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Full Scale Test of the 380 KV double circuit pylons (Wintrack type III)

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SUMMARY

TenneT has introduced Wintrack towers for high voltage transmission lines since few years ago. This innovative design provides a reduction in the magnetic field, austere shape and flexibility in the multi-voltage lines. A Wintrack tower consists of two steel poles, to which the high-voltage conductors are connected. The slender and tapered poles appear separate from each other. The tower is low-maintenance due to lower number of bolts and smoother body.

The original Wintrack tower design included a double 380 kV circuit and a combination line of two 380 kV circuits and two 150 kV circuits. However, projected grid utilisation in the Netherlands for the coming years suggested that four-circuit 380 kV towers with transport capacity of 4000 A would also be required. The four-circuits means double 380kV circuit on each pole and higher mechanical loading and as the tower are aimed to be used in northern Netherlands, the load cases will be combined with the severe icing condition. Moreover, the maintainability of single circuit with other circuit being live is introduced as an additional requirement.

The new Wintrack generation with four 380 kV circuits were designed based on the international overhead line standards and structural norms considering the TenneT specific design requirement regarding the maintenance and safety. Advanced design methodologies and finite element software were used in the design of the Wintrack towers, however, TenneT asset management planned further full-scale test on the representative tower types to validate the simulation results with the experimental tests. The aim of the full-scale test was:

- To approve the maintainability and manufacturability of the design towers and details.
- To investigate the global structural behaviour and the structural integrity of the design towers
- To investigate the load capacity of all critical parts and components.

In order to perform the full-scale tests, two representative Wintrack towers have been selected among all tower families and types to be manufactured and installed on a testing site in the Netherlands. Twelve testing were designed and performed on the selected towers which validate the resistance and structural integrity of the design towers.

The aim of this paper is to review full-scale test procedure and present a set of tests on the towers. Respectively, the results are compared with the finite element simulation to show the accuracy and applicability of the design methodology.

KEYWORDS

Transmission Towers, Wintrack Pylons, Full-scale test, Finite element simulations, experimental validation.

1 Introduction

TenneT developed a new type of high-voltage pylon a few years ago, the four-circuit Wintrack pylon, winner of the Dutch “Building in Steel”- prize in 2018. This innovative pylon has a number of features such as a smooth design, a narrow magnetic field and is maintenance friendly. The Wintrack tower responds to social and technological developments and makes it possible to make optimal use of the available space in the area to fit in line connections in the landscape.

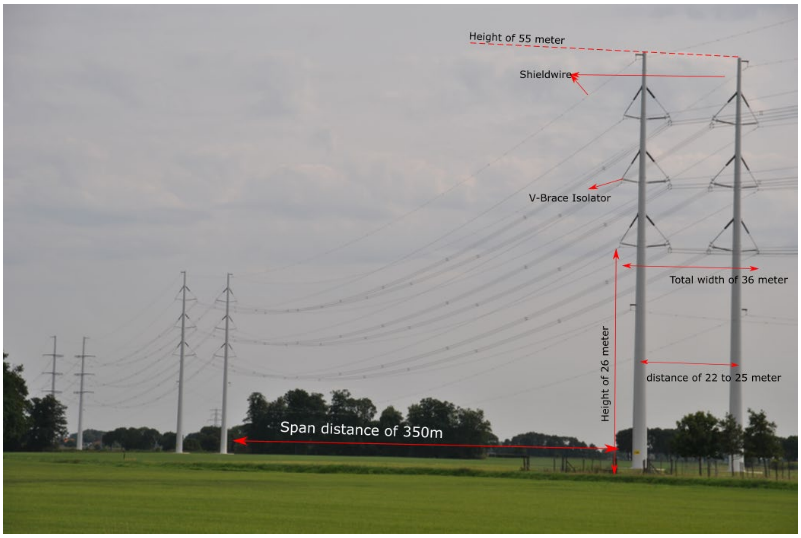


Figure 1: Wintrack connection with indicative dimensions.

