Rudder Analysis Report

24-25-Systems Design and Computing for Ships

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Abstract

This report provides a detailed analysis of rudder performance under varied operational conditions using Finite Element Analysis (FEA) and Computational Fluid Dynamics (CFD). FEA identifies critical stress concentration points essential for structural safety and reliability, while CFD evaluates hydrodynamic forces on the rudder at representative inflow speeds. The results demonstrate that FEA accurately captures complex stress distributions, while CFD highlights the significant impact of rudder taper and thickness-to-chord ratio on lift and drag forces. Findings not only confirm the suitability of the current design parameters but also offer insights into refining boundary conditions and enhancing simulation accuracy, ultimately improving design reliability and overall vessel performance.

Introduction

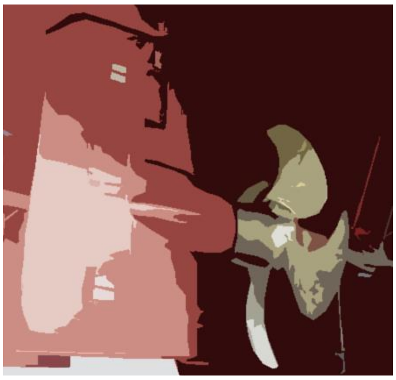

Fig1 rudder for single-screw container ship

The accurate design and analysis of ship rudder systems is crucial to maintaining vessel manoeuvrability, stability, and safety under varying operational conditions. This report investigates the application of Finite Element Analysis (FEA) and Computational Fluid Dynamics (CFD) in analysing the structural performance and hydrodynamic forces acting on a rudder for a single-screw container ship. Given that rudders are exposed to complex forces, including bending and torsional stresses, precise modelling is essential to predict potential failure points and ensure compliance with regulatory standards, such as those by Lloyd's Register.

FEA and CFD are essential tools in structural engineering, widely used to model stress distribution and fluid-structure interaction in maritime components. Their ability to simulate stress, strain, and displacement under various loading conditions makes them invaluable for optimizing rudder designs to reduce material fatigue and enhance structural integrity. However, accurate FEA and CFD modelling in marine applications presents challenges due to boundary condition specification, load application, and mesh convergence. This study addresses these issues by implementing mesh sensitivity studies, boundary condition variations, and load adjustments using SolidWorks.

Given the rudder's crucial role in ship control, advanced simulations enhance vessel design and structure reliability. This study uses FEA and CFD to refine rudder modeling for future research and industry applications.

Method

I. Finite Element Analysis (FEA): Stress Analysis of Rudder Side Plating and Rudder Stock

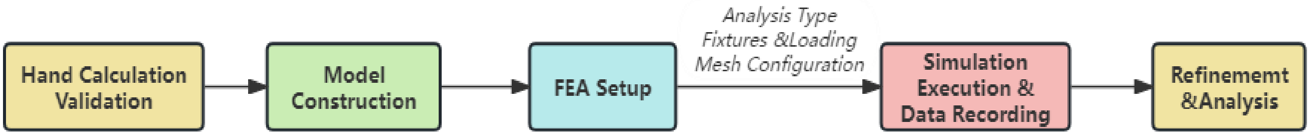

Fig2 process of FEA

Model 1: Rudder Side Plating

Initial hand calculations were conducted to establish the expected stress range under uniform pressure using the Von Mises stress formula, providing a baseline for model validation. A side plating model was constructed in SolidWorks, extruded to the required thickness, and set up as a "Static" analysis with plain carbon steel. All edges were fixed, and a lateral pressure load was applied based on Lloyd's Rules. A mid-sized mesh was initially used, with stress convergence verified across various densities. Mesh density and boundary conditions were then further refined to ensure the accuracy of the stress distribution.

