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Elastic behaviour of bolted connection between cylindrical steel structure and concrete foundation

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ABSTRACT

The paper deals with bolted connection between cylindrical steel structures and concrete foundations. In the considered connection, the circular steel structure of large diameter is welded to a base plate, and then anchor bolts are used to connect the base plate to the concrete foundation. Repartition plates are also placed to ensure an appropriate distribution of the stresses from the steel parts into the concrete. The studied configuration is often met in industrial chimneys, wind towers, cranes, etc. To characterise the studied connection, an elastic model is more relevant than plastic model but no appropriate and efficient tools for the characterisation of its elastic behaviour are available in the codes and literatures.

In the present paper, a complete analytical procedure is proposed to predict the elastic responses of the connection from their geometrical and material characteristics. Several effects are taken into account in the model, such as the effect of the bolt preloading, the long term effects in the concrete and 3D behaviour of the concrete foundation. The analytical results are validated through comparisons with numerical results. Numerical examples are also given to illustrate the proposed calculation procedure.

1. Introduction

Normally, cylindrical steel structures with large diameters, such as industrial chimneys, wind towers, and cranes, are connected to a concrete foundation by a bolted joint (Fig. 1). For this type of connection, the body of the structure is welded to a base plate, and then the anchor bolts are used to connect the base plate to the foundation. Repartition plates are also placed to ensure an appropriate distribution of stresses from the steel parts into the concrete foundation.

Globally, this type of structure works as a cantilever beam; therefore, the characteristics of the structure–foundation connection strongly influence the overall behaviour of the structure. Moreover, experience shows that the base connection of the structure is the zone where premature failures often occur, mainly due to fatigue in the bolts. So the design and execution of the structure–foundation connection require an important vigilance.

Since the diameter of the assembly is very large (about 2 m to 6 m), and the bending effect is predominant in the structure body, the use of a plastic model would result in important ductility requirements that most configurations could not meet in the practice. Therefore, an elastic approach appears to be the most relevant one. In addition, an elastic model can provide useful information, as the connection rigidity, the evolution of the stress in the elements. These information allow us to assess the fatigue strength or calculate static/dynamic responses of the structure in the design process.

Concerning the design codes, the following remarks can be drawn: EN-1993-1-8 (design of joints) [8] provides rules for calculating column bases, especially for columns in buildings with I/H sections. So, improvements of these rules are required in order to cover the joint configuration investigated here. EN-1993-1-9 dedicated to fatigue design [9] provides us details to estimate the fatigue resistance of elements of steel structures. The bolt is classified as a nominal detail for which the effects of bending and prying must be considered. However, the determination of the stress in the bolt taking into account these effects in the elastic range is questionable in many cases. Other codes may be considered, such as CEN/TS1992-4-1 (design of fastenings) [7], EN1993-3-1 and 3-2 (design of towers, mats and chimneys) [10, 11] or EN1993-4-1 (design of silos) [12] but they do not specifically address the design of connections between cylindrical structures and concrete foundations.

Looking in literature, several researches regarding the behaviour of column bases [e.g. 13,14,16,17,19–21, among others] have been carried out in the past 20 years. Most of them investigate the possibility to extend the component method (initially developed for beam-to-column) to column bases of buildings with columns with I, H or hollow sections. The application of these results on the analysis of cylindrical structures, especially in the elastic range, requires more developments. In particular, the presence of bolt preloading is not addressed in the existing tools, due to a lack of knowledge in terms of loss of preload in the anchor bolt.