Wintrack towers carry four bundles AMS620 conductors on both sides with catenary of 1800 which fulfils strict clearance criteria. The towers are designed to resist high tension loads from conductors (~360 kN) and bending moment (~100 kN) at the foundation. At the beginning of 2020, the realization of the Wintrack III generation has started for two 380kV routes in the northwest and southwest of the Netherlands with length of more than hundreds of kilometres.

All the towers and components are designed according to the national and international building standards using advanced methodologies and finite element software, however, one of the requirements that is important for the asset management department of TenneT is full-scale testing and structural integrity checks of representative towers. This paper presents a set of experimental tests results on the full-scale towers and its components to validate the design and verify the manufacturing and maintenance feasibility of the towers.

2 Full Scale Test

2.1 Tower types

The new generation of the Wintrack towers includes three tower families W2, W4 and W6 to carry 380 kV and 150 kV double circuits and four circuits. Moreover, there are three tower types within each tower family, namely, suspension, tension and terminal tower. Each location along the route includes two poles standing beside each other and carry the 380 kV or 150 kV circuits.

A transmission tower is predominantly loaded by the weight of the conductors and by the wind and/or ice load on the tower body and conductors. A suspension tower is transition of two straight lines in the line route while the tension tower is permanently subject to tension due to the existing line angle and must be able to absorb catastrophic events, such as a conductor break. A terminal tower is located at the end of the line and at the connection with a high-voltage substation. These towers are (mainly) loaded on one side by tensioning conductors.

In this full-scale test, two representative four-circuit Wintrack towers were tested from the W^tower family of the ZWW380 and NW380 projects:

- The heaviest common tension tower (HM400)
- The common suspension tower (S350U) of which the most are build.

2.2 Design and test criteria

European EN-50341-1[1] standard defines the general design requirements for high voltage power lines and its national annex, NEN EN 50341-2-15[2], specifies parameters such as wind, ice, special loads, and load combinations for the design of high voltage connections in the Netherlands. Based on this standard, it must be demonstrated that towers and foundations achieve the level of constructive safety, as required by the Dutch building regulations. This product standard also includes additional requirements that are additional to NEN-EN 1990[3] and the Dutch National Annex to EN 1990.

NEN EN 50341-2-15 describes the load cases for the ultimate limit state and the serviceability limit state with the associated partial and combination factors, specifically support angle and terminal towers. The designs of all towers and underlying families and types are based on the same requirements with the same design principles, tools and modelling.

The towers are designed for consequence class of CC2, wind load of maximum wind speed of 45 m/s and ice load of maximum 28 N/m with a reference return period of 50 years. In addition to the prescribed loads from the standard, the design must meet architectural requirements and requirements that exceed standards, such as those developed by TenneT itself based on lessons learned from the previous Wintrack generations [4].

Twelve test groups were designed for suspension and tension towers to validate the displacement and stress distribution in the attachment and clips, cross arms, shield wire connection, return conductor extension, flange connection, cross arm bolted connections, tower body, vibration, and the foundation foot plate. All these tests validate the respective component against the serviceability and ultimate limit state conditions. The criteria that the towers and components should fulfil during the tests are mainly related to the permanent deformations and opening of the bolted flange connected under ULS load levels. Moreover, the tower and the components displacement under EDS and SLS load cases should meet the requirements and the base plate and flange should not lose any pressure contact.

2.3 General Test layout

A training location of TenneT's management & maintenance organization at Geertruidenberg was chosen as the full-scale test location. Suppliers perform maintenance on high-voltage lines on this site and after the full-scale tests, the towers will also be used for training purposes. Figure 2 shows the Wintrack towers test setup. The two suspension and tension towers are located at both sides. When one of the towers is being tested, the other one works s as the anchor of the tensioned pulling wires. Additionally, an auxiliary tower (suspension tower type) has been placed in between as an "intermediate" support point to facilitate the horizontal loads on the testing towers and then anchor the slings to the foundation of the other tower. The tower distances are approximately 60 m and the loads are applied using pull wires that run over pulleys fitted in the "intermediate" support tower. During testing of the NWW6HM400UY, the "intermediate" support tower must be reinforced by means of guy wires to avoid significant displacement and secure the horizontal loading on the tower.

