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SHORT COMMUNICATION

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A study of action point correction factor for L-type flanges of wind turbine towers

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Abstract

A correction factor accounting for the effect of elastic deformation of flange is proposed for the ultimate strength analysis of L-type flanges used for wind turbine towers. It is derived based on systematic analyses and explicitly expressed as a function of flange dimensions. The proposed factor is simple and suitable for the engineering applications, comparing with the conventional formula for the ultimate strength analysis of flange connections.

KEYWORDS

action point, bolt, flange, lever ratio, tower, wind turbine

1 | INTRODUCTION

An accurate prediction of the ultimate strength of L-type flanges used for wind turbine towers is crucial in typhoon and earthquake active areas, because the high strength is required at the flange connection of wind turbine towers. Typical tower flange connections use the L-type flanges located inside the tower for the maintenance.

Two typical formulas are used for the design of flange connection of wind turbine towers. One is used for the ultimate strength analysis of flange connection. The other is used for the fatigue strength analysis of bolt.

Some formulas for the ultimate strength analysis of flange connection have been proposed,[1-4] and FE modellings for L-type flanges have been investigated.[5-8] Eurocode[1] provided a formula for the T-type flange, which cannot be used for the L-type flange. Petersen[2] proposed a formula for the L-type flange based on the elastoplastic theory. The resistance obtained from the formula is determined by 3 destruction modes, that is determined by combination of acceptable pulling force acting on bolts and plastic bending resistance of shells and flanges. This formula underestimates the pulling force acting on the bolt when the flange stiffness is low. Seidel[3] proposed a formula which has 2 additional destruction modes and a geometrical limitation. However, this formula needs many steps of calculation to define the geometrical limitation. RISO/DNV[4] shows a formula to evaluate the ultimate strength of bolt for the L-type flange connection, but it has the same problem as the formula proposed by Petersen[2] because it did not consider the bolt pretension and the elasticity of flange.

In this study, an action point correction factor for the ultimate strength analysis of a L-type flange connection is proposed. The formula for the pull force acting on a bolt and the definition of the action point correction factor are described in Section 2. Systematic FE analyses for various flange dimensions are then performed, and the action point correction factor is proposed to explicitly estimate the equivalent acting point of flange reaction force considering the effect of flanges deform in Section 3. Finally, conclusions are summarized in Section 4.

2 | ULTIMATE STRENGTH ANALYSIS FOR A L-TYPE FLANGE CONNECTION

The formula for the pull force acting on a bolt is shown in Section 2.1, and the action point correction factor is then described in Section 2.2. In this study, it is assumed that the pull force acting on the bolt reaches an acceptable limit first before the plastic failure of flange connection occurs.

2.1 | Formula for the pull force acting on a bolt

In this study, the strength evaluation of the flange is evaluated by a model for 1 bolt, and the force acting on the tower section is expressed by the T_S as shown in Figure 1.

As shown in Figure 1, a couple of forces by the shell tension force T_S and the bolt reaction force F_A is supported by the flange reaction force F_R at the inside corner of the flange. On the bolt, pull force acting on bolt T_A has an equivalent value of F_A but acts in the opposite direction by the law of action and reaction.

The flange connection surface separates when the pull force acting on the bolt is higher than the pretension force of bolt. Regarding the flange in the radial direction as a beam, the pull force acting on the bolt T_A is a function of shell tension force T_S as represented in Equation 1 and derived from the moment balance.

$$T_A = F_A = A \times T_S, \; A = 1 + \frac{g}{\lambda e}, \; T_S = \left(\frac{M}{Z_t} - \frac{N}{A_t}\right)\left(\frac{A_t}{n}\right) \tag{1}$$

where A represents an amplification factor of the shell tension force to the pull force acting on the bolt and is known as the lever ratio, λ expresses an action point correction factor and is 1 when the flange is assumed as a rigid body, n is the total number of bolts for a tower section, M and N are the bending moment and the axial force acting on the section, and Z_t and A_t are the section modulus and the area of section, respectively.

