

BOLTED CIRCULAR FLANGE CONNECTIONS

Bending and axial static resistances

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INTRODUCTION

Bolted circular flange connections can be used in tubular members such as chimneys, pylons for wind turbines and ski-lift installations. Most of these connections must be designed for a combined moment and axial load. In this paper, a model is proposed for the determination of the static resistance of a bolted circular flange connection subjected to the full range load combinations of moment and compressive or tensile axial load. This model is based on the limit analysis and considers two general failure modes based on the ductility of the tensile part and the shell buckling resistance of the compressive part of the connection. The resistance of all the components can be fully reached provided that they are sufficiently ductile, this mode is then called “ductile mode”. In the case of a “non ductile mode”, the resistance of the compressive and/or tensile component is reached locally. A finite element model considering an elasto-plastic behaviour and contact elements is used to perform a parametric study. The results obtained from the proposed analytical model are in good agreement with the numerical results.

1 ANALYTICAL MODEL

1.1 General hypothesis

Two types of model have been developed to determine the ultimate resistance of bolted circular flange connections subjected to the combination of a bending moment and/or an axial force:

- Models based on elastic analysis ([2]-[4]) where the ultimate state corresponds to attaining the resistance of just one component of the connection (tensile or compressive). This criterion doesn't always reflect the real resistance of the connection as other components may possibly reach their plastic resistance. However, in the presence of a lack of ductility (tube wall buckling, premature bolt rupture), this hypothesis is not far from the experimental and numerical observations ([7]-[9]).
- Stamatopoulos & Ermpopoulos [6] have developed a model based on the limit analysis where all the components of the connection are assumed to reach their full plastic resistance at the ultimate state. Hence, the tensile components would have to be sufficiently “ductile” to permit the mobilization of the all the components in the tensile zone and tube wall buckling would have to be excluded.

The type of failure mode depends on the ductility of the different components of the connection; the authors have chosen to consider two types of failure mode:

- A “ductile” failure mode (see Fig. 1) where the full resistance of each component is reached,
- A “non ductile” failure mode (see Fig. 2) where the full resistance of only some of the most highly stressed components of the connections is reached.

How to identify the relevant failure is explained in paragraph 4.

In the model, a force per unit length, $f(\theta)$, is applied by the tube wall to the flange (see Fig. 1 and Fig. 2).

In the case of the “ductile” failure mode, since the resistance of each component of the connection is reached (see Fig. 1), thus we have:

$$f(\theta) = \begin{cases} f_{c,pl}, & \text{for } 0 \leq \theta \leq \alpha \\ f_{t,pl}, & \text{for } \alpha \leq \theta \leq \pi \end{cases} \quad (1)$$

where $f_{c,pl}$ Compression resistance per unit length of the tube wall (see paragraph 1.3),
 $f_{t,pl}$ Resistance per unit length of the tensile part of the connection (see paragraph 1.2),
 α Angle defining the position of the neutral axis (see Fig. 1).

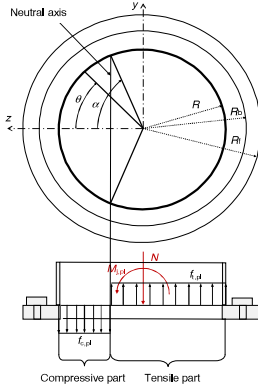


Fig. 1. “Ductile” failure mode

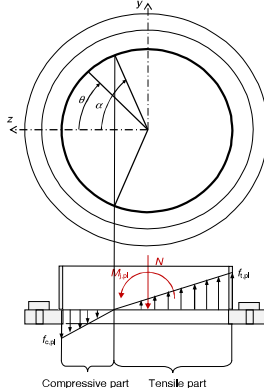


Fig. 2. “Non ductile” failure mode

In the case of the “non ductile” failure mode, the resistances of the most highly stressed tensile and compressive components of the connection are reached (see Fig. 2), thus we have:

$$f(\theta) = \begin{cases} f_{c,pl} \frac{\cos \theta - \cos \alpha}{1 - \cos \alpha}, & \text{for } 0 \leq \theta \leq \alpha \\ f_{t,pl} \frac{\cos \alpha - \cos \theta}{\cos \alpha + 1}, & \text{for } \alpha \leq \theta \leq \pi \end{cases} \quad (2)$$