Figure 2: Overview of the Wintrack towers test setup

In this full-scale test, the tower body and the cross arms have been loaded in a stepwise manner, the loads are increase to 25% of the load level, then it is released. Subsequently, the loads are applied again, and the load are increase to 50%, 75%, 90% and 100% respectively and it is maintained constant for 5 minutes after reaching each level. The behaviour of the flange connections, shell structure, welded connections and preloaded bolts were investigated and recorded during the load increase from 0% to 100% loading condition.

When performing the tests on the cross arms and attachments, the horizontal and vertical loads are introduced at the attachment point of the respective conductor or wire at the end of the component. For the tests of the V-braces, the load is applied to the relevant attachment points to which the insulators will eventually also be attached. Moreover, the loads were applied at three different heights to simulate the conductor loads at each cross arm and to test the tower body.

2.4 Measurement and instrumentation

Several parameters were measured during the various tests including the strains, displacements, flange openings, bolt and anchor forces. These measurements are collected and registered by means of data loggers. Furthermore, independent from the static tests, vibration measurements were also carried out to determine the natural frequencies of the towers.

(a) (b)

Figure 3: (a) the strain gauges on the tower shell and (b) LVDT to measure flange opening

Pressure sensors between the nuts are used to measure bolt forces. Several pressure sensors were fitted per location for the bolt forces and there was sufficient redundancy in case any pressure sensor failed. LDVT displacement transducers (Figure 3(b)) have been used to measure the flange opening and the anchor plate displacement. Tower displacement was measured using Trimble SX10 camera technology. For each component test, additional prism mirrors have been placed to measure the displacements of the relevant component. Accelerometers have been placed to determine the natural frequency of both the suspension and the tension tower. The measured values are logged by a separate data logger. Figure 3(a) shows the sensors around the door and anchor plate of the support tower. Strain gauges are glued under the gray color areas on the tower. The bolt load sensors are visible under the nuts at three bolts in front of the tower door.

3 Results and discussion on cross arms and attachments tests

A total of seven component tests were carried out in a full-scale set-up on the cross arms and V-braces, four on the suspension tower and three on the tension tower. These tests were performed for the normative load combination (Ultimate Limit State, ULS X). This is a special ultimate limit state, in which the relevant tensioned conductor is broken from one side of the cross arm or component. In addition, strains are measured at specific locations of the connection of components to the tower body Later, the measured parameters were validated with the FEM analyses. In this section the results of the test on the so-called tension arm of the suspension tower are presented. This test was performed on the lower tension arm. This test is not considered necessary on the other cross arms, because the FEM analyses show that the material stress occurring at the normative ULS load is lower than at the lower tension cross arms. (When connecting to the tower, the tower diameter is greatest at the lower crossbar). After Each load step, strain measurements were recorded at the location as shown in Figure 4. For information, the deformation at the end of the draw bar is also measured to compare with the FEM tower calculation. The vertical lines indicate the different load steps according to the script.

