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*Published in:*

Proceedings of the 29th Nordic Seminar on Computational Mechanics (NSCM-29)

*Publication date:*  
2016

*Document Version*  
Peer reviewed version

[Link back to DTU Orbit](#)

*Citation (APA):*

Pedersen, N. L. (2016). Design of Bolted L-Flanged Connections. In R. Larsson (Ed.), Proceedings of the 29th Nordic Seminar on Computational Mechanics (NSCM-29)

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# DESIGN OF BOLTED L-FLANGED CONNECTIONS

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**Key words:** L-flange, bolt, eccentric, contact, design, FE.

**Summary.** In wind turbine towers the preferred design is circular tubes that are connected to each other by a bolted flange joint. The design is typically that of an L-flange resulting in an eccentrically loaded bolted connection. The eccentricity results in a non-linear relationship between external load on the tower and the tensile force in the bolt. In the literature and also in design standards different models are presented for this important non-linear response. The present work presents a simplified expression for the non-linear force response based on finite element calculations using contact analysis. Secondly, focus is on simple modifications of the flange design that considerably improves the strength of the connection.

## 1 BOLT FORCE TRANSFER FUNCTION

Bolted connections are one of the most important assembly methods in relation to both mechanical engineering and civil (structural) engineering. The different sections of a wind turbine towers are typically tubular, the sections are bolted together and the bolts are preloaded, see e.g.<sup>1</sup> for an overview. The preload is important for the strength of the connection between the different tubular sections of the tower where the connections are primarily loaded by a varying bending moment and by the weight of the nacelle.

In a traditional preloaded bolted connection the fatigue strength is controlled primarily by the amplitude of the external load on the bolt, the mean value of the stress is not important as long as the total value of the stress is below the yield stress. The ratio,  $\Phi$ , of the external load on the structure that is transmitted to the bolt is controlled by the stiffness of the clamped members,  $K_m$  relative to the stiffness of the bolt  $K_b$ .

$$\Phi = \frac{K_b}{K_b + K_m} \quad (1)$$

The calculation of the stiffness can be found in e.g. the standard<sup>2</sup>. With concentrically load the relationship between external load and transmitted load to the bolt is linear; this is also the case for eccentric load as long as the boundary condition, i.e. the contact

area between the clamped members, is constant. For an eccentric load this is typically only valid for a relatively small external load (relative to the preload). The L-flange is an example of an eccentrically loaded connection, many paper in the literature are related specifically to this connection type, see e.g. the recent papers<sup>3,4</sup> and<sup>5</sup>. In Figure 1 a typical L-flange connection is shown.

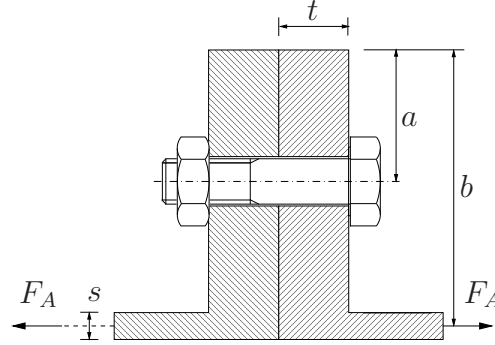


Figure 1: Bolted L-flange connection shown with dimensions and eccentric external load.

As the external load increase the bolt load is first linear related to the external load with a favorable ratio much like the concentrically loaded connection, with an increase of the load the change in the bolt load relative to the external load is non-linear as the boundary condition (contact) changes. Finally at high load the contact conditions do not change and there is again a linear relation between external force and bolt load, in principle the connection acts in the end as if there is no preload. For a concentric connection the loss of clamping force between members result in a one to one correspondence between external load and bolt load, but for an L-flange the load in the bolt load is higher than the external load and controlled by equilibrium of moment and can be estimated in the limit by the ratio  $\Phi_l$ .

$$\Phi_l = \frac{b}{a} \quad (2)$$

assuming that there is no bending of the bolt. This assumption is of cause not completely true as will be discussed in more details. The purpose of the present work is twofold.

