INFLUENCE OF GEOMETRICAL IMPERFECTIONS ON ANALYSES OF DOOR OPENINGS IN TUBULAR STEEL TOWERS FOR WIND TURBINES

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INTRODUCTION

Initial geometrical imperfection is an important factor in analyses of steel structures. Towers for wind turbines are particularly sensitive to the geometrical imperfection pattern and the amplitude. Consideration of global and local geometric imperfections in design may be found in EN1993-1-1[1], EN1993-1-5[2] and EN1993-1-6 (Annex D) [3]. Various equipment may be used for measurements of initial imperfections: Low Voltage Displacement Transducers (LVDTs) [4,5,6], close-range photogrammetry, optical levelling and Leitz PMM 866 coordinate measuring machine [7]. The most popular way is using LVDTs. In this technology, LVDTs were connected to a reference frame and moved along a member. However, it is difficult to achieve high accuracy using this technique.
The main purpose of this paper is to present the influence of geometric imperfections on the resistance. The work is organized in three steps combining experimental data and FE analysis by Abaqus [8]. Firstly, the geometric imperfection was measured by laser scanning technology and stored electronically. In the second step, measured data were evaluated using Matlab [9] and GOM Inspect software [10], and exported as input data for a nonlinear analysis. In the next step, the nonlinear analysis is performed using measured geometric imperfections and geometric imperfections recommended in Eurocode. Finally, results of FE analysis have been compared with experiments.

1 THE MEASUREMENT OF GEOMETRIC IMPERFECTIONS

1.1 Geometry of specimens

Geometric imperfection using laser scanning equipment was measured in 16 specimens. The testing program was made of 4 circular specimens (the specimen consisted of a part of a circular cross-section), 4 circular specimens with opening, 4 polygonal specimens (the specimen consisted of a polygonal cross-section) and 4 polygonal specimens with opening. All specimens have 1000 mm length and 4 mm plate thickness. The widths of the specimens were 307 mm and 305 mm for circular specimen and polygonal specimens respectively see Figure 1.

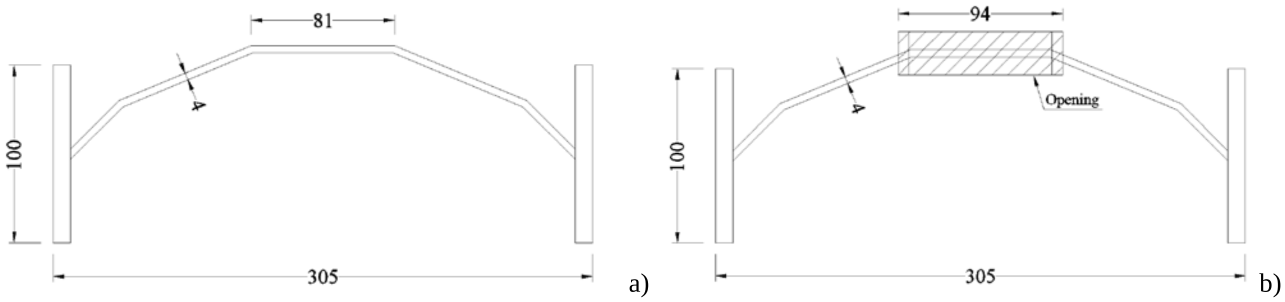


Fig. 1. a) Polygonal specimen; b) Polygonal specimen with opening

1.2 Preparation of specimens

The surface of the specimens was painted with special grey colour in order to restrain reflection of light when using the laser equipment. Target points were glued on the surface of specimens, Fig 2. The distance of target points is about 5 cm. This distance needs to be close enough for interpolation of the measurements. Target points were placed on the flat part of the surface and were organized in a fixed coordinate system.

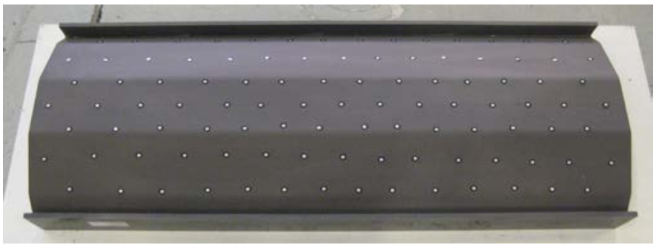


Fig. 2. Preparation of specimen for scanning geometric imperfections

1.3 Measurement

The laser scanner used was VIU scan Handyscan 3D. The equipment has following characteristics: measurement rate (18000 measures/s), resolution (0.1mm), accuracy up to 0.05mm and the software Vxelements were used. The laser scanner moves over the surface of the specimen. The right distance between specimen and the equipment is controlled and a signal is indicated in the handyscan and on the monitor as well. The specimens were scanned by moving of laser lines parallel to the edges. The scanning area was observed on the monitor. The scanned data were analysed by GOM Inspect software [10].