For the same shell tension force, A decreases and the flange resistance increases when e increases. However, excessive extension of e causes a flange elastic deformation, and the action point of flange reaction force moves to e' as shown in Figure 1. This is why the formulas by Petersen[2] and RISO/DNV[4] may underestimate the pull force acting on the bolt. Eurocode[1] limits the flange geometry to $e \leq 1.25g$, and the flange is regarded as a rigid body.

2.2 | Definition of the action point correction factor

The action point correction factor shown in Equation 2 is a ratio of an equivalent action point e' to an ideal action point of flange reaction force e.

$$\lambda = e'/e \tag{2}$$

In order to identify λ, FE analysis is used to evaluate e'. For a flange with an extended length e longer than $1.25g$, the limit shell tension force $T_{S,lim}$ can be obtained from a FE analysis when the bolt tension reaches the acceptable pull force acting on the bolt $T_{A,\,lim}$ and e' can be calculated from Equations 1 and 2 as follows:

$$e' = \frac{g}{\left(\frac{T_{A,\,\mathrm{lim}}}{T_{S,\,\mathrm{lim}}} - 1\right)}. \tag{3}$$

In this study, the acceptable pull force acting on the bolt $T_{A,lim}$ shown in Ishihara[9] is used as:

$$T_{A,\,\mathrm{lim}} = 0.80 \cdot \sigma_y \cdot A_S \tag{4}$$

where σ_y is the 0.2% proof stress and A_S is the stress area of bolt.

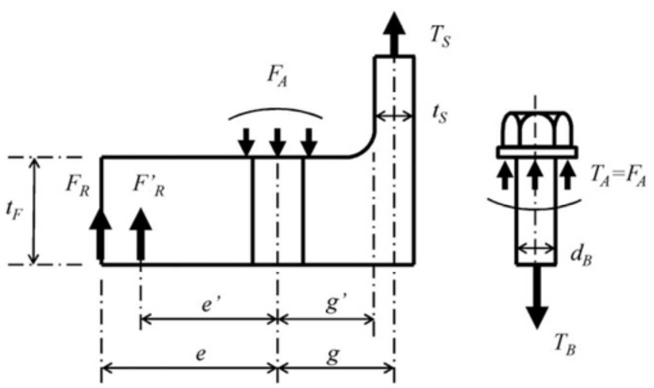

FIGURE 1 Dimension and acting forces on a L-type flange

3 | PROPOSAL OF AN ACTION POINT CORRECTION FACTOR FOR A L-TYPE FLANGE

Systematic finite element analyses are performed in Section 3.1, and a formula for an action point correction factor for a L-type flange is then proposed in Section 3.2.

3.1 | Finite element analysis and validation

In this study, 672 cases of FE analysis using ANSYS[10] are performed, and parameters are listed in Table 1 to cover the variation of flanges for wind turbine towers. Some cases are excluded because the shell of tower exceeds the elastic limit before the bolt achieves to the acceptable pull force.

A model of L-type flange used in FE analyses is a segment model as shown in Figure 2, which is connected to the shell with an enough length. The segments are modeled by the solid elements with 20 nodes, and the number of elements comprised between 2500 and 6500 depending on the flange model size. Contact condition with a friction coefficient of 0.176 based on examinations is applied for the contact area between each flange but is not applied for the seat area of bolt and nut in order to improve analysis convergence because those contact areas do not open normally and do not affect the results even if they slide slightly. Symmetry condition is applied for the flange axial plane. The lower end of shell is fixed, and a displacement is applied at the upper end of shell. According to Ishihara,[9] an initial pre-tension is applied to the bolt, which is 70% of the 0.2% proof stress of bolt. Convergence is checked by comparing the square root sum of the squares of force and moment imbalance.

Material properties shown in Figure 3 are used to consider elastic and plastic behavior of steel, which are typically used for flanges, bolts, and tower shells.

The FE model used in this study is validated and compared with experimental data by Seidel.[5] The flange model used in the experiment and the FE model used for the validation are shown in Figure 4, respectively.