Model 2: Rudder Stock

The rudder stock, restraining bar, and load plate were modelled in SolidWorks, with the stock diameter specified per Lloyd's Rules. The restraining bar ends were constrained with sliding joints, and a lateral load based on the CR was applied. A finer mesh was applied in the stock area to capture detailed stress distribution. The model was further optimized by replacing sliding joints with bearing supports and adding contact relationships between the stock and support blocks to improve reliability.

II. Computational Fluid Dynamics (CFD): Free-Stream Rudder Force Analysis

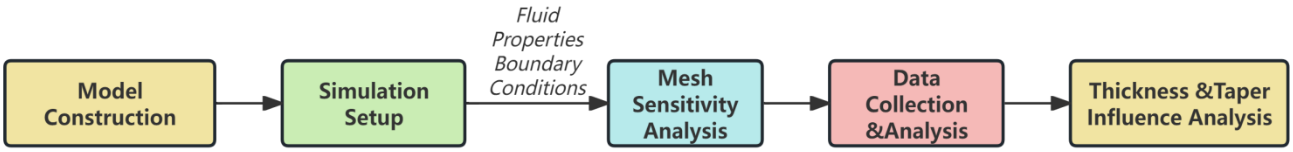

Fig3 process of CFD

A rudder model with a NACA 0020 air foil, chord length of 0.667 m, span of 1 m, and stock positioned at 30% of the chord was created in SolidWorks. Air was set as the working fluid at 20°C and standard pressure, with an inflow speed of 10 m/s applied over a computational domain from X: -1 to 3 m, Y: -3 to 0 m, and Z: -1 to 1 m. An automatic global mesh at level 4, with a refinement factor of 2, was used, running density levels from 3 to 7 to balance efficiency and accuracy. Rudder angles from 0° to 45° were analysed, recording lift (Z-direction) and drag (X-direction). The influence of thickness-to-chord ratio (t/c) and taper on lift and drag was analysed by adjusting the tip thickness to 65% of the root thickness. Here is the academic report-style write-up for the NACA airfoil section thickness calculations:

Result

Table 1: Rudder details

Area (m^2)	Span (m)	Cord (m)	V_s (m/sec)	V_a (m/sec)	J
26.04	6.249	4.167	10.288	7.716	0.56

Table 2: Summary of stock and rudder blade scantlings

	Ahead
Assumed stock diameter (D_L) mm	850
Plate thickness side, top & bottom (t) mm	16.251
Thickness webs (t_w) mm	11.376
Thickness nose plate (t_n) mm	20.313
Thickness mainpiece (t_m) mm	24.827

Thickness of rudder at 25% cord

$D_L + 2\,(50) + 2\,(t_m) = 999.654$

Table 3: Rudder offset (y) for stock position, as percentage of cord, (x/c)

x/c	0	10	20	25	30	40	60	80	100%
y (mm) at root	0	390.261	478.15	495.102	500.099	483.354	378.95	214.31	0
y (mm) at tip	0	253.67	310.798	321.816	325.064	314.18	246.318	139.301	0

From Table 3. **Maximum** thickness/cord ratio of rudder t/c = 0.2 @ x/c = 0.30

Result

I. CFD results

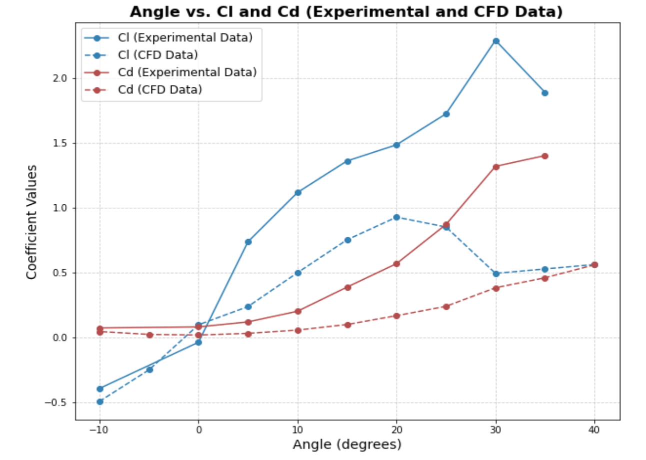

Fig2 l and Cd against rudder angle for t/c =0.2 and no taper compared to experimental results at inflow speed V of 10 m/sec

