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Tensile resistances of bolted circular flange connections

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A B S T R A C T

A closed form solution for the ultimate tensile resistance of a bolted flange joint is derived considering yield line failure mechanisms developed by Igarashi et al. The position of the prying force is determined based on formulations previously developed by the authors. Under various simplified assumptions and approximations, a design approach similar to that of the Eurocode 3 for T-stubs is proposed. To validate this approach, experimental tests have been performed on six connections of circular hollow sections made of bolted ring flange. A finite element model considering the elastoplastic behaviour of steel and contact conditions has been developed and the results showed a good agreement with experimental results. Based on the FEM model, a parametric study shows that the proposed analytical model is valid for a wide range of connections.

1. Introduction

Bolted flange connections are commonly used for both support and continuity connections of tubular members in a variety of structures such as trusses, communication tower pylons, chimneys, pylons for wind turbines and ski-lift installations as well as lighting and road signal posts. Many of these connections may need to be designed for both static and fatigue loads under combined axial force and bending moment. The CIDECT [1] design guide propose a design method for blank flange connections subjected to static tensile force but no guidance is provided for the case of ring flanges or flanges with central hole. The latter design method is based on the work carried out by Igarashi et al. [2] on the tensile resistance of bolted flange connections. They considered both blank and ring flanges and used limit analysis of circular plates (annular plate) to derive approximate expressions for the ultimate load. Using the upper bound theorem, Kato and Hirose [3] proposed an almost axisymmetric yield line mechanism quite similar to the failure mode proposed by Igarashi et al. [2]. Cao and Packer [4] have proposed design formulae derived from an elastic analysis ([5–7]). While the complex expressions derived by Cao & Packer give safe results, a limit analysis approach will use the full plastic capacity of the plate. Van-Long et al. [8] performed tests on two blank flange connections made of high strength steel. They found good agreement between the experimental results and the predictions given by the Eurocode approach [22] applied to these types of connection [9].

It is well accepted that prying force is particularly important for this type of connection as it can increase significantly the value of the bolt force and thus modify the plastic or ultimate resistance of this type of connection. This prying force corresponds to the resultant of contact pressure distribution that develop between the two opposite flanges. In all the cited research papers, the prying force has been represented by a concentrated force acting at or near the flange plate edges. Further it is assumed that the position of the prying force does not depend on the flange thickness. This is in contrast with a recent investigation [11] where it is shown that for T-stubs and L-stubs, the shape of the contact pressure distribution depends on the size of the contact area. The effect of contact is particularly important in presence of thin flanges where the prying force is not located near the free edge of the flanges as assumed by several authors; but rather close to the bolt. It is then obvious that the position of the prying force plays an important role and cannot be disregarded.

The objective of this work is to develop an analytical model able to predict the static resistance of bolted blank and ring flange connections of circular hollow sections (see Fig. 1). This model is an improved version of the one suggested earlier by the authors [13]. The model proposed by Igarashi et al. [2] is enhanced to better account for the effect of the position of the prying force as well as for the action of the tube on the connection. The closed-form expressions of the ultimate load of blank and ring flange connections considering different failure modes are derived. These expressions being too complex for a day-to-day use, we suggest to replace them with simplified but accurate expressions quite similar to those of Eurocode 3.

To validate this new model, experimental tests have been performed on six connections composed of ring flanges and completed by a numerical parametric study. These tests also highlight the impact of bolt preloading and initial imperfections of flanges on the stress evolution in

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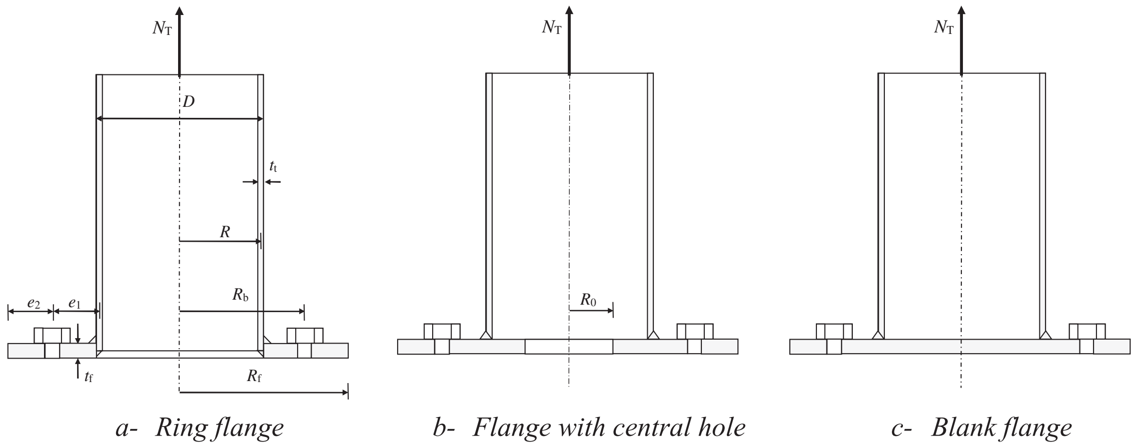

Fig. 1. Bolted circular flange connections of circular hollow sections.

the main joint components; particularly bolts and tubes at the junction with the flange.