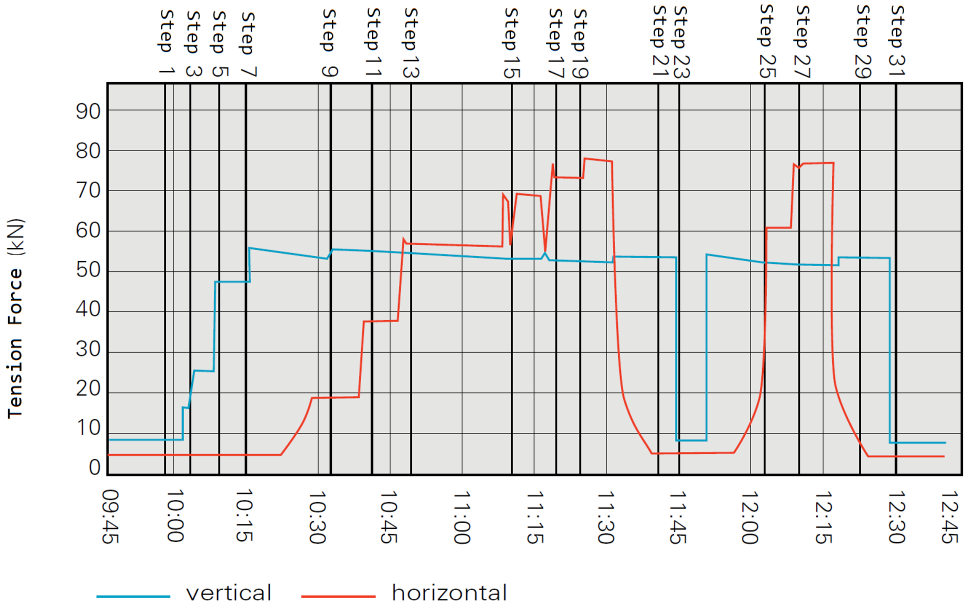


Figure 4: Tension force measurement in protrusion (small cross arm) of the suspension tower

The tension arm is welded directly to the tower wall without any reinforcement plate. The extension of the arm is connected to the part welded to the tower with bolted connections (so-called diabolo). The stresses around the welded connection to the tower was measured at six locations on the tower wall and six locations on the tension arm, distributed evenly clockwise around the connection. Figure 5 shows the measured strain at each sensor.

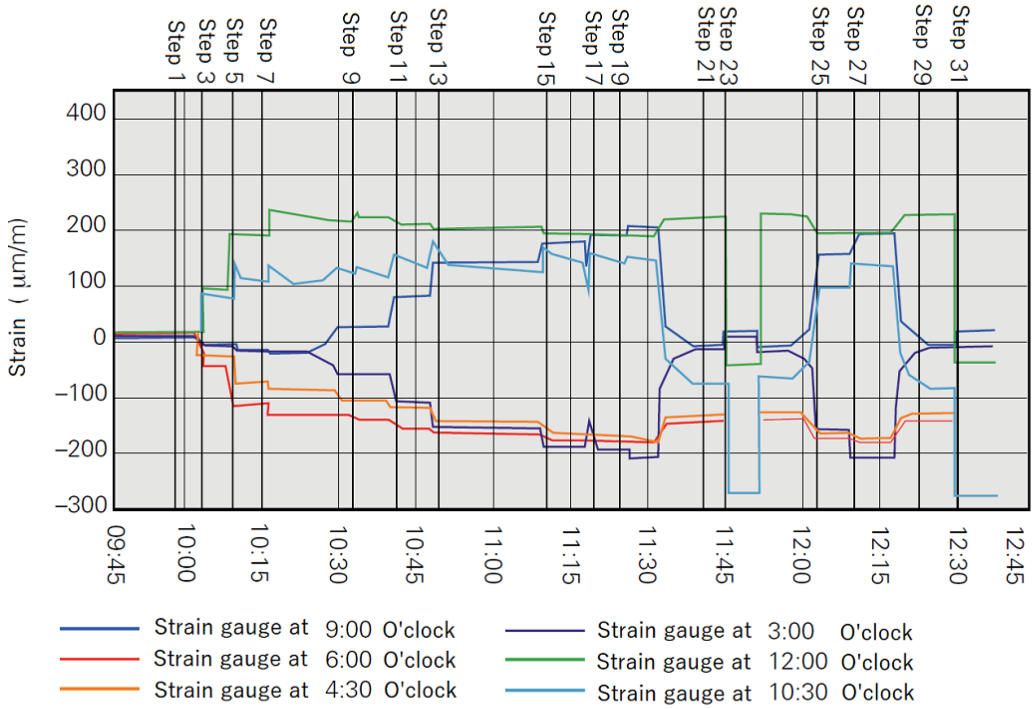
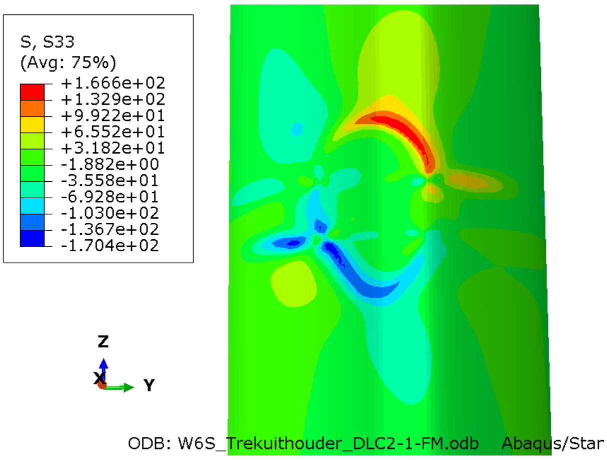
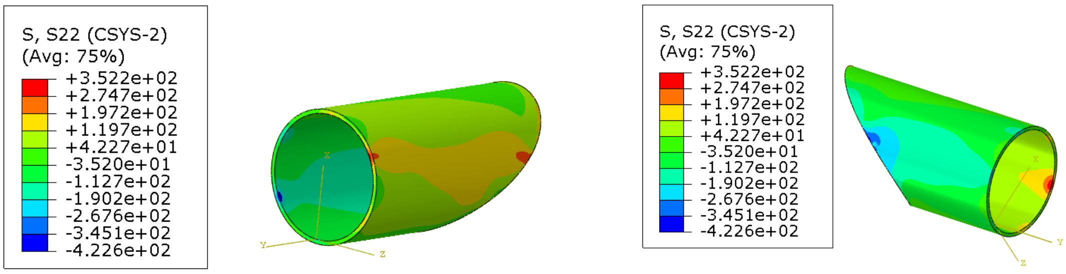


