Drag coefficients of lattice masts from full-scale wind-tunnel tests

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Keywords: lattice masts, drag coefficients, full-scale section model, Reynolds number, wind-tunnel

ABSTRACT

In this paper, the drag coefficients obtained from a series of full-scale section model wind-tunnel tests of several lattice mast configurations are presented and compared to those provided in Eurocode 3 and ESDU. The drag coefficients provided in Eurocode are conservative interpretations of 1:5 scale section model tests performed at the National Physics Laboratory and the National Maritime Institute in the UK in the 1970’s. ESDU provides velocity-dependent drag coefficients equivalent to those obtained from the same series of tests. In all cases, the mast legs and diagonals are comprised primarily of circular hollow sections, putting into question the validity of the scaled tests from the 70’s. The results of the full-scale tests show that the drag coefficients of the masts have lower values than those obtained from the scaled tests for turbulent wind and higher for winds with low turbulence.

1. INTRODUCTION

The evaluation the wind loading of existing lattice masts using the current Eurocode often reveals that these masts should have little or no available reserve load bearing capacity. Nevertheless, it is rare that masts collapse due to wind, as in most cases collapses can be credited to other causes, e.g.
construction faults, bearing failures and poor maintenance (Nielsen, 2001). This implies that the current Eurocode may be overly conservative when estimating the wind loading – with the main cause of this most-likely attributable to the erroneous evaluation of the drag coefficients for lattice masts.

The erroneous evaluation might be traced back to a series of wind-tunnel tests performed in the United Kingdom in the 1970’s on scaled models of lattice masts (Whitbread, 1977). As many modern lattice masts are constructed with circular profiles, testing at the appropriate Reynolds numbers is important when determining the drag coefficients. The current paper hopes to address the aforementioned problem of testing at scale, by presenting the drag coefficients of several typical lattice mast configurations tested at full-scale.

2. WIND TUNNEL TESTS

2.1 Section Models

Four different lattice mast configurations were chosen and built for section model testing. For all of the configurations, the mast is an equilateral triangle in cross-section. The four configurations – 1A, 1B, 1C and 2A, are presented in Fig.1.

![Figure 1: Lattice mast configurations used for full-scale section model testing. From left to right: 1A, 1B, 1C, 2A.](image)

Each section is 3.0m long with a leg-to-leg distance of 1.2m. The diameter of the circular hollow legs is 76mm in all cases and the diameter of the diagonal bars is 33mm for the first three configurations (1A, 1B and 1C, Fig.1). The diagonals in the fourth and final configuration are angles 50mm x 50mm, with a plate thickness of 5mm.

Configuration 1A is a plain lattice mast without an internal ladder or feeders. Configurations 1B and 1C have an internal ladder and an internal latter with attached feeders, respectively. Configuration 2A has no ancillaries, similar to 1A. All of the models were constructed in galvanised steel.

2.2 Test Configuration

For the tests, the models were placed on rotating turntables horizontally, with the ends attached to 6-DOF dynamic force transducers (Fig.2), which allowed for the measurement of the shear forces parallel to the wind (drag) and vertically perpendicular to the wind (lift). The moments about the horizontal axis were also measured.
The rotating turntables were placed in flow splitter plates that measure 4m x 4m and that were 3m apart (Fig 3).

2.3 Flow Properties

Two different flow conditions were used to test the mast section, namely smooth and turbulent. Smooth flow was found to have a turbulence intensity of 1.1%, whilst the turbulent flow was found to have an intensity of 9.6%. Wind turbulence and profiles were measured using “Cobra Probes” developed by TFI (Turbulent Flow Instrumentation). The integral length scale of the wind, achievable in the tunnel, was in the order of 9cm. The turbulence generating grid is shown in Fig.3.

2.4 The Wind-Tunnel

The wind-tunnel tests were undertaken at the Velux closed-circuit wind-tunnel in Østbirk, Denmark. The test section of the wind-tunnel is partially open, with the inlet measuring 3.4m x 3.4m and a maximum smooth flow velocity in the current test configuration of 45m/sec (Fig.4).
3. DRAG COEFFICIENTS

3.1 Wind angle of attack and wind resistance
At present, most international codes and standards use approaches that are similar to each other when defining the wind resistance of a lattice mast. The area used for the calculation of wind resistance is defined as the ‘shadow’ area of the front face of the mast. Here the front face or front frame is defined as in Fig.5. Thus, the total wind resistance will be a product of the presented drag coefficients and the area of the front face. The derivation of drag coefficients are based on mean flow velocities.