2 FINITE ELEMENT MODELS

Results obtained from 20 finite element (FE) models were analysed and the resistances obtained in nonlinear analysis were compared. Critical buckling mode shape and amplitude of geometric imperfections according to Eurocode 3 were used in four FE models. Geometric imperfections obtained from the laser scanning were used in 16 FE models. All models have 1000 mm length and 4 mm plate thickness. Material used was steel grade S650.
Boundary conditions were determined as follows: fixed all translation and rotation on bottom, fixed all translation and rotation except direction of load on top.. Abaqus software [8] was used to calculate the resistance of the members. The FE models were made using shell elements S4R. Figure 3 shows the mesh of the circular model and the model with the opening. Refinement of FE mesh was especially considered in order to have nodes appropriate for implementation of geometric imperfections.

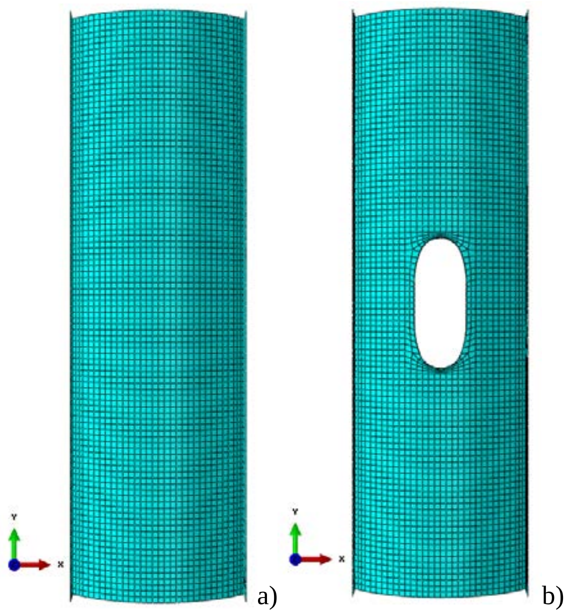


Fig. 3. a) FE mesh of the circular model; b) FE mesh of the circular model with the opening

3 NUMERICAL INVESTIGATION

The amplitude of local geometric imperfections of plate is given in EN1993-1-5 Annex C [2]: min (a/400, b/400) for component (longitudinal stiffener with length a or b) and min (a/200, b/200) for component (panel or subpanel with short span a or b). Imperfections of shells are recommended by EN1993-1-6 Annex D [3]:

$$\Delta w_k = \frac{1}{Q}\sqrt{\frac{r}{t}} * t \tag{1}$$

Where: t is thickness, r is radius and Q is the meridional compression fabrication quality parameter. Q is given in Table 1.

Table 1. Values of fabrication quality parameter Q

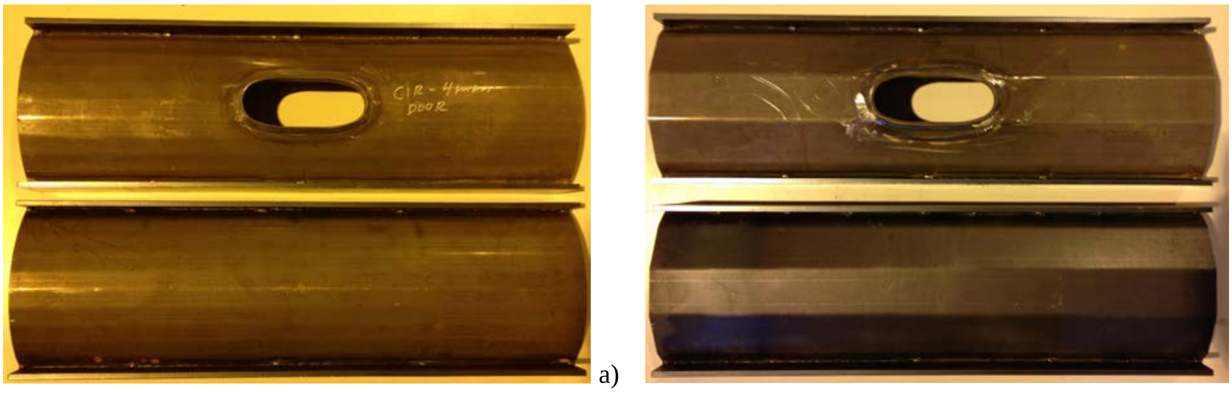
Fabrication tolerance quality class	Description	Q
Class A	Excellent	40
Class B	High	25
Class C	Normal	16

