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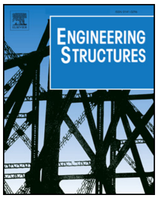

Experiment and design methodology of a double-layered flange connection in axial loads

Hongzhou. Deng[a,*], Xueqi Song[a], Zhenhua Chen[a], Pengcheng Fu[b], Jianyao Dong[b]

[a] *Department of Structural Engineering, College of Civil Engineering, Tongji University, Shanghai 20092, China*
[b] *East China Electric Power Design Institute Co., Ltd., Shanghai 200063, China*

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ABSTRACT

This paper introduces a new type stiffened flange connection called inside and outside double-layered (IODL) flange connection for large circular hollow sections (CHS). This kind of connection not only make full use of the inner space of the circular tubes but also avoid safety problems by using smaller bolts and thinner flange plates. The purpose of the research presented in this paper is to thoroughly analyze the behavior of the connections by an experimental testing program and advanced finite element analysis (FEA) and propose corresponding design method for practical engineering. Experiments on four types of down-scaled specimens were performed. Results of advanced quasi-static FEA, using explicit dynamic solver and ductile damage material model for bolts, are compared to experimental results. Failure modes, bolt forces and distribution of stresses in the upper plates, stiffened plates and end plates are analyzed. Design models for high strength bolts, upper plates, stiffened plates and end plates are proposed. The connections designed according to these models will meet the demand of safety and economy.

1. Introduction

Bolted flange connections, as an important solution of splicing steel circular tubes, are widely used in high-rise structures especially in transmission towers due to the unique advantage of fast installation. Typical bolted flange connections for circular hollow sections (CHS) used in transmission towers can be generally classified into two types—unstiffened flange connections (Fig. 1(a)) and stiffened flange connections (Fig. 1(b)). Unstiffened flange connections are usually used in brace members while stiffened flange connections are used in main members where loadings are very large.

In recent years, the research emphasis mainly focuses on the typical flange connections for CHS, especially typical unstiffened flange connections. The main concern of the researches on unstiffened flange connections is the prying action. Several theoretical models have been put forward to calculate the prying forces and show good agreement with experimental results [1–6]. Stiffened flange connections are generally regarded as no prying actions and the ultimate behavior of the flange plates is the main concern [7]. Yet, some researchers also find that the prying forces exists in stiffened flange connections and are related to the thickness of flange plates [7]. The existence of the prying forces will increase the design force of the bolts and makes the bolts larger as well as the thickness of the flange plates.

With the increasing of voltage level, long-span transmission towers with CHS are becoming much higher, which inevitably makes the loadings much larger. Typical stiffened flange connections can no longer meet the requirements of such large loads because the thick plates and large diameter bolts designed through Chinese codes [8,9] may cause lamellar tearing and hydrogen embrittlement fracture as well as construction problems [10]. To solve these problems, Deng et al. [11] and Feng et al. [12] proposed a stiffened inside and outside (IO) flange connection with inner and outer bolts respectively, see Fig. 1(c). Two scaled-down specimens were tested under monotonic axial loads and the experiment showed that the force ratio of outer bolts to inner bolts was about 1.0 when the diameters of bolts were the same. Although the IO flange connection makes the bolts smaller and the flange plates thinner, the mechanical behavior is the same as the typical stiffened flange connection because the flange plates are still under tension of the stiffened plates, which cannot avoid the lamellar tearing completely [13]. In addition, the minimum distance of two adjacent bolts is still three times the diameter of bolts in the IO flange connections.

Recently, a 1000 kV double circuit transmission tower across the Yangtze River is under planning with a tension length of 5053 m and a crossing span of 2150 m. To meet the navigation requirements and to ensure the safety of transmission lines, the tower is designed to be 455 m high which will be the highest transmission tower in the world

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* Corresponding author.
E-mail address: denghz@tongji.edu.cn (H. Deng).

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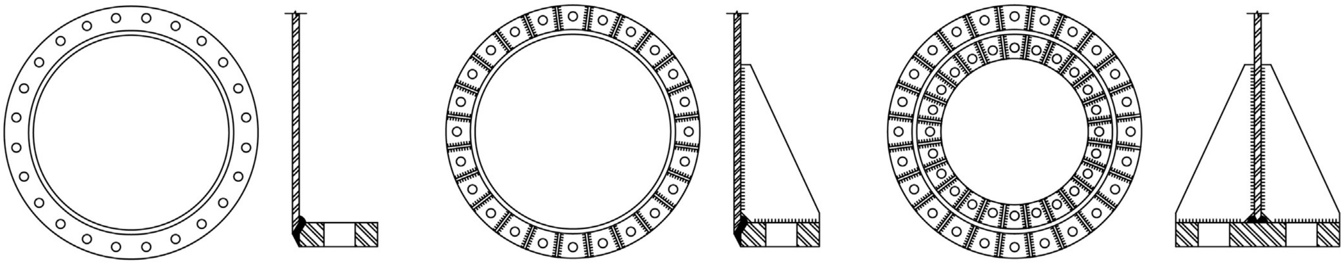

(a) Typical unstiffened flange connection (b) Typical stiffened flange connection (c) Stiffened inside and outside flange connection

Fig. 1. Different types of flange connections.

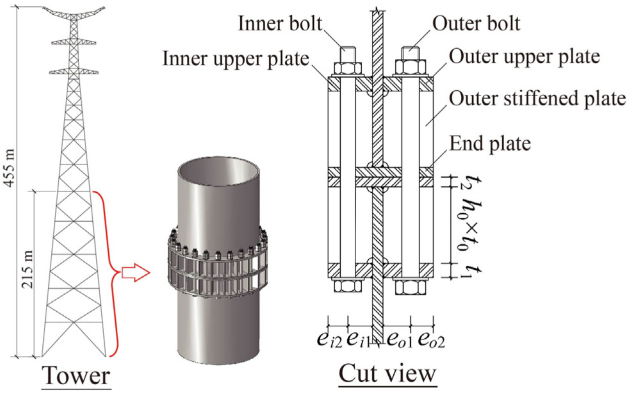

Fig. 2. The IODL flange connection in the transmission tower.

after completion, see Fig. 2. The design tension and compression for critical CHS are 6.9×10^4 kN and 1.5×10^5 kN, respectively. With these large loads, the diameter of the main members will reach to 2450 mm, the thickness of flange plates will reach to 62 mm and the diameter of bolts will reach to 90 mm if typical stiffened flange connections are used. Hence, hydrogen embrittlement fracture of bolts and lamellar tearing of flange plates may occur. Based on this background, this paper introduces another kind of new-type stiffened bolted flange connections called inside and outside double-layered (IODL) flange connections. The definition of dimensions and parameters of a typical IODL flange connection are shown in Fig. 2. The connection consists of upper plates, stiffened plates, and end plates, each of which has inside and outside parts. Different from the IO flange connections, both the upper plates and end plates are under compression of the stiffened plates in the IODL flange connections, which eliminate the lamellar tearing fundamentally. As the diameter of the tubes is large enough, the workers can enter the tubes with the electric wrench and the inner bolts can be tightened. What's more, the minimum distance of two adjacent bolts in the IODL flange connections decreases to 2.3 times diameter of bolts as there are no stiffened plates between the nuts. Therefore, compared with typical stiffened flange connections and IO flange connections, IODL flange connections not only make full use of the inner space of large CHS but use thinner plates and smaller bolts.

Although existed codes, such as AISC [14], AASHTO [15] and GB50017 [16], have design methodology for traditional bolted connections, they cannot be used to design an IODL flange connection. To investigate the behavior of IODL flange connections in axial loads and to create new knowledge about the design rules, scaled-down experiments were conducted on IODL flange connections. Besides, detailed finite element (FE) models are established and non-linear analysis is carried out using the powerful FE software ABAQUS. With the help of ABAQUS, corresponding FE analyses are compared with the results of the experiments.

The purposes of this paper are: to evaluate the reliability of the IODL flange connections by experimental tests, to verify the validity of the FE models and to provide useful recommendations for the design of full-scale transmission towers.

Major symbols

D	External diameter of circular tube, $D/2$ is denoted by R
d_i	Nominal diameter of inner bolt
d_o	Nominal diameter of outer bolt
e_{i1}	Distance from center of inner bolt to inner face of CHS
e_{i2}	Distance from center of inner bolt to edge of inner upper plate
e_{o1}	Distance from center of outer bolt to outer face of CHS
e_{o2}	Distance from center of outer bolt to edge of outer upper plate
f	Design value of the steel yield stress
f_y	Measured steel yield stress
f_u	Measured steel ultimate stress
k	The distribution coefficient of bolt forces, equal to N_o/N_i
h_0	Height of stiffened plate
l_{AB}, etc.	Length of line L_{AB}, etc.
m_p	Full plastic moment of upper plate per unit length
n	Number of inner or outer bolts
N_{tube}	The axial capacity of the tube
N^t	Tensile force applied on the tube
N^c	Compressive force applied on the tube
$N_{y,E}$, $N_{y,E}$	Overall axial yield capacity of the connections obtained from experiment and FEA
$N_{u,E}$, $N_{u,E}$	Overall axial ultimate capacity of the connections obtained from experiment and FEA
N_i, N_o	The bolt force of a single inner bolt and a single outer bolt
$N_{b,i}^t$	Design value of the inner bolt tensile capacity
P	The compression resisted by an outer stiffened plate
T	Tensile capacity of plate zone
t	Thickness of circular tube
t_0	Thickness of stiffened plate
t_1	Thickness of upper plate
t_2	Thickness of end plate
φ	Angle of one segment, be equal to π/n
θ_{AB}, etc.	Rotation of line L_{AB}, etc.
γ	Tensile capacity index of one plate zone.

2. Experimental program

2.1. Description of the specimens

Four types of specimens, NWFL1, NWFL2, NWFL3, and NWFL4, were tested to explore the failure modes and the behavior of the connection in axial loads. Among all specimens, NWFL1, with the same geometric dimensions as NWFL2, was tested under compression while NWFL2, NWFL3 and NWFL4 were tested under tension. Specifically, Specimen NWFL2 was tested as a contrast to compare with Specimen NWFL3 and NWFL4 which were selected to investigate the effect of