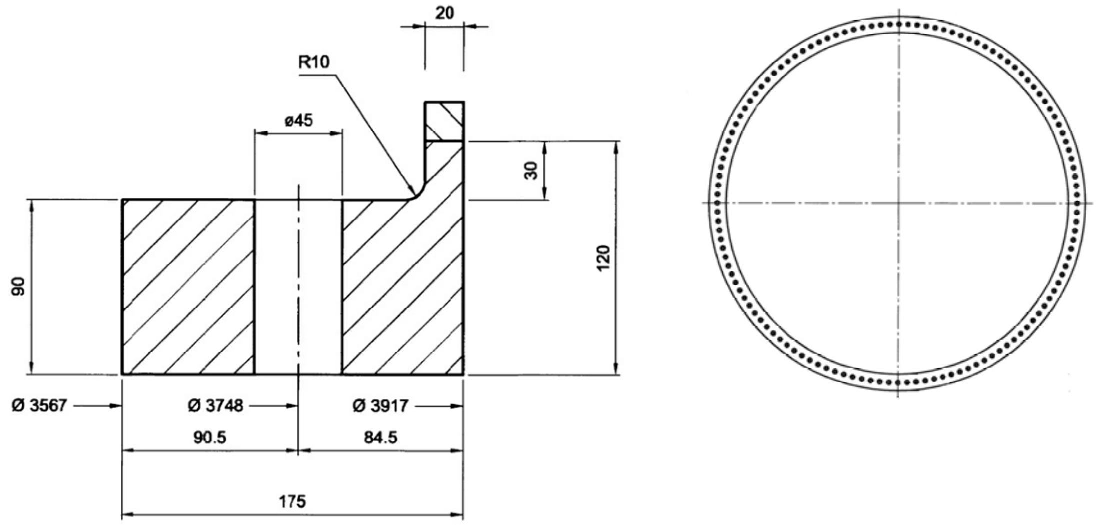


Figure 4. Dimensions and properties of the flange connection at section 1.

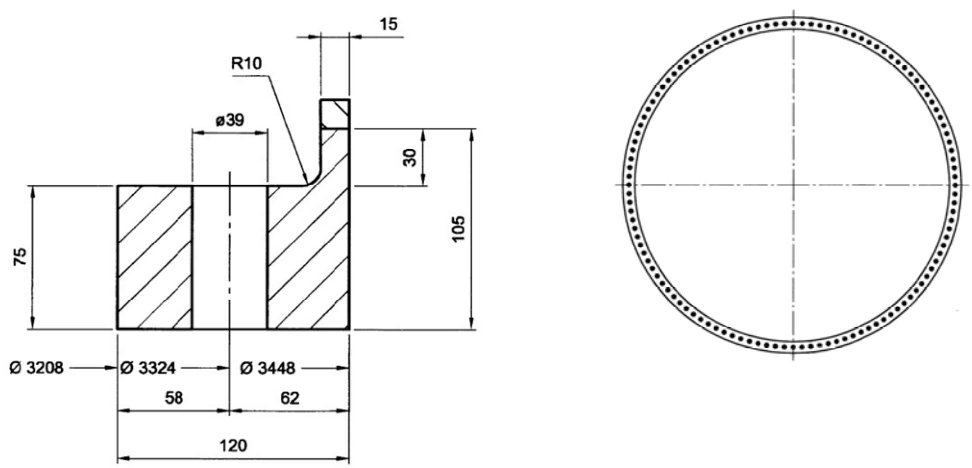


Figure 5. Dimensions and properties of the flange connection at section 2.

Table 1. Design section loads

	Tilting moment [kNm]	Vertical load [kN]	DEL (tilting moment) [kNm]
Section 1	48631	-2443	4243
Section 2	25221	-1846	2359

4.2 *Alternative friction connections*

The previous bolted ring flange connections may be replaced by friction connections. The sections diameters and shell thickness are unchanged. It is assumed that the influence of the connections on the tower behavior is small enough and does not introduce significant changes of the section loads.

Two alternatives are considered: connections with the maximum resistance equal to the gross section resistance and with the same resistance provision as the bolted ring flange connections.

The faying surfaces receive a treatment similar to that currently used by the tower manufacturer, i.e. they are first grit blasted to a quality $Sa2^{1/2}$ (ISO8501 2004) and then coated with an ethyl silicate zinc rich primer with a nominal zinc content of 90wt%. The coating thickness is between 50 and 80μm.

The friction coefficient of steel plates coated in this way was determined experimentally following the requirements of EN1990. It was found to be μ_S=0.45 (Husson 2008). Investigations were also conducted with the considered bolt type as well as open slotted holes and normal holes. The correction factor was statistically determined as k_S=0.64 (Husson 2008).

