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ДРУШТВО НА ГРАДЕЖНИТЕ КОНСТРУКТОРИ НА МАКЕДОНИЈА

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WIND TOWERS – DESIGN OF FLANGE RING CONNECTION

SUMMARY

Today, wind power is second largest available renewable resource of energy, with 870 TW (terawatts). Large wind farms, with hundreds of wind towers are big opportunity for steel production industry. Designers and manufacturers of wind towers pay special attention on every single detail, always looking for some new solutions, trying to reduce price of wind towers. Some of the most interesting design and manufacturing details are connections used to assemble sections of tubular steel towers supporting wind turbins. There is traditional and actually more used flange ring connection and on the other side, as a new proposal which is used more and more, friction connection. In this paper theoretic basis of design of flange ring connection of wind towers is given.

Key words: wind tower, flange ring connection, ULS, SLS, fatigue, plastic-hinge method

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УПАТСТВА ЗА ПОДГОТОВКА НА ТРУДОТ

РЕЗИМЕ

Соопштението треба да биде подготвено почитувајќи ги следните правила: вкупниот број на страници не треба да надминува 6, со исклучок на воведните и повиканите соопштенија, кои се ограничени на 12 страници. Текстот треба да биде напишан на македонски или англиски јазик, а резимето на двата јазика. Текстот треба да биде напишан во **Times New Roman** фонт (со македонска подршка) 11 pts, без проред помеѓу редовите, а 6 pts проред пред секој параграф. Првата страница започнува со името на авторот/авторите, а под него насловот на соопштението со сите букви големи, во **Bold, 12 pts,** и двете центрирани во средина на страницата. Под насловот следат резимеата на македонски и на англиски јазик. Адресата на авторот/авторите се наведуваат во фуснотата на првата страница. Резимето не треба да надмине 8 реда.

Клучни зборови: Максимум еден ред

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1. GENERAL

Currently, assembling sections of tubular steel towers with bolted ring flange connections is more often used than the friction connections. Bolted flange ring connection consists of steel rings which are welded at both tube ends and of high strength bolts which connect these rings. For design purpose it is assumed that the resistance of the three dimensional connection detail, which is loaded mostly in bending, can be described by the resistance of a segment with a single bolt. The segment width *c* is equivalent to the arc length between two bolt holes (Fig.1). The segment is considered to be loaded in tension. The required design checks are: resistance at ultimate limit states (ULS), fatigue strength and resistance at the serviceability limit states (SLS).

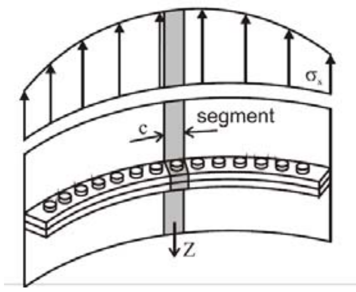

Fig. 1. Segment with a single bolt

2. DESIGN OF FLANGE RING CONNECTION

2.1. Ultimat limit states

The static resistance of a flange connection at ULS is determined by the failure of the bolts or of the flange. The verification in the ultimate limit state is usually done according to the plastic hinge theory 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).

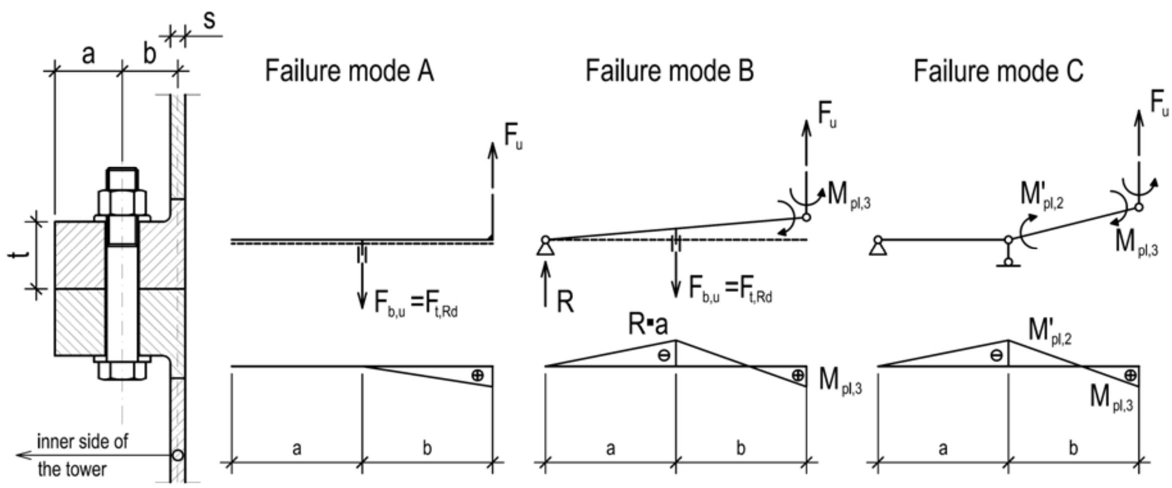

Fig. 2. Failure modes A, B and C

Failure mode A – bolt failure (flanges and shells stronger than bolts):