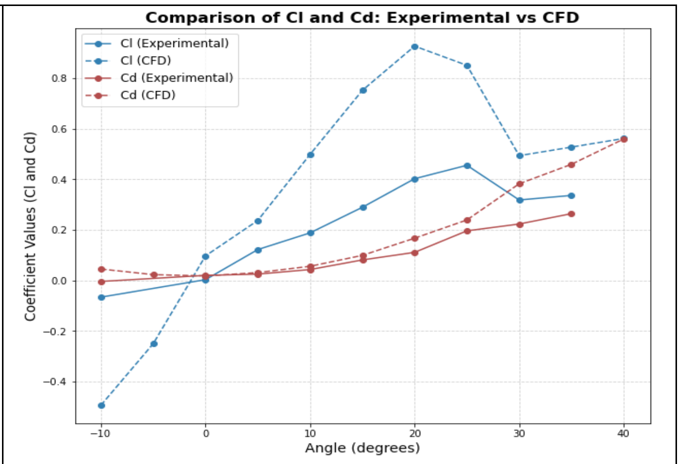

Fig3 Cl and Cd against rudder angle for t/c = 0.2 and with taper of 65% compared to experimental results V of 10 m/sec

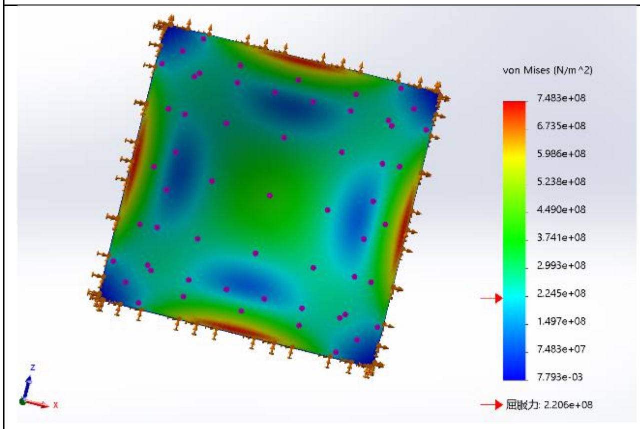

Fig4a & 4b EA screen shot of stress in rudder side panel

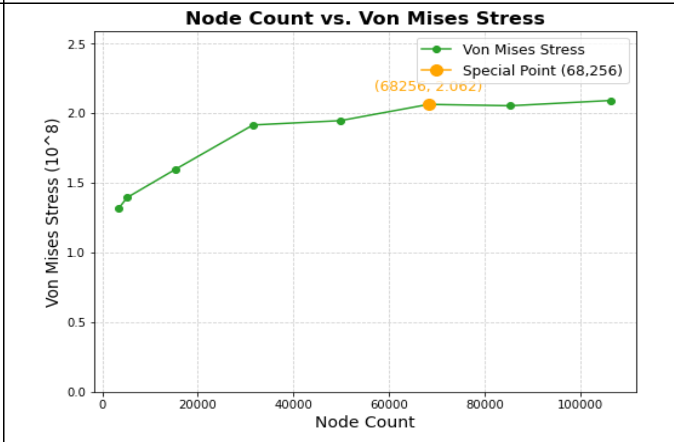

Fig5 on Mises stress against total number of nodes for rudder side panel

II. FEA results

Table 5: Results for FEA plate analysis

Plate width (m)	Plate height (m)	Plate thickness (mm)	Applied load (MN)	Max Von Mises Stress (MN/M2)	Maximum deflection (mm)
1	1	24.340	1.764	748.3	8.157
1	1	20.587	0.321	191.7	1.461