Figure 5: strain measurement around the welded connection of the tension arm at suspension tower.

The results of one of the component tests are illustrated in Figure 6. It concerns the connection of the so-called tension arm to the tower body of the support tower NWW6S350UY. Since the strain gauges measure the stress in their local coordinate, the stress component in the tower is illustrated according to the global coordinate of the model and the stresses in the draw arm are illustrated matched to the local coordinate of the draw arm. The results of the measurement and simulation are compared in Table 1. The measurement results and simulation results are generally the same. Relatively large deviations occur in locations where stresses are low. The displacement was measured at a height of 51m and the end of the draw arm.



(a)



(b) (c)

Figure 6: stress distribution in the tower (a) and the tension bar (b and c).

Table 1: Comparison of calculated and measured stresses

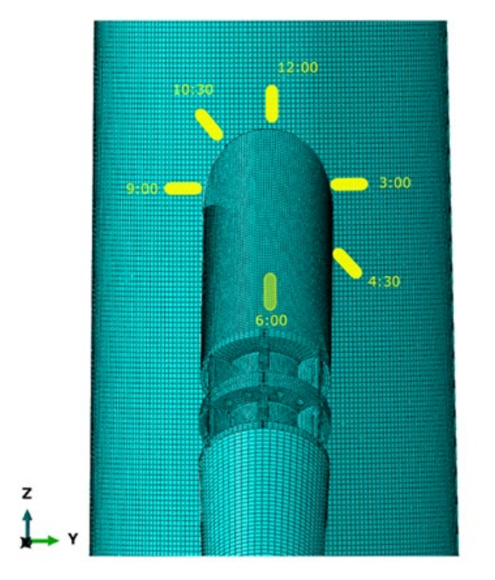
	location	Measurement [MPa]	Simulation [MPa]	Deviation [%]	
tower	12	61	60	2	
	3	58.2	60	-3	
	04:30	50.5	55	-9	
	6	52.1	54	-23	
	9	53	56	-28	
	10:30	47.4	44	7	
Tension arm	12	8	11	-38	
	3	137.8	140	1.5	
	04:30	243.5	246	1	
	6	68	69	1	
	9	157	166	-5	
	10:30	28	32	-14	

Figure 7 also shows the displacement in the FE model. Both the measured and simulated results are shown and compared in Table 2. The displacement in the FE model is slightly higher than measured in the test. This could be partially due to the preloaded bolts and extra weld materials in the tower and at the connection which increased the rigidity of the structure.