2. Experimental tests

2.1. Objectives of the tests

The main purpose of this experimental campaign is to investigate the elastic and elasto-plastic behaviour of bolted ring flange connections subjected to a tensile force. In order to gain deeper understanding of the response of this type of connection to tensile force, tests were conducted at the M&S laboratory (laboratory for mechanic of Material and Structures, University of Liège, Belgium). In these tests, bolt forces, displacements and stresses were measured. The main dimensions of specimens (see Fig. 1a) tested are given in Table 1. The steel grade of the tubes and flanges is S355, and bolts are class 8.8. These type of connections are widely used in pylons of communication towers and more details can be found in [10]. The tube-wall thickness was not varied because of the limited influence it has on the static resistance of these types of connections.

The objectives of the experimental campaign is to quantify the influence of pitches e_1 and e_2, the flange thickness as well as bolt preloading. In total, six specimens were tested. The geometry of these specimens has been produced by varying the flange thickness, the pitches e_1 and e_2, and the tube diameter (see Table 1).

The loading protocol, described in detail in paragraph 2.2, involves three elastic cycles that corresponds to three level of preloading, followed by monotonic loading to failure. During the elastic regime, stress variations of two fatigue details (tube-wall at the weld toe and bolts in tension) were recorded for three level of bolt preloading (snug tightening, half and full nominal preloading as defined in EN 1090-2 [20]). Only HR bolts [21] are used during the elastic stage. At the end of the elastic stage, HR bolts are replaced (except one) by non-preloaded bolts and the load is increased until complete failure of the connection.

Table 1
Main dimensions of connections tested.

Specimen	R_f	R_b	e_1	e_2	Tube ($D \times t_t$)	t_f	Bolts
	mm	mm	mm	mm	mm × mm	mm	
1	130	95	41,85	35	114,3 × 8	20	8M20
2	130	95	41,85	35	114,3 × 8	30	Class 8.8
3	160	120	66,85	40	114,3 × 8	20	
4	160	120	66,85	40	114,3 × 8	30	
5	160	120	39,85	40	168,3 × 8	20	
6	160	120	39,85	40	168,3 × 8	30	

2.2. Tests set-up and loading procedure

A SHENCK machine with a capacity of 2500 kN in both tension and compression is used for the tests (see Fig. 2). The loading is force-controlled during the elastic regime and displacement-controlled during the elasto-plastic regime.

Connections were tested firstly in the elastic regime for three level of bolt tightening: 10, 50 and 100% of nominal preloading of EN 1090-2 [20] with the aim to evaluate effect of preloading on the evolution of elastic bolt forces. The connection is loaded by a tensile force avoiding yielding and unloaded for each level of preloading. All bolts were instrumented, so that tightening was performed by reading the strain gauge according to the calibration factor. The three cycles are labelled stage 1, 2 and 3, respectively.

After these three elastic cycles, HR instrumented bolts are removed

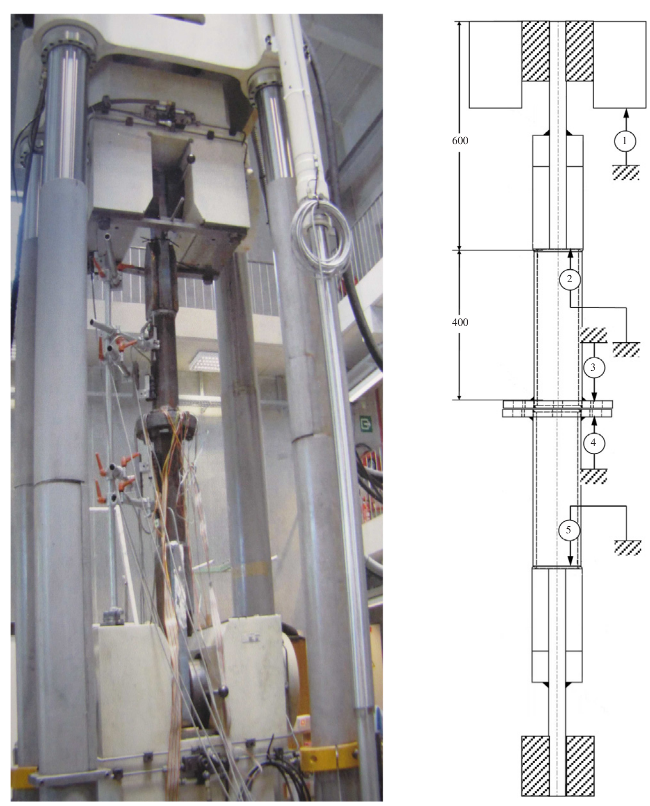

Fig. 2. Tests set-up and displacement measurement.