For these two failure modes the position of the neutral axis, defined by the angle α , will be determined via the axial equilibrium equation:

$$F_{c,pl,tot} = N + F_{t,pl,tot} \quad (3)$$

where $F_{c,pl,tot}$ Resultant of the compressive part,
 $F_{t,pl,tot}$ Resultant of the tensile part,
 N Axial force.

Furthermore, the plastic bending moment of the connection for a tube of mid wall diameter R is:

$$M_{j,pl} = M_{j,t,pl} + M_{j,c,pl} + NR \cos \alpha \quad (4)$$

Where $M_{j,c,pl}$ Resultant moment arising from the compressive part,
 $M_{j,t,pl}$ Resultant moment arising from the tensile part.

1.2 Resistance of the tensile part

The resistance per unit length of the tensile part of the connection, $f_{t,pl}$, is derived from the tensile resistance of the joint:

$$f_{t,pl} = \frac{N_{T,pl}}{2\pi R} \quad (5)$$

where $N_{T,pl}$ Tensile resistance of the joint,

The tensile resistance of the connection can be determined via the L-stubs model ([2], [5]) or considering the polar symmetry of the circular flange [10]. In the present paper, the latter has been considered.

1.3 Resistance of the compressive part

Noting that the limit state is reached in the compression part when the tube wall buckles or yields, the resistance per unit length of the compressive part of the connection, $f_{c,pl}$, is derived from the compressive resistance of the tube :

$$f_{c,pl} = \frac{N_{c,pl}}{2\pi R} = \sigma_{\chi,Rk} t_t \quad (6)$$

where $N_{c,pl}$ Compressive resistance of the tube,

t_t Thickness of the tube wall,

$\sigma_{\chi,Rk}$ Longitudinal characteristic stress of the tube wall calculated via §8.5.2(3) of EN 1993-1-6 [11].

2 DUCTILE FAILURE MODE

When the failure mode is “ductile”, the resulting forces of the compressive and the tensile parts are obtained from (1):

$$F_{c,pl,tot} = 2 \int_0^\alpha f_{c,pl} R d\theta = 2\alpha R f_{c,pl} \quad (7)$$

$$F_{t,pl,tot} = 2 \int_\alpha^\pi f_{t,pl} R d\theta = 2(\pi - \alpha) R f_{t,pl} \quad (8)$$

Introducing the resulting forces (7) and (8) into the axial equilibrium equation and considering the relation (5) and (6), we get an expression for the angle α defining the position of the neutral axis:

$$\frac{\alpha}{\pi} = \frac{N + N_{T,pl}}{N_{c,pl} + N_{T,pl}} \quad (9)$$

One observes that the position of the neutral axis depends on the axial force, the compressive and tensile resistances of the joint. When the connection is entirely in tension ($N = -N_{T,pl}$), the angle α is equal to 0. On the other side, when the joint is entirely in compression ($N = N_{c,pl}$), the angle is equal to π . Simultaneous to the axial load N , the bending moments resulting from the tensile and compressive parts of the connection are:

$$M_{j,c,pl} = 2 \int_0^\alpha f_{c,pl} d_c(\theta) R d\theta = N_{c,pl} R \frac{\sin \alpha - \alpha \cos \alpha}{\pi} \quad (10)$$

$$M_{j,t,pl} = 2 \int_\alpha^\pi f_{t,pl} d_t(\theta) R d\theta = N_{T,pl} R \frac{\sin(\pi - \alpha) - (\pi - \alpha) \cos(\pi - \alpha)}{\pi} \quad (11)$$

where d_c and d_t are the distances between the neutral axis and the forces $f_{c,pl}$ and $f_{t,pl}$ respectively.