- Determine simple transfer function between load and bolt force for L-flange joints.
- Suggest simple design modifications to improve the strength.

The overall inherent shortcomings of the L-flange can be improved in quite many ways. The reason for choosing the simple L-flange design for the wind turbine towers (as shown in Figure 1) is related to the price, both in relation to production and inspection. The present work therefore focuses on moderate design modifications of the original simple

design to improve the strength. For strength estimation (fatigue) of the bolts in a L-flange connection it is not enough only to find the normal bolt force as presented in most papers on the subject, the moment is also highly important because it is the maximum stress in the bolt that controls the strength. A derivation is therefore made for both.

The essential first part of the transfer function is found from the stiffness of the bolt and the stiffness of the members. The stiffness's can be estimated using<sup>2</sup>. In<sup>6</sup> the stiffness for the concentrically bolted connection is discussed and it is shown how the estimation of the stiffness found in the literature has a rather large variation, and a new estimate of the stiffness is proposed based on curve-fitted FE results. The stiffness was in this paper found using the elastic energy found from the FE analysis and the same is done here for the eccentric case. The physical and mathematical details will be presented. The transfer function between external load and bolt load depends highly on the point of attack of the external load as it is discussed in<sup>7</sup>. In Figure 2 the FE model is shown together with a course mesh.

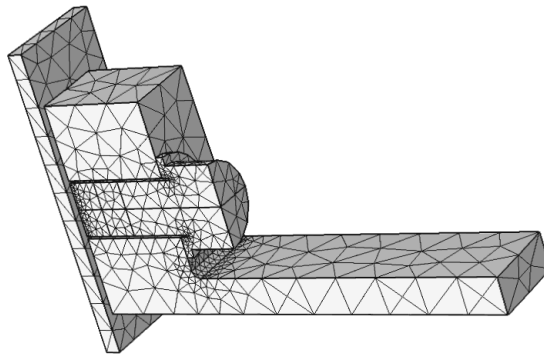


Figure 2: FE mesh of L-flange and bolt (For illustration a course mesh is shown).

## 2 Design modifications

One way of transferring the load from tower wall to the L-flange is to add stiffeners as seen in Figure 3(left). This design change will increase the flange production price. The stiffeners will in themselves improve the design, however in order to fulfill the requirements with respect to spacing around the bolt the number of bolts have to be reduced. This reduction in the number of bolts increases the external load on the individual bolt. The overall conclusion is that the negative effects are stronger than the positive effects and therefore the design with stiffeners has a smaller strength than the design with the maximum number of bolts. An alternative way of improving the design is to improve the flange bending stiffness. In many other design of flange a neck as seen in Figure 3(middle) is used. For the present design where the external loading is primarily tower wall bending the neck design is not beneficial. This is primarily due to the negative effect this design

has on the moment equilibrium as compared to the design where we put the bolt as close as possible to the tower wall. It is also possible to control the contact surface as seen in Figure 3(right). here the design is not superior compare to the simple one for the whole loading range. From the many different design modifications that have been attempted

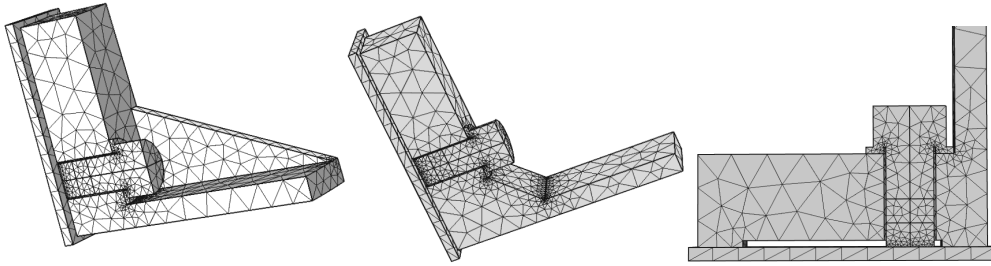


Figure 3: Different L-flange design modifications

it is concluded that: the best design improvement is found by putting the bolt as close to the tower wall as possible. Further significant improvements are found by increasing the flange thickness.

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