Table 2: Comparison of calculated and measured displacements

	displacement [mm]	
	Tower	Tension arm
Measurement	60	100
Simulation	65	116

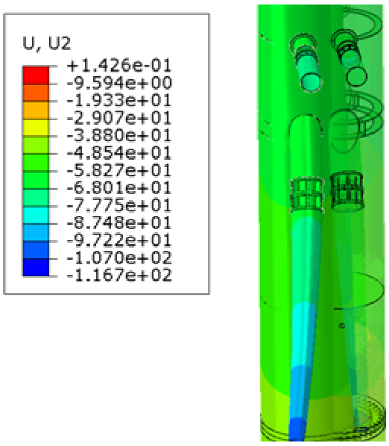


Figure 7: Measured displacement

4 Results and discussion on tower body tests

The behaviour of the tower body, everyday stress load level (EDS), the serviceability limit state (SLS) and ultimate limit state (ULS) have been applied on the tower body at the crossarm height level. The EDS and SLS tests were used to assess the deflection curvature, deformation of the tower and identifying the share of the foundation in the deformation. This validates the stiffness values used in the calculation models. Moreover, the ULS test validate if the door in the tower body introduces any weakening to the structure specially because of the buckling behaviour of the tower shell structure.

In Figure 8, the measured displacements and the respective locations of the measurements are illustrated throughout SLS test cycle. It should be noted that at the displacements the rotational stiffness of the foundation plays a role. For support tower NWW6S350UY are the location-specific upper and lower limits of rotational stiffness certain. For both situations, the deformations calculated for the SLS test. The lower limit of the top displacement has been calculated at 956 mm and the upper limit at 1023 mm. The measured value was in between: 975 mm.

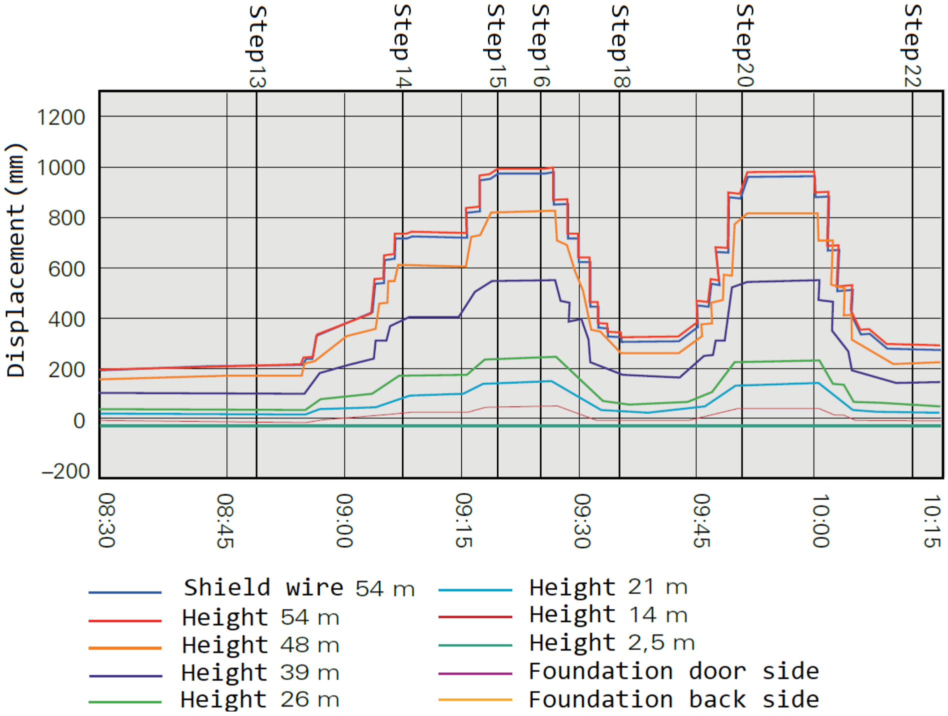


Figure 8: measured displacement in tensile direction during the SLS test

The locations of the strain gauge measurements the tower body is just (0.5 m) above the thickened part with the door opening and on an intermediate height between the two flange connections. Flange connections are as close as possible measurements at the weld on the inside and outside performed, both on the pressure and on the tension side. Also, with six bolts (three on the pull side and three on the pressure side) in the flange connection the bolt force is measured. In addition, two sensors on the pull side of the flanges to determine whether the flanges remain closed. The areas around the doorway and just above the wall thickening are the most critical areas.