Rudder Stock FEA

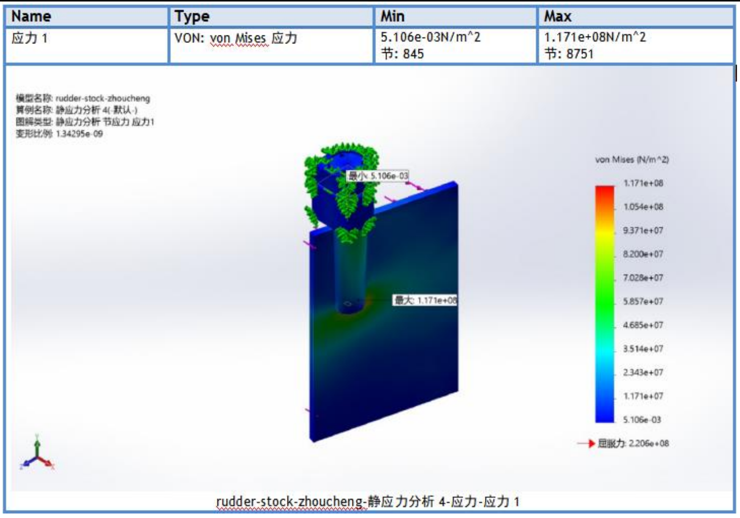

Fig6 Rudder Stock Bearing - Static Stress Analysis 2 - Stress - Stress1

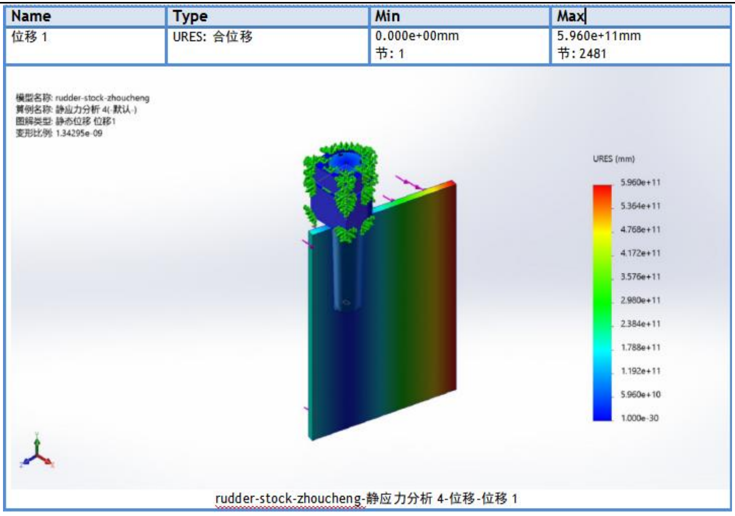

Fig7 Rudder Stock Bearing - Static Stress Analysis 2 - Displacement - Displacement1