The wind (or flow) angle of attack is considered zero when the wind is perpendicular simultaneously to the front face and the longitudinal axis of the mast and moving from the front face to the ‘rear’ face. All other angles of attack are defined as an angular deviation from zero (0) degrees, assuming that the wind remains perpendicular to the longitudinal axis of the mast.

3.2 Configuration 1A – Plain mast with circular hollow sections
The results from the smooth-flow tests show that both Eurocode 3 (2007) and ESDU (1993) may be underestimating drag coefficients for several of the mast configurations and wind angles of attack. Fig.6 shows the Reynolds-dependent drag coefficients for mast configuration 1A at 0, 30 and 60 degrees angle of attack, as obtained from the full-scale tests. The resulting coefficients are compared to those provided by Eurocode 3 and ESDU.
The tests show an underestimation of the drag coefficient for flow angles of attack 30 and 60 degrees at lower wind velocities, typically below 25m/sec. It is also worth noting that, whilst ESDU assumes the drag coefficients for 0 and 60 degrees to be the same, the tests reveal a slight variation in drag between the two angles of attack.

Contrary to the results from the smooth-flow tests, the drag coefficients for the turbulent-flow tests show that both Eurocode and ESDU are generally overestimating drag coefficients for the majority of the mast configurations at higher wind velocities. Fig.7 provides the comparison of the Reynolds-dependent drag coefficients for mast configuration 1A at 0, 30 and 60 degrees angle of attach, under turbulent flow.
3.3 Configuration 1B – Mast with circular hollow sections and internal ladder

The Reynolds-dependent drag coefficients for mast configuration 1B under turbulent flow are presented in Fig. 8. From this, it can be seen that there is an overestimation of the drag for wind angles of attack 0 and 180 at higher wind velocities, whilst Eurocode and ESDU seem to overestimate and underestime the drag, respectively, for 80 and 90 degrees.

![Figure 8: Reynolds-dependent drag coefficients in turbulent flow for configuration 1B, 0 and 180 degrees angle of attack (left) and 80 and 90 degrees (right).](image)

3.4 Configuration 1C – Mast with circular hollow sections, internal ladder and feeders

![Figure 9: Velocity-dependent drag coefficients in turbulent flow for configuration 1C, 0 and 180 degrees angle of attack (left) and 90 degrees (right).](image)
Once again, as can be seen from Fig. 9, there is an overestimation of the drag for wind angles of attack 0 and 180 at higher wind velocities, whilst Eurocode and ESDU seem to overestimate and underestimate the drag, respectively, for 80 and 90 degrees.

3.5 Configuration 2A – Plain mast with circular legs and angle cross members

The Reynolds-dependent drag coefficients for mast configuration 2A under smooth flow are presented in Fig. 10. Similarly to configuration 1A, Eurocode and ESDU generally underestimate the drag for lower wind velocities.

Figure 10: Reynolds-dependent drag coefficients in smooth flow for configuration 2A, 0 angle of attack (left) and 90 degrees (right).

Figure 11: Reynolds-dependent drag coefficients in turbulent flow for configuration 2A, 0 angle of attack (left) and 90 degrees (right).
Also similarly to mast configuration 1A, Eurocode and ESDU overestimate the drag coefficients for 2A under turbulent flow, for 0 degrees wind angle of attack. For 30 degrees angle of attack, there is an overestimation and an underestimation of the drag from Eurocode and ESDU, respectively, for almost the full wind velocity range (Fig.11).

CONCLUSIONS

The wind-tunnel tests on full-scale sections of several lattice mast configurations have shown that drag coefficients derived from scaled tests in the 70’s might need to be re-examined. Drag coefficients for masts subject to smooth flow are generally underestimated, whilst the same coefficients under turbulent flow are overestimated.

It should be noted that the aforementioned conclusions apply to a small range of lattice solidity ratios. Further tests on a range of solidity ratios, velocities and wind angles of attack are planned, so as to create a codifiable set of data.

ACKNOWLEDGEMENTS

The authors would like to thank Norkring A/S, Norway; Teracom AB, Sweden; Digita OY, Finland and Valmont Polska Sp.o.o. for their research funding contributions.

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