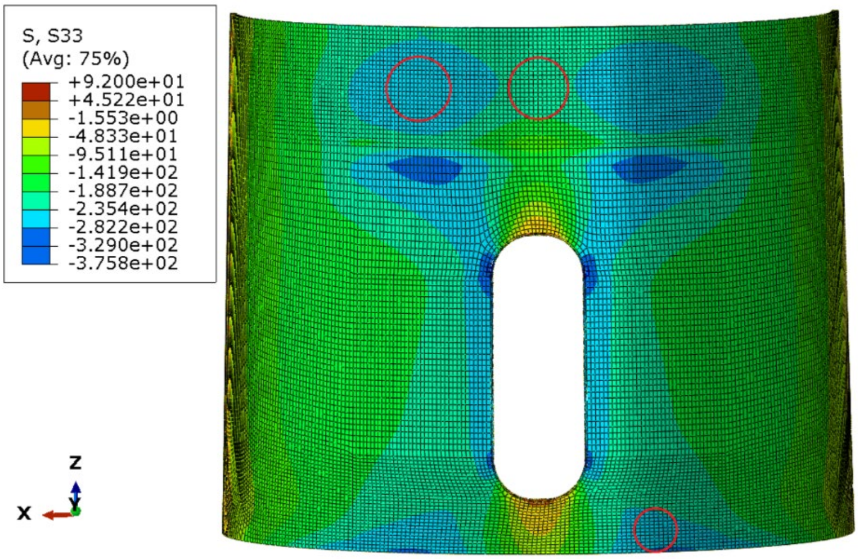


Figure 9: Axial stress distribution in the tower around the door frame.

Figure 10 illustrates the measured strains around the door during the entire test cycle. From this calculation and comparison with the calculation, it can be concluded that there is no permanent deformation in the structure. Table 3 compared the calculated and the measured stress distribution. The measurement and the simulation results agree to each other, and the deviation percentage is negligible.