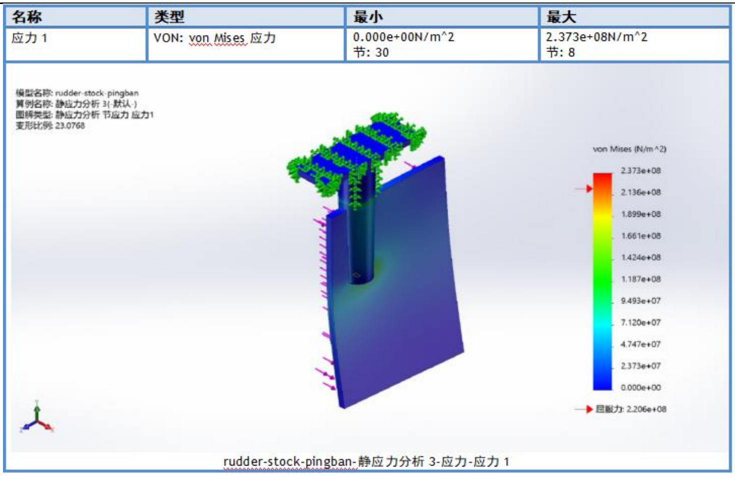

Fig8 Rudder Stock Plate - Static Stress Analysis 3 - Stress - Stress1

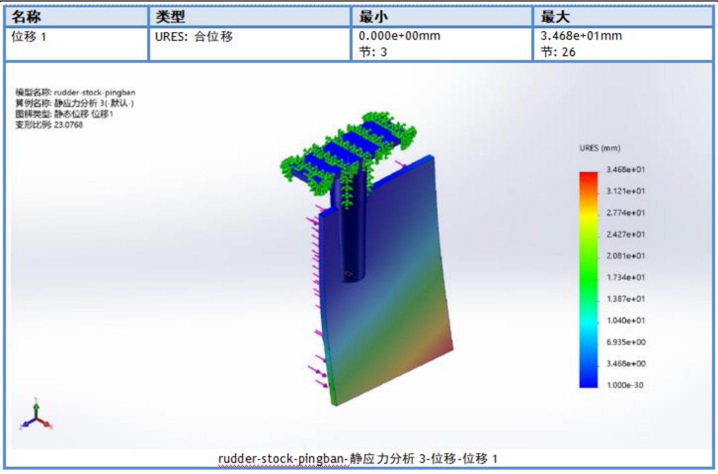

Fig9 Rudder Stock Plate - Static Stress Analysis 3 – displacement – displacement1

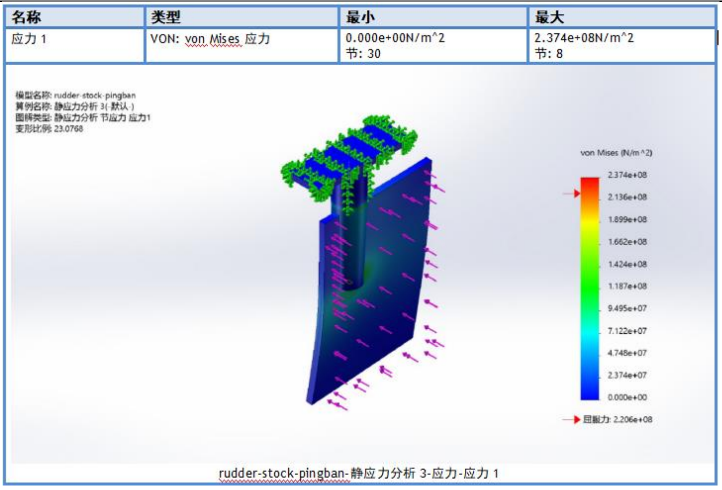

Fig10 Rudder Stock Plate - Static Stress Analysis 3 - Stress - Stress1(symmetric, the direction of the force is opposite)

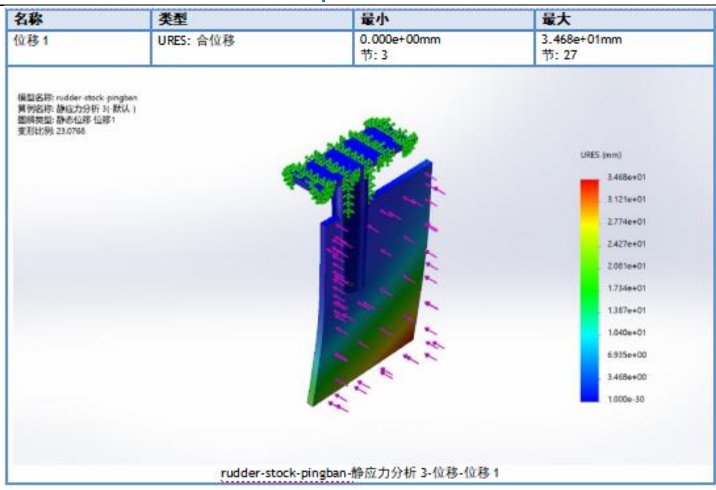

Fig11 Rudder Stock Plate - Static Stress Analysis 3 – displacement – displacement1 （symmetric）