Amplitudes of geometric imperfections according to Eurocode 3 were used with the buckling mode shape obtained in the buckling analysis as the input data of nonlinear analysis.
Nonlinear analyses of models using geometric imperfection amplitudes from laser scanning were carried out as following steps. Firstly, the geometric imperfection was measured by laser scanning technology and stored electronically. In the second step, measured data were evaluated using Matlab [9] and GOM Inspect software [10], and exported as input data for a nonlinear analysis. In the next step, the nonlinear analysis is performed using measured geometric imperfections and assumption widely accepted and recommended in Eurocode. Finally, results of FE analysis have been compared with experiments.

4 EXPERIMENT

4.1 Specimens

The experimental program consisting of 16 specimens in compression was performed. Specimens see Figure 4, have 1000 mm of length and 4mm of thickness. Thicknesses of stiffeners at the opening and of the two stiffeners along the sides are 6 mm and 10 mm respectively.



a) b)

Fig. 4. a) Circular specimen with opening and Circular specimen; b) Polygonal specimen with opening and polygonal specimen

The Instron machine with a capacity of 4500 kN was used in testing. Figure 5 shows the setup of the experiment and the LVDTs arrangement. Speed of displacement was 0.001 mm/s. There were four LVDTs were used to measure displacements. Two LVDTs were attached to the machine to measure the displacements of steel blocks. Two LVDTs were attached to the specimens.

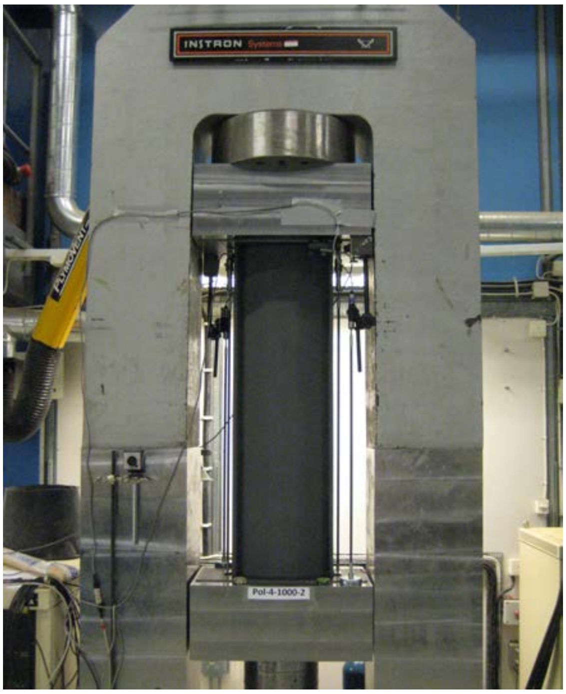
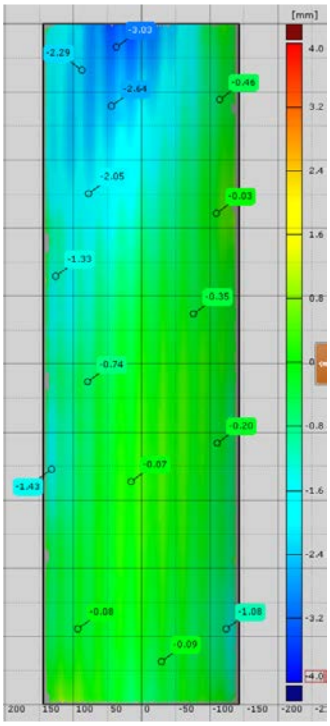