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Notations

Materials

E_s and ν_s are the Young modulus and Poisson ratio of the steel plates respectively
E_b is the Young modulus of bolt material
E_c and ν_c are the Young modulus and Poisson ratio of the concrete respectively
$\varphi(t)$ is the creep coefficient of the concrete at time t
$\delta_{shrinkage}$ is the deformation due to the shrinkage of the concrete at time t

Geometrical parameters

a_1 is the distance from the base plate edge to the repartition plate edge (the wall side)
a_2 is the distance from the base plate edge to the repartition plate edge (the free side)
b is the width of the sub-part (equals to the base/repartition plate width)
b_{eff} is the effective width of the base plate
c is the flange width of the equivalent rigid T-stub of the repartition plate
d is the nominal diameter of the bolt
d_w is the diameter of the washer
e_{01} is the distance from the bolt centre to the prying force position (with preload effect)
e_{02} is the distance from the bolt centre to the prying force position (without preload effect)
e_1 is the distance from the centre of the tube wall to the bolt centre
e_2 is the distance from the bolt centre to the free edge of the base plate
e_x is the distance from the centre of the tube wall to the base plate edge
H_c is the height of the concrete part between two repartition plates
l_b is the grip length of the bolt
r_w is the radius of the tube wall (structure body)
r_b is the radius of the bolt pitch
t_b is the thickness of the base plate
t_p is the thickness of the repartition plate
t_w is the thickness of the tube wall
w is the width of the repartition plate
w_r is the width of the rigid part of the repartition plate

Forces

B_0 is the initial preload in the bolt
B_1 is the force in the bolt from which the preload effect is absence
F_t and F_c are respectively the tension and compression forces applied to the sub-part
F_1 is the tension force from which the preload effect is absence
M is the bending moment applied to the whole connection
M_b is the bending moment in the bolt shank (at the bolt head)
M_w is the bending moment in the tube wall (at the section attached to the base plate)
N is the axial force applying to the whole connection

Rigidities

E_sI is the bending rigidity of the base plate (equivalent beam)
G_sA is the shear rigidity of the base plate (equivalent beam)
$k_{\Delta,b}$ is the rigidity of the bolt in tension
$k_{\theta,b}$ is the rigidity of the bolt in bending
$k_{\Delta,c}$ is the rigidity of the concrete under compression
$k_{\theta,c}$ is the rigidity of the concrete under bending
k_w is the flexural rigidity of the tube wall
K_{t1} is the rigidity of the sub-part in tension with the preload effect
K_{t2} is the rigidity of the sub-part in tension without the preload effect
K_c is the rigidity of the sub-part in compression

Due to the above mentioned reasons, engineers encounter difficulties when designing the considered type of assembly and a sophisticated numerical model through finite element methods is often used, even it is known to be expensive and time consuming.

In the present paper, a complete analytical procedure is proposed to predict the elastic responses of the connection from their geometrical and material characteristics. Several effects are taken into account in the model, such as the effect of the bolt preloading, the long term effects in the concrete and 3D behaviour of the concrete foundation. The analytical results are validated through comparisons to numerical results. Numerical examples are also given to illustrate the proposed calculation procedure.

2. Behaviour of a sub-part of the connection

As the considered connection is axis-symmetric (both geometry and material), the studies may be carried out on a sub-part, as described in Fig. 2; this is a 1 / n part with n, the number of anchor bolts. By extracting this sub-part from the circular connection, this means that the shape of the plates is quite complex. However, for the sake of simplicity, a rectangular form is adopted for the conducted investigations. As the diameter of the connection and the number of bolts are normally significant, the above assumption leads to negligible uncertainties. The width, b, of the sub-part may be estimated as the arc length at the level of the bolts (place on a circle with a radius r_b — see Fig. 2), meaning that b may be calculated by Eq. (1).

$$b = \frac{2\pi r_b}{n}. \tag{1}$$

When the whole structure is subjected to external loads (i.e. horizontal and vertical loads), the tension/compression forces are transferred to the sub-part through the structure wall. Accordingly, based on the component method concept, the following components should be considered to obtain the behaviour of the sub-part:

- Structure wall in traction/compression and bending
- Base plate in flexion and shear
- Bolt in tension and bending
- Repartition plate in bending
- Concrete in compression.

The mentioned components will be characterised in Section 2.1. The procedure to obtain the global behaviour of the sub-part will be presented in Section 2.2. Then, the assembly procedure of the sub-part to obtain the whole joint behaviour will be dealt with in Section 3. The calculation procedure will be summarized in Section 4. Section 5 aims at validating the proposed method and at illustrating the calculation procedure. Section 6 finally addresses some conclusions.