$$F_U = F_{t,Rd} = \frac{0.9 \cdot A_s \cdot f_{ub}}{\gamma_{M2}} \tag{1}$$

The bending resistance of shell is not exceeded:

$$F_U \cdot b \leq M_{pl,3} \tag{2}$$

Failure mode B – bolt failure and plastic hinge in the shell:

$$F_U = \frac{F_{t,Rd} \cdot a + M_{pl,3}}{a + b'} \tag{3}$$

The minimum bending resistance of the flange, at the bolt axis, is not exceeded:

$$R \cdot a \leq M'_{pl,2} \tag{4}$$

Failure mode C – plastic hinges in the shell and in the flange:

$$F_U = \frac{M_{pl,2} + M_{pl,3}}{b} \tag{5}$$

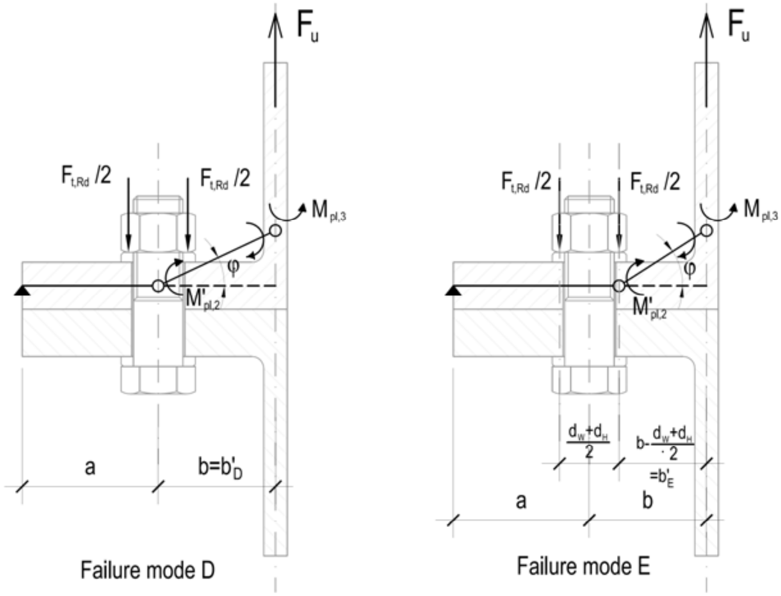

Fig. 3. Failure modes D and E

Failure mode D – plastic hinge at the bolt axise. The bending resistance of the flange is reduced by the bolt hole and the extra resistance from the bolt force eccentricity is considered:

$$F_U = \frac{M'_{pl,2} + \Delta M_{pl,2} + M_{pl,3}}{b'_D} \tag{6}$$

The full bending moment of the flange is not exceeded at mid-washer:

$$\left(\frac{F_{t,Rd}}{2} - F_{U,D}\right) \cdot \left(\frac{d_W + d_H}{4}\right) \leq M_{pl,2} - M'_{pl,2} \tag{7}$$

The reaction force R, must act on the flange:

$$r = \frac{M'_{pl,2} + \Delta M_{pl,2}}{F_{t,Rd} - F_U} \le a \tag{8}$$

Failure mode E – Plastic hinge forms away from the bolt axis, at mid-washer. The full bending resistance of the flange is considered:

$$F_U = \frac{M_{pl,2} + M_{pl,3}}{b'_E} \tag{9}$$

The minimum bending moment of the flange is not exceeded at the bolt axis:

$$\left(\frac{F_{t,Rd}}{2} - F_{U,E}\right) \cdot \left(\frac{d_W + d_H}{4}\right) \ge M_{pl,2} - M'_{pl,2} \tag{10}$$

The reaction force R, must act on the flange:

$$M'_{pl,2} + 2 \cdot \Delta M_{pl,2} = R \cdot \left(r + \frac{d_W + d_H}{4}\right) \tag{11}$$

$$r = \frac{M'_{pl,2} + 2 \cdot \Delta M_{pl,2}}{F_{t,Rd} - F_U} - \frac{d_W + d_H}{4} \le a \tag{12}$$