Introducing the expressions (10) and (11) into (4), we get the plastic bending moment:

$$M_{j,pl} = M_{j,pl,D} \sin \alpha \quad (12)$$

$$\text{where } M_{j,pl,D} = \frac{N_{T,pl}R + N_{c,pl}R}{\pi}.$$

The plastic bending moment is linked to $M_{j,pl,D}$ and to the angle α which itself depends on the axial force N .

3 NON DUCTILE FAILURE MODE

3.1 Case 1: Dominant bending moment

When the failure mode is “non ductile” and the bending moment is dominant, there are always both compressive and tensile parts with the following resultant forces:

$$F_{c,pl,tot} = 2 \int_0^{\alpha} f(\theta) R d\theta = \frac{N_{c,pl}}{\pi} \frac{\sin \alpha - \alpha \cos \alpha}{1 - \cos \alpha} \quad (13)$$

$$F_{t,pl,tot} = 2 \int_{\alpha}^{\pi} f(\theta) R d\theta = \frac{N_{t,pl}}{\pi} \frac{\sin \alpha + (\pi - \alpha) \cos \alpha}{1 + \cos \alpha} \quad (14)$$

Introducing the resulting forces (13) and (14) into the axial equilibrium equation (3), we get an equation depending on the angle α :

$$\frac{N}{N_{T,pl}} = \frac{N_{c,pl}}{N_{T,pl}} \frac{1}{\pi} \frac{\sin \alpha - \alpha \cos \alpha}{1 - \cos \alpha} - \frac{1}{\pi} \frac{\sin \alpha + (\pi - \alpha) \cos \alpha}{1 + \cos \alpha} \quad (15)$$

An explicit expression of the angle α can't be determined from this equation and it must be evaluated iteratively. The bending moments, simultaneous to the axial load N , resulting from the tensile and compressive parts of the connection are:

$$M_{j,c,pl} = 2 \int_0^{\alpha} f(\theta) d_c(\theta) R d\theta = \frac{N_{c,pl}R}{2\pi} \frac{\alpha - \cos \alpha \sin \alpha}{1 - \cos \alpha} - F_{c,pl,tot} R \cos \alpha \quad (16)$$

$$M_{j,t,pl} = 2 \int_{\alpha}^{\pi} f(\theta) d_t(\theta) R d\theta = \frac{N_{t,pl}R}{2\pi} \frac{\pi - \alpha + \cos \alpha \sin \alpha}{1 + \cos \alpha} + F_{t,pl,tot} R \cos \alpha \quad (17)$$

Introducing the expressions (16) and (17) into (4), we get the plastic bending moment:

$$M_{j,pl} = -\frac{R \cos \alpha N}{2} + \frac{N_{T,pl}}{2\pi} R (1 - \cos \alpha)(\pi - \alpha) + \frac{N_{c,pl}}{2\pi} R (1 + \cos \alpha) \alpha \quad (18)$$

The latter expression can be used for all the values of N comprised between $-N_{c,pl}/2$ and $-N_{t,pl}/2$. In fact the absolute value of N has to be less than $2M_{j,pl}/R$. When that condition is not met, the axial force is dominant for which the connection is either completely in tension or completely in compression.

3.2 Case 2: Dominant axial force (tension/compression)

When the axial force is dominant, the ultimate state is reached in the highly stressed part of the joint, so the plastic bending moment becomes:

$$M_{j,pl} = \begin{cases} \frac{N_{c,pl}R}{2} \left[1 - \frac{N}{N_{c,pl}} \right], & \text{if } N \geq N_{c,pl}/2 \\ \frac{N_{t,pl}R}{2} \left[1 + \frac{N}{N_{t,pl}} \right], & \text{if } N \leq -N_{t,pl}/2 \end{cases} \quad (19)$$