Fig. 5. Typical experiment setup

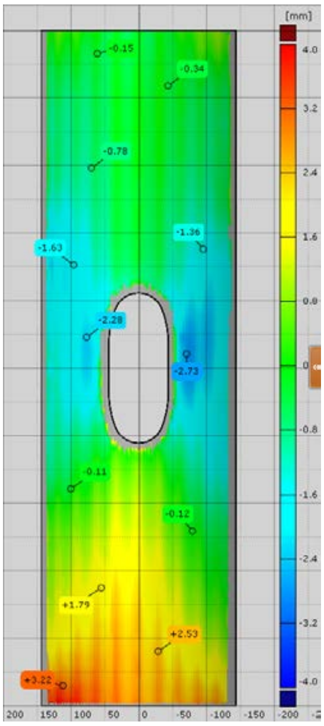
5 RESULTS AND DISCUSSION

5.1 Difference of geometric imperfections

Figure 6 shows the result of geometric imperfection amplitudes of circular specimen and circular specimen with opening. The maximum geometric imperfection of the circular specimen is higher on the left top side. Whereas the large imperfection amplitudes of the circular specimen with the opening is on left bottom side. The pattern of imperfection is not close to the critical buckling shape.



a)



b)

Fig. 6. Geometric imperfection from laser scanning: a) circular specimen; b) circular specimen with opening

In common procedure of nonlinear analysis according to Eurocode 3, the buckling mode obtained in buckling analysis with geometric imperfection according to Eurocode 3 is used. Figure 7 presents the difference between geometric imperfections of the polygonal model according to Eurocode 3 in Fig 7a and two particular polygonal models with geometric imperfection according laser scanning in Fig 7bc.

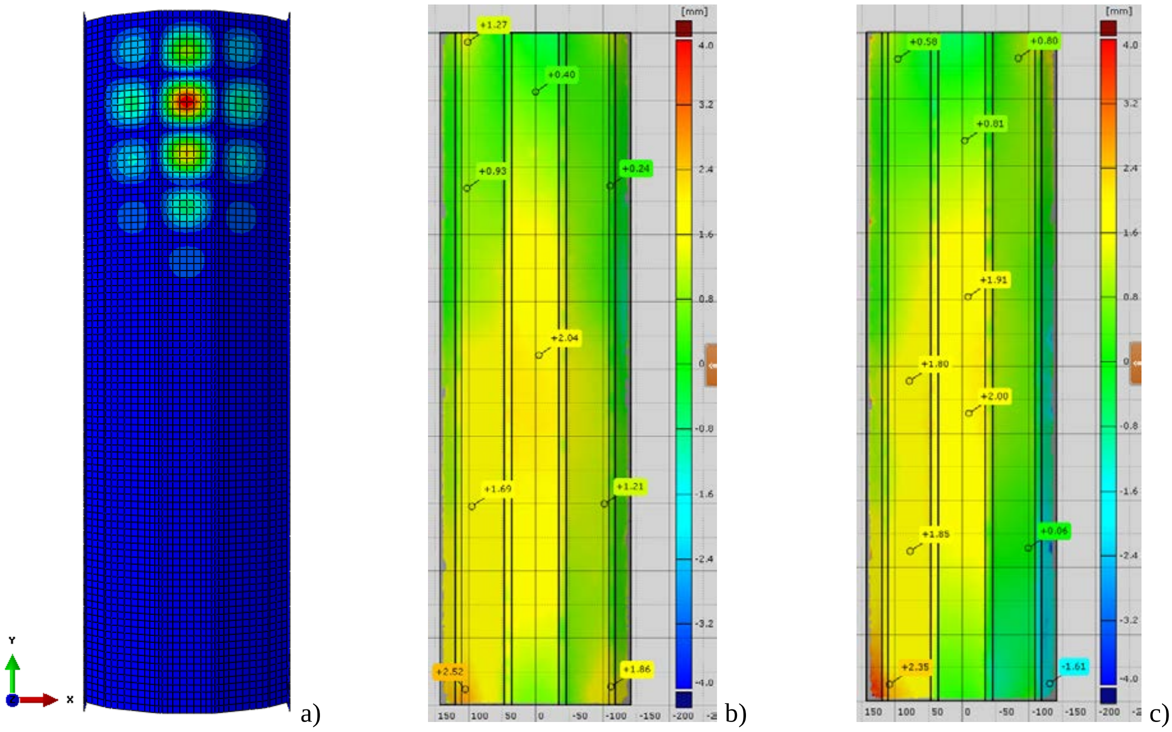


Fig. 7. a) buckling mode shape of polygonal model; b, c) geometric imperfection of specimens from laser scanning

5.2 Comparison of nonlinear analyses

In this study, 20 models were analysed in nonlinear analyses to compare the ultimate load and deformation between models and experiments. Table 2 presents ultimate loads of models in nonlinear analyses and experiments. The ultimate load of models with geometric imperfections from laser scanning is closer to the ultimate load of experiments than of models with geometric imperfections according to Eurocode 3.