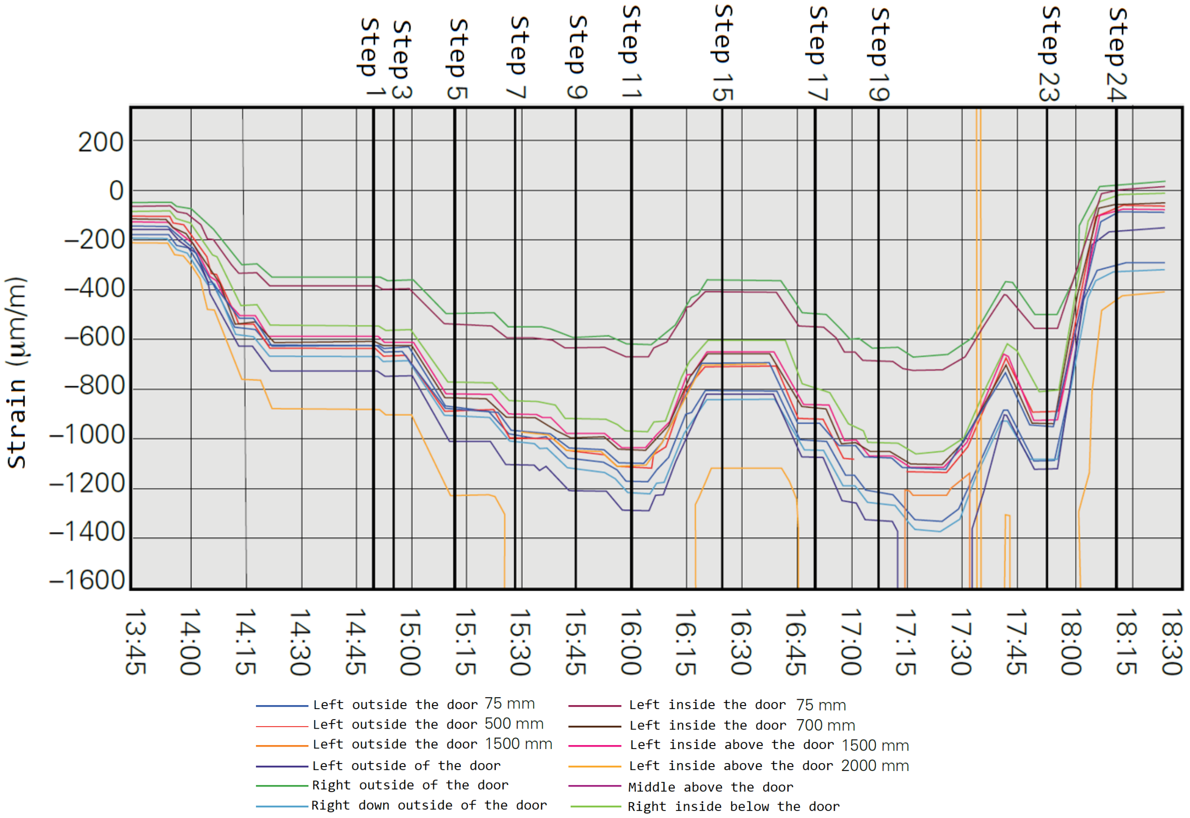


Figure 10: Measured strains during the test cycles.

Table 3: Comparison of measured and calculated axial stress distribution at three locations around the door frame.

	Measured stress [MPa]	Measured stress (axial) [MPa]
Outside above the door on the left	294	280
Inside above the door in the middle	245	224
Outside below the door on the right	283	280

5 Dynamic behaviour of the Tower

The vibrations were measured using accelerometers to determine the natural frequency of the towers. The verification of the calculated natural frequencies is important to avoid any frequency collision between the tower and the vortex shedding, conductor galloping and the first two fundamental harmonics of the conductor bundles and shield wires.

The measured signals were analysed with the Fast Fourier Transformation (FFT) method which gives the amplitude at each frequency. Figure 11 shows the calculated eigenfrequencies form the measured signal of the tension tower. The first four frequencies can be noticed clearly on the graph.

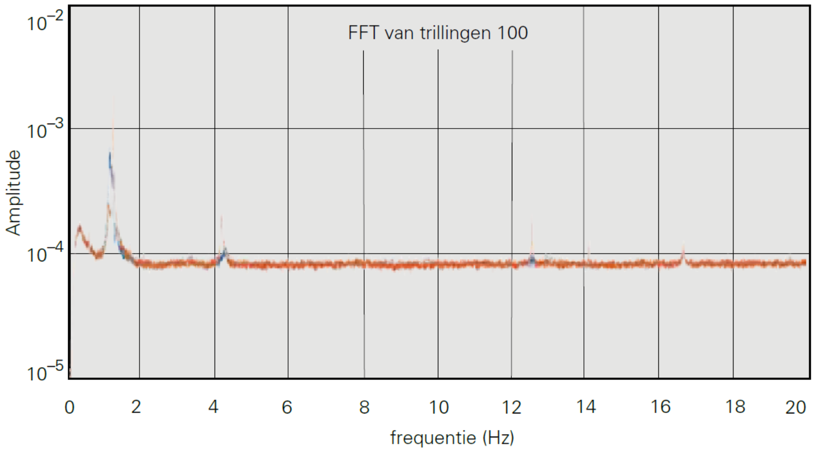


Figure 11: frequency signal from the tower vibration

The first three natural frequencies are compared with the calculated values in Table 4. It can be seen that the deviation for the first two eigenfrequencies are negligible.

Table 4: Overview of eigenfrequencies

Mode	**Measured Eigenfrequency [Hz]**	**Calculated Eigenfrequency [Hz]**
1	1.17	1.00
2	4.12	3.58
3	12.56	8

6 Conclusion

In this paper, the full-scale test on two tension and suspension Wintrack towers are presented. The experimental stress and displacement of the components are presented and compared with the finite element simulation models in Abaqus software. It is shown that the finite element simulation predicted the stress, displacement and natural frequencies with high accuracy and deviation within 5%. However, the deviation of the results is slightly higher for the locations with low displacement or stress distribution.

From the performed tests it can be concluded that:

- The Wintrack towers are adequately designed to resist high mechanical loads and fulfils TenneT requirements for permanent deformations and bolted connection opening.
- The structural integrity between the whole body and the components can be validated.
- The manufacturability and the maintenance ability of the towers are proven and approved.

From the obtained results, it can be concluded that structural integrity and resistance of other tower types and families can be also approved.

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