The comparisons between predicted and measured bolt tension and bending moment are shown in Figure 5. Predicted bolt tension and bending moment show good agreement with the experimental data and the results of FE analyses by Seidel.[5]

TABLE 1 Summary of parameters used in FE analyses

Parameter	Value	
Bolt diameter d_B[mm]	36, 48	56, 64
Tower diameter D[m]	3, 4, 5	4, 5, 6
Shell thickness t_S[mm]	20, 30, 40	30, 40, 50, 60
Bolt interval p[mm]	(2.25, 2.50) d_B	
Flange thickness t_F[mm]	75,100,125	100,125,150
Length g[mm]	1.3 d_B	
Length e[mm]	(1.25, 1.5, 1.75, 2, 2.25) g	

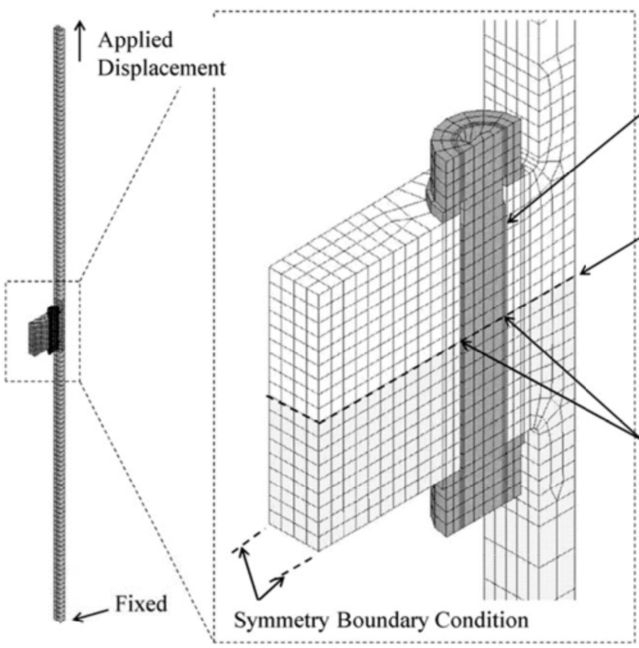

FIGURE 2 A model of flange used in FE analyses

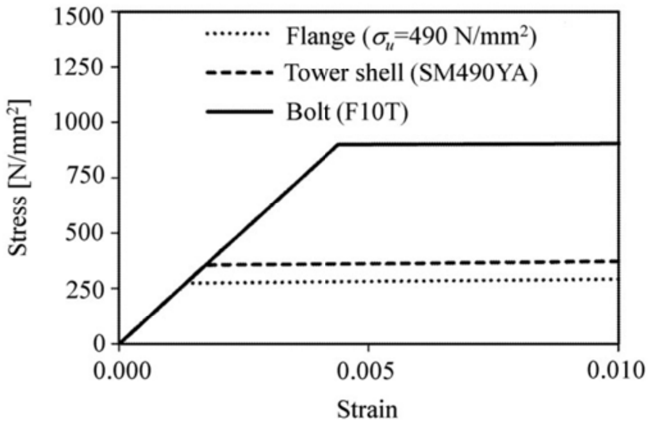

FIGURE 3 Material property used in FE analyses

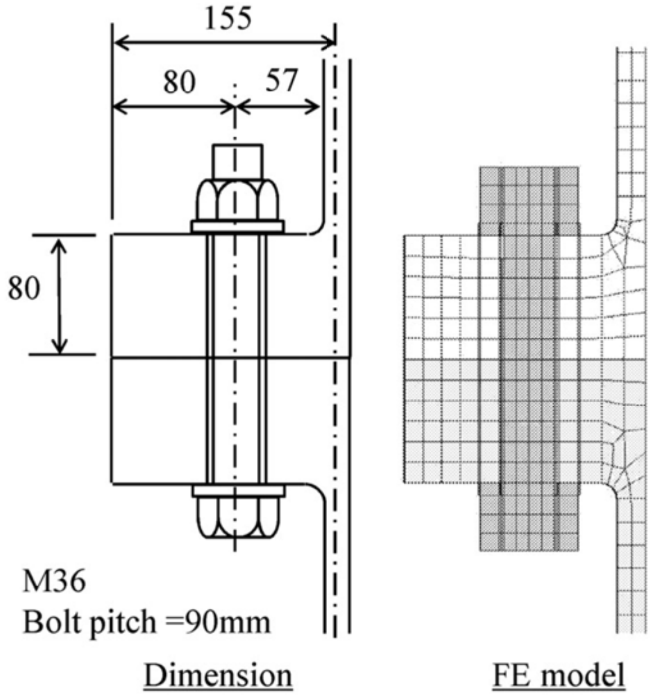

FIGURE 4 A flange model used for the validation

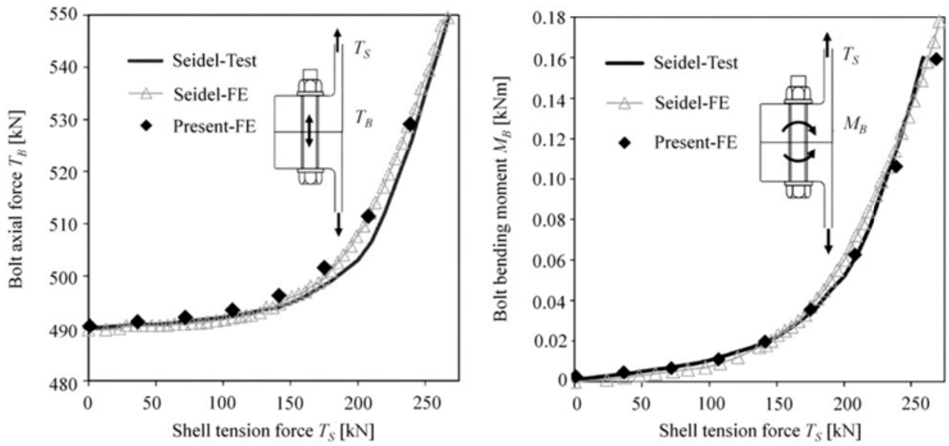

FIGURE 5 Comparison between predicted and measured bolt tension and bending moment

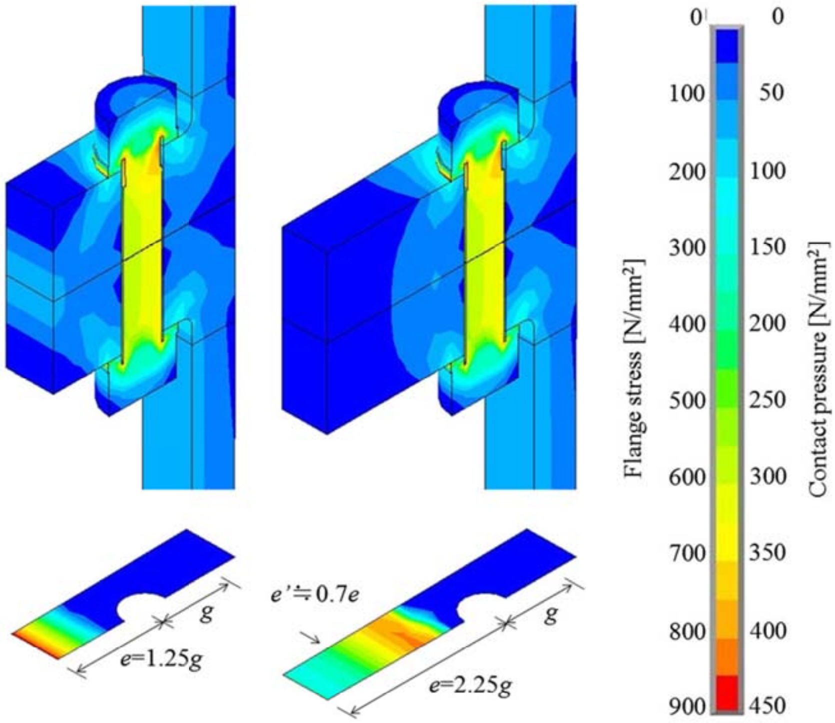

FIGURE 6 FE results for 2 typical flanges [Colour figure can be viewed at wileyonlinelibrary.com]