R – is the reaction force at the flange edge,

a – is the distance from the bolt axis to the flange edge,

b – is the distance from the bolt axis to the shell mid plane,

t – is the flange thickness,

s – is the shell thickness,

c – is the segment width,

c'=c-d_B – is the segment width reduced by the bolt hole diameter,

d_H – is the bolt hole diametar,

d_W – is the washer diametar,

b'_D – is the distance between bolt axis and plastic hinge in the shell or flange,

b'_E – is the distance between mid-washer and plastic hinge in the shell or flange

For L-flanges the plastic hinge can indeed develop alternatively in the shell or in the flange. Conservatively it can be considered in the shell and the distances become:

$$b'_D = b \text{ and } b'_E = b - \frac{d_W + d_H}{4} \tag{13}$$

In the presence of a fillet the distances may be reduced by 80% of the fillet radius.

$$M'_{pl,2} = \frac{c' \cdot t^2}{4} \cdot f_{yd} \tag{14}$$

– is the reduced bending resistance of the flange at the bolt axis,

$$M_{pl,2} = \frac{c \cdot t^2}{4} \cdot f_{yd} \tag{15}$$

– is the full bending resistance of the flange,

$$\Delta M_{pl,2} = \frac{F_{t,Rd}}{2} \cdot \frac{d_W - d_H}{4} \tag{16}$$

– is the additional resistive moment introduced by the eccentricity of the bolt force,

$M_{pl,3}$ - is the bending resistance of the shell or of the flange, considering the M-N and M-V interaction respectively. It is iteratively derived from:

$$M_{pl,3} = \min\left\{ \frac{M_{pl,N,shell} = \left[1 - \left(\frac{N}{N_{pl,shell}}\right)^2\right] \cdot M_{pl,shell} = \left[1 - \left(\frac{F_U}{c \cdot s \cdot f_{yd,shell}}\right)^2\right] \cdot \frac{c \cdot s^2}{4} \cdot f_{yd,shell}}{M_{pl,V,flange} = \left[\sqrt{1 - \left(\frac{V}{V_{pl,flange}}\right)^2}\right] \cdot M_{pl,flange} = \left[\sqrt{1 - \left(\frac{F_U}{c \cdot t \cdot f_{yd,flange}}\right)^2}\right] \cdot \frac{c \cdot t^2}{4} \cdot f_{yd,flange}} \right\} \tag{17}$$

2.2. 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. The design verification is performed according to EN1993-1-9 by ensuring that the Palmgren-Miner damage accumulation is lower than unity:

$$D_d = \sum \frac{n_i}{N_i} \leq 1 \tag{18}$$

The most difficult aspect of the flange connection fatigue check is the transformation of the shell loads into bolt forces. This relationship is nonlinear and it can be described by the foolowing curve, 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 FS the stress ranges can be derived and the corresponding damages are extracted from appropriate Wöhler curve.

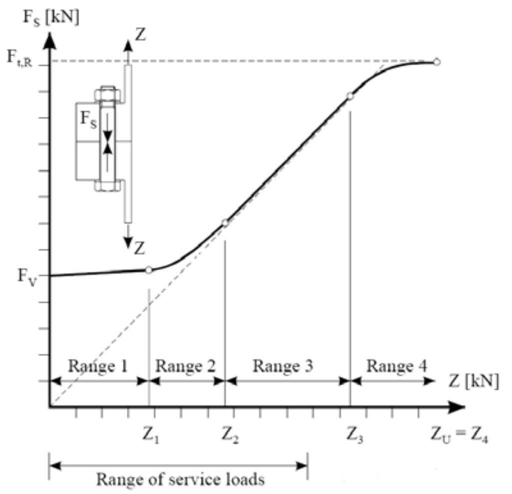

Fig. 4. Nonlinear relationship between bolt force and applied load in the shell (Seidel 2001b)

Range 1: Approximately 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

3. CONCLUSION

At this momment, bolted ring flange connection is most often used assembling detail for wind towers. Table 1 illustrate material costs for this type of connection (defined by the radius and type of bolts). It is very obviously that this price is not low and because of that is very important for designers to pay special attention designing this connections.

Component	Unit price [€]	Amount	Total price [€]
Flange (d_a=3917mm)	6762	2	13524
Bolt (M42x245 10.9)	20.32	124	2520
		Total:	**16044**
Flange (d_a=3448mm)	4395	2	8790
Bolt (M36x205 10.9)	11.40	116	1322
		Total:	**10112**

Table 1. Prices of bolted flange ring connection

Although future tendencies are to improve friction connections for frequent use, according to all that was written, it’s very important to introduce bolted ring flange connection to civil engineers in general.

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