Table 2. Ultimate load

		Circular model (kN)	Circular model with opening (kN)	Polygonal model (kN)	Polygonal model with opening (kN)
Experiment		2114.5	1612.5	2101.8	1668.1
With geometric imperfection according to Eurocode 3		2274.4	2001.5	2338.4	1981.5
With geometric imperfection from laser scanning	S1	2214.6	1980.9	2270.6	1911.6
	S2	2211.0	1980.6	2184.8	1925.5
	S3	2216.7	1981.4	2185.1	1938.5
	S4	2195.7	1975.5	2277.5	1939.0

Figure 8 presents the comparison between the deformation of models and specimens after the test. The deformation of the polygonal model with opening using geometric imperfection according to

Eurocode 3 is symmetric. However the deformation of the model using geometric imperfection from laser scanning is asymmetric. This is verified by deformation of specimen after the compression test. After the compression tests, all specimens were scanned again in order to get the deformation of specimens in Fig 8d.

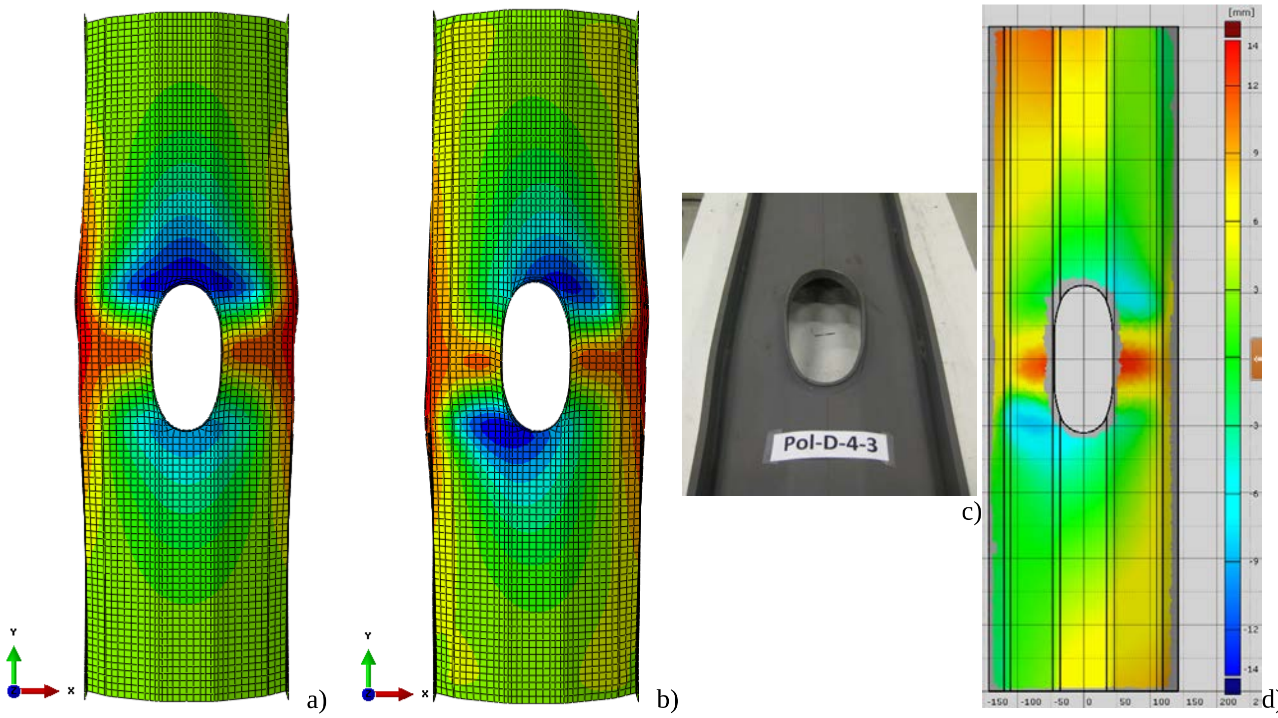


Fig. 8. Deformation of a) model with geometric imperfection according to Eurocode 3; b) model with geometric imperfection from laser scanning; c) specimen after the test; d) specimen after the test with laser scanning technology

6 ACKNOWLEDGMENT

The authors wish to gratefully acknowledge the financial grant provided by Research Fun for Coal and Steel, as a part of the Research Project HISTWIN 2.

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