4 DUCTILITY OF THE JOINT

Each joint component will reach its resistance only if the most deformed components are sufficiently ductile in both the tensile and the compressive parts. It is obvious that the tensile part of the joint is non ductile when its failure mode corresponds to the rupture of bolts without prying action. On the other side, the compressive part of the joint is ductile when the tube is class 1 or 2. However, even if the class of the tube is 3 or 4, the tensile part of the joint when sufficiently ductile can reach its entire potential resistance if its resistance is significantly lower than that of the compressive part of the joint. Finally, with the benefit of a series of comparisons with numerical and experimental results, the authors have chosen that a joint can be classified as “non ductile” if one of the following conditions is fulfilled:

- The class of the tube is 3 or 4 and the compressive resistance of the tube isn't 20% greater than the tensile resistance of the connection, $N_{T,pl}$,
- The tensile resistance of the connection, $N_{T,pl}$, is greater than 95% of the sum of tensile resistance of bolts.

5 VALIDATION OF THE MODEL

5.1 Numerical model

A numerical model has been developed [7] to carry out a parametric study and to complete the available experimental results ([7]-[9]). The numerical model was built using the Finite element code ANSYS V11.0 with contact and brick elements. This model is quite similar to that developed for bolted circular flange connections subjected to a tensile force [10]. Due to symmetry, just an half of the connection is studied. A symmetry plane cut the joint and a rotation is applied. The plastic bending moment, $M_{j,pl}$, has been determined via the moment-rotation curve (see Fig.4) obtained by the numerical model considering the ECCS method [1].



Fig. 3. Meshing of the numerical model

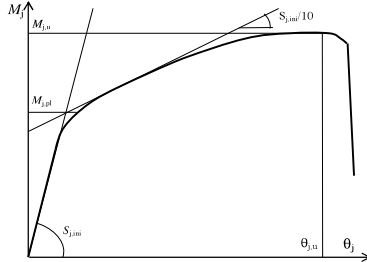


Fig. 4. A typical moment-rotation curve of a joint

5.2 Comparison with numerical results

A total of 16 joints have been studied numerically for different combinations of the bending moment and the axial force [7]. A typical M - N Diagram obtained via the analytical and numerical model is presented for the specimen M11 in Fig.5. The yield strength of steel of flange, tube and bolt are respectively equal to 355, 475 and 900 MPa. The results obtained via the numerical and analytical models are in quite good agreement. In some cases, the resistance of the joint is overestimated by the analytical model but the difference is less than 9%. Comparisons have been performed with experimental results ([7]-[9]) for other joints and they show that the analytical model presented here underestimates the resistance of the joint.

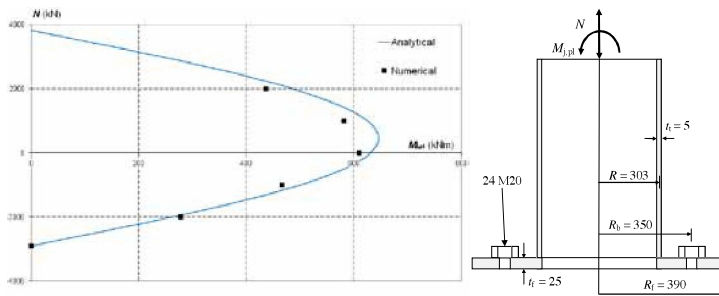


Fig. 5. Interaction M-N and geometry of Specimen M11

6 CONCLUSION

In the present paper, an analytical model has been proposed to determine the resistance of bolted circular flange connections subjected to a combination of a bending moment and an axial force (tension/compression). Two failure modes are considered to determine the plastic bending moment depending on the ductility of the tension and the compressive parts of the connection. For the “ductile” failure mode, all the components reach their plastic resistance. For the “non ductile” failure mode, only the highest stressed component reaches its resistance locally. The resistance calculated via this model has been compared elsewhere [7] to those of experimental and numerical tests and the results were in quite good agreement.

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