The results are presented in terms of required amount of bolts in Table 2. The design alternative yielding the same resistance provision as for the bolted ring flanges is excessively resistant. It reaches stresses in excess of the yield strength. The first solution is more realistic.

Table 2. Connections designed based on static resistance at ULS

	Bolts	Rows	Bolts/row	Utilisation ratio
Section 1	588	147	4	0,99
Section 2	351	117	3	0,99
Section 1	882	147	6	0,67
Section 2	702	117	6	0,53

EN1993-1-8 does not recognize ethyl silicate zinc rich primers as surface treatment for friction connections. Another type of primer, with an alkali silicate binder, offers better friction properties. The design value is μ_S=0.5. Experiments have yielded even better results of about μ_S=0.7. Increase of the friction coefficient leads to more beneficial design as less bolts are required. Other faying surfaces such as oxidized weathering steel could increase friction even more (Husson 2008).
Furthermore, it should be noted that the safety factors and statistical analyzes are based on the lifetime and failure probabilities requirements of Eurocode for buildings. Wind towers having a shorter lifetime and the consequences of failure being mainly economical, the safety factors could be decreased thus improving the design.
The design check for fatigue resistance is performed with a partial safety factor γ_M=1.25 (GL guideline 2004). The fatigue strengths are sufficient and independent of the number of bolts. The design ratios are 0.79 and 0.75 for flange 1 and flange 2 respectively. With regard to fatigue design the shell thickness may thus be reduced by about 20 to 25%.

4.3 *Comparison*

First of all the fatigue strength of friction connections depends solely on the gross cross-section and the static resistance is obtained by selecting appropriate faying surfaces and defining the amount of bolts. It is thus possible to independently adjust both resistances. It makes optimization possible. The engineering models are also very simple.
On the other hand the fatigue strength of ring flange connections depends on the amount of bolts and their size which are both limited for a given geometry. Thick flanges are required to meet the stiffness requirements and fatigue design is tedious because of the intrinsic nonlinearity.
Table 3 compares the material costs for both solutions. Costs for the flange connections were provided by *REpower Portugal* in December 2007 and those for the friction connections are based on a quote for 1000 pieces from *TCB ltd.* in August 2007. The steel flanges account for most of the material costs of the standard solution. Friction connections using smaller bolts produced in large series therefore are much more economical. Material costs can be reduced by about 20k€ per tower. The costs for the overlapping of material are not taken into account, since this amount is minimal in comparison with the costs for producing the flange connection.

Table 3. Connections designed based on static resistance at ULS

	Component	Unit price [€]	Amount	Total price [€]
Bolted ring flange connections				
Section 1	Flange (d_a=3917mm)	6762.00	2	13524
	Bolt (M42x245 10.9)	20.32	124	2520
			Total :	16044
Section 2	Flange (d_a=3448mm)	4395.00	2	8790
	Bolt (M36x205 10.9)	11.40	116	1322
			Total :	10112
Friction connections				
Section 1	Bolt (M30x110 S10T)	5.45	588	3205
Section 2	Bolt (M30x110 S10T)	5.45	351	1913

Fabrication and installation costs were not included in this comparison. However welding, machining and drilling operations involved in the flange solution are tedious and expensive (Lanier 2005). The additional cutting operations for the friction solution shall reasonably be more economical in serial production. Installation and tightening of the many required bolts may increase the erection time but some work can be performed at ground level and effective tightening methods can be implemented. Promising results have been obtained within HISTWIN project.

5 CONCLUSION

The implementation of a new type of friction connections in wind towers can offer many benefits.
The design process is simplified. In particular, the response is linear and Damage Equivalent Loads can be used for fatigue calculations.
The static and fatigue resistances depend on different parameters and can thus be adjusted independently. Design optimization is thus simplified.
The fatigue strength may be improved by increased shell thickness if necessary. In the considered example it is however largely sufficient and the plate thickness may be decreased by about 20% with regard to fatigue life.
The expensive ring flanges are not necessary and the material costs savings are estimated about 20k€ for a typical 80m-high tower.

6 ACKNOWLEDGEMENTS

Experimental results were obtained within the on-going research project, HISTWIN. The financial support obtained from the Research Programme of the Research Fund for Coal and Steel RFSR-CT-2006-00031, and Energimyndigheten, Dnr. 2008-000225 is acknowledged. Authors are grateful for excellent co-operation with our project partners: RWTH Aachen, Germany; GL-WIND, Germany, AUTH, Thessaloniki, Greece; REpower, Portugal; FCTUC, Coimbra, Portugal; and RUUKKI, Finland.

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