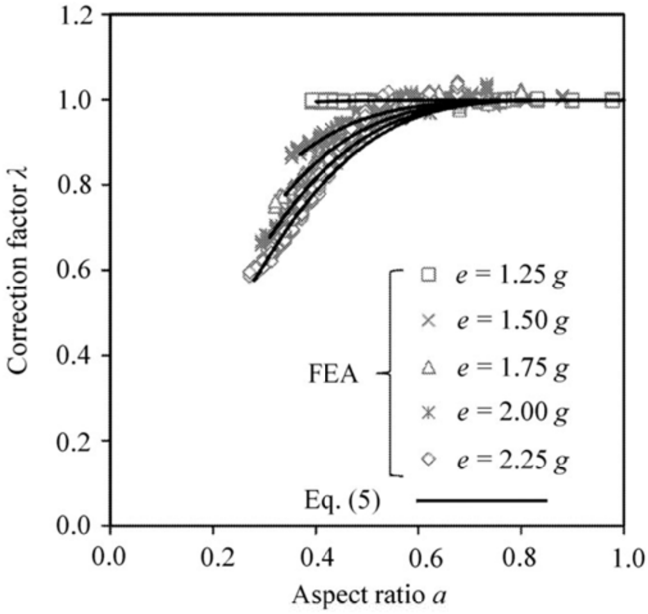

FIGURE 7 Variation of the action point correction factor with the aspect ratio a

Figure 6 shows the von Mises stress distribution of flange connection and the surface pressure distribution of contact area for 2 typical flanges with e = 1.25 g and e = 2.25 g, when the bolt tensions reach the acceptable pull force acting on the bolt. In the flange with e = 1.25g, maximum surface pressure is appeared at the corner of flange. Therefore, the flange with e = 1.25g is regarded as a rigid body. On the other hand, the flange with e = 2.25g shows the maximum surface pressure at the location near e = 1.0 g. The equivalent action point of flange reaction force e' calculated by Equation 3 is approximately 0.7e.

3.2 | Formula for the action point correction factors

The action point correction factors for L-type flanges obtained by FE analyses are shown in Figure 7. A formula for the action point correction factors λ is proposed by fitting FE results and expressed by Equation 5.

$$\lambda = \begin{cases} 1-(1-a^b)^5 & 1.25 \le e/g \le 2.25 \\ 1 & e/g \le 1.25 \end{cases} \quad (5)$$

where

$$a = t_F/(e+g) \qquad -0.12(e/g) + 0.55 \le a \le 1$$

$$b = (e/g - 1.25)^{0.32} + 0.45 \qquad 1.25 \le e/g \le 2.25$$

It is a function of aspect ratio of flange only, and the parameters d_B, D, t_S, and p as shown in Table 1 are not included in Equation 5 because the effect of these parameters is negligible from the FE analyses. The proposed formula can be applied to the ultimate strength analysis of flange connection when the bolt first reaches an acceptable limit. It provides a conservative, lower bound estimate of the true position of the action point when the plastic limit state is reached because the further inside movement of the action point appears in this situation.

4 | CONCLUSIONS

In this study, systematic FE analyses on various flange dimensions are performed. An action point correction factor and its geometrical limitation are proposed. The following conclusions are obtained.

1. An action point correction factor of flange reaction force for L-type flange of wind turbine tower is proposed based on systematic FE analyses and explicitly expressed as a function of flange dimensions.
2. The proposed factor is simple and suitable for the engineering applications, comparing with the conventional formula for the ultimate strength analysis of flange connections.

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