Table 6: Comparison of experimental, Lloyds and FEA results stress and loads on rudder stock

	Experimental results	Lloyds	
Torque Q (MNm)	0.846	0.588	
Bending Moment M (MNm)	8.495	5.954	
Resultant Force R (MN)	2.486	1.764	
Diameter stock (mm)	903	808	
Design Max Stress (MN/m^2)	121.35	118.88	
	FEA	FEA	FEA
Applied force (MN)	1.764	-1.764	1.764
Diameter stock (mm)	850	850	850
Max Von Mises stress (MN/m^2)	237.4	237.3	117.1
Position of max stress	(100, -4335, -369)	(100, -4340, -369)	(100, -4305, -493)
Total number of nodes	106358	106358	107079
Constraints applied at bearings	Sliding Joint	Sliding Joint	Bearing Connection
Max stress from hand calculations (MN/m2)	284.88	284.88	187.36

Discussion

I. FEA Analysis

The FEA model effectively captures the rudder's geometry, boundary conditions, and material properties, closely mirroring real operating conditions. Stress distribution in high-stress areas aligns with expectations, and mesh sensitivity analysis shows stress convergence as mesh density increases from 4207 to 112631 elements, ensuring accuracy in critical areas.

Maximum stress appears near bearing constraints under both positive and negative loading. For example, under positive loading, the maximum stress is 237.4 MN/m^2 at (100, -4335, -369), and similarly, 237.3 MN/m^2 under negative loading. These results confirm accurate stress capture around critical areas.

FEA-predicted stress levels exceed those from basic plate and beam theory due to FEA's inclusion of complex loads and constraints. Theoretical stress is about 3.16 × 10^8 N/m^2, while FEA yields lower stresses due to real-world bending and torsional effects not fully accounted for in simpler models.

Most FEA-calculated stresses comply with Lloyd's limits, though stresses around constraints approach the 250 MN/m^2 yield threshold, suggesting the need for reinforcements in high-stress areas under peak loads.

Switching from sliding joints to fixed supports increases stress concentration, creating a more rigid model. Node count rises from 106358 to 107079, reflecting greater structural rigidity with fixed constraints, which may more accurately simulate actual conditions.

Stress increases proportionally with applied load, with maximum Von Mises stress rising from 6.25 × 10^8 N/m² at lower loads to 7.765 × 10^8 N/m² at higher loads. This supports the selected plate thickness and stock diameter, both of which withstand varying loads within safety limits.

Refining mesh density in high-stress areas and applying more detailed boundary conditions, such as bearing clearances, would improve accuracy, especially under complex loads.

II. CFD Analysis

An inflow speed of 10 m/s was chosen to reflect typical container ship conditions, providing realistic hydrodynamic force assessments.

The SolidWorks-calculated forces differ from experimental values, particularly in lift coefficients, due to idealized simulation conditions. The experimental lift coefficient C_L peaks at 2.639, whereas the CFD model shows 1.029. Such discrepancies arise from factors like turbulence and surface roughness, which simulations can't fully capture.

Increasing taper or reducing t/c ratio significantly decreases lift and drag, as shown at a 25° angle where taper-to-chord ratio is 0.212, lowering drag. These results suggest that tapered designs are effective in reducing drag, improving fuel efficiency and manoeuvrability.

Conclusions

The FEA and CFD analyses provided a comprehensive evaluation of the rudder's structural and hydrodynamic performance. FEA results confirm the suitability of the selected plate thickness and stock diameter under standard loading conditions. The CFD findings underscore the importance of taper and t/c ratio optimization in reducing hydrodynamic drag. Future improvements to the FEA model—such as refined mesh densities and enhanced boundary conditions—will further validate the design's reliability under extreme operational conditions. Overall, these analyses affