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Connections in towers for wind converters, part I: Evaluation of down-scaled experiments

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ABSTRACT

The cost of a tubular steel tower supporting a wind converter becomes increasingly important in a competitive energy market. In-situ connection between tower segments is an important factor of the design. The tower segments are usually connected by welded ring flanges. An alternative solution based on a novel single lap friction connection is analysed. The purpose of the research presented in this paper is to thoroughly analyse the behaviour of both connections by an experimental testing programme and advanced finite element analysis (FEA). Down-scaled experiments of ring flange and friction connection in circular towers were performed using a 4-point bending test set-up. Altogether eight connections joining cylindrical shell, 1 m diameter, plate thickness 8 mm and total span of about 7 m were tested. A friction connection with long open slotted holes and two different cases of the ring flange connection are considered: with perfectly flat flanges and flanges with geometric imperfection. Results of advanced quasi-static FEA, using explicit dynamic solver and ductile damage material model for bolts, are compared to experiments. Failure modes, bolt forces and distribution of meridional membrane stresses in the shell in the vicinity of connections are analysed. Existing hand-calculation models, for the bolt force and normal stress distribution in the shell are validated by experiments and FEA.

1. Introduction

Common onshore towers for wind converters are mostly constructed of tubular steel shells, reaching heights of about 80 to 100 m. This limit is based on the size of the shell diameter of 4 to 4.5 m, which is imposed by transportation reasons. The towers are usually fabricated in segments 20 to 30 m long and in-situ connected with the ring flange connections. The design is governed by fatigue endurance, as the common ring flange connection between two tower segments belongs to a fatigue design class of 71 for a typical detail according to EN 1993-1–9 [1]. In addition, to relatively costly ring flanges this solution leads to rather thick tower shell. Recently finished research projects, HISTWIN, High-strength tower in steel for wind turbines, [2] and HISTWIN2, High steel tubular towers for wind turbines, [3], have mainly focused on use of the friction connections with long open slotted holes (the friction connection) as a competitive alternative for the in-situ connection, see Fig. 1. This solution has much higher fatigue endurance. Class 100 is proposed in HISTWIN2 project [2] because of the limited number of fatigue endurance experiments performed. The new solution turns the stability of the tower shell into the governing design criterion in many cases.

In the new friction connection, bolts are pre-installed in the upper segment (Fig. 2a) and easily slide on the top of the lower segment (Fig. 2b), which is proved by feasibility tests within [2,3]. During the execution, bolts are tightened from the inside of the tower, see Fig. 2c. The cover plates with normal clearance holes on the inner side are used to facilitate the assembling process by holding the bolts in position.

To achieve a better understanding of the friction connection and to be able to develop design rules, down-scale experiments have been performed on ring flange and friction connections. Results of these experiments and corresponding finite element analyses (FEA) are presented in the paper. The friction connection and two different cases of the ring flange connection are considered: perfectly flat flanges and flanges with geometrical imperfection. Two different levels of complexity of FE modelling are considered: a complete model of the 4-point bending test and a segment model (one bolt row model), in which the critical segment of the connection is considered.

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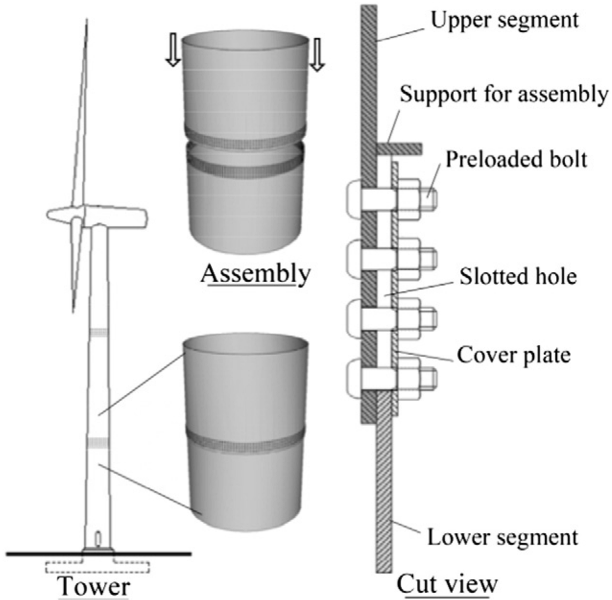

Fig. 1. The friction connection in tower for wind converters [2].

The overall objectives of the paper are: to validate a FE model which can be used for further analysis of the full-scale tower, to evaluate quality of the existing hand-calculation models and to create new knowledge that is relevant for design recommendations of connections in towers for wind converters.

2. Set-up of the down-scaled experiments

Experiments on the ring flange connections and the new type of friction connection were performed by RWTH Aachen University [4] within the scope of the HISTWIN project [2], see Fig. 3a. The main objectives of the experiments were as follows: to investigate the behaviour of the connection in bending, to test the feasibility of the assembling the friction connection and to evaluate effects of flanges with parallel flange imperfections. Totally eight specimens were tested: four with the ring flange connection and four with the friction connection. Experiments were conducted on 8 mm thick shells (S355J2) with diameter of 1 m.

The test set-up of the experiments is shown in Fig. 4. Each specimen consists of four tubular segments: two rather stiff flange-mounted adaptor-segments (Part A) with a length of 2570 mm each and two test-segments (Part B and Part C) with the ring flange or the single lap connection between them. The same adaptor-segments were used for all specimens. They were fabricated with a shell thickness of 15 mm (S460ML) in order to remain in the elastic range during all experiments.

Flanges (S355J2) with thickness $t_{fl} = 35$ mm were connected by 32 high-strength bolts M20, grade 10.9, as shown in Fig. 3c, preloaded to a force $F_{p,C} = 160$ kN. In case of the ring flange connection test-segments (parts B and C in Fig. 4) were identical. Specimen FC1 was fabricated with a perfect connection (machined flanges) to serve as the reference experiment.

Imperfections of the flange are mentioned in the GL Wind Certification Guideline [5] but the design recommendations are not given except that FEA can be used to analyse the influence of flange imperfection. Fig. 5 shows possible imperfections of the L-shaped ring flange connection.

Specimen FC4 was fabricated with parallel gap imperfection over one fourth of the circumference and maximum imperfection amplitude of about 6 mm in the tension zone, see Fig. 3b. Such large imperfections were imposed in the experiment to investigate effects of a reparation method performed in a subsequent experiment which is not content of this paper. The aim was to derive the bolt-force function of an unrepaired flange connection. Specimens FC2 and FC3 were fabricated with the same kind of imperfection as specimen FC4 but different methods using lining plates were used to retrofit the imperfection [4]. Only FC1 and FC4 specimens are analysed in this study.

The friction connection consists of 24 long open slotted holes, length 256 mm, width 23 mm, on the inner shell, and 72 M20 bolts assembled in normal clearance holes on the outer shell, see Part B and Part C in Fig. 4. Cover plates (8 mm thick) are used below washers and nuts on the inner shell in order to ensure proper preloading of the bolts and to facilitate the assembling process, see Fig. 6. Four specimens are tested with two different types of M20 bolts preloaded to $F_{p,C} = 160$ kN: "knurl" bolts in FJ1 and FJ2 specimens and tension control bolts (TCB) in FJ3 and FJ4 specimens. The knurl bolt is a non-standard high strength bolt with grooves in the shank under the bolt-head. It enables fast fixation of the bolt in the fitted bolt hole by press-fitting and allows preloading of the bolt from one side with conventional tools. Specimens FJ1 and FJ2 are examined in this study.

The contact surfaces of the inner and outer segments as well as the cover plates are coated with a zinc shop primer with a characteristic

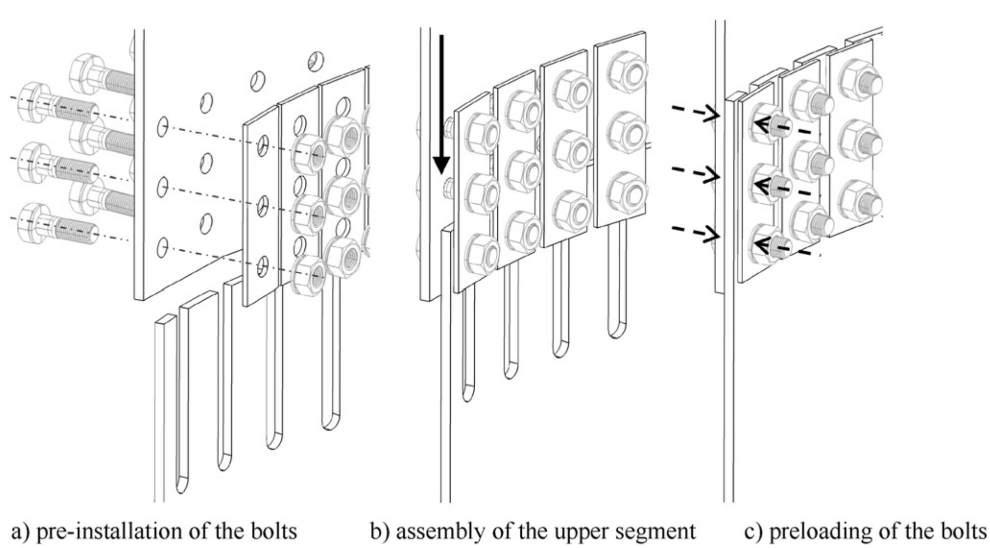

Fig. 2. Execution of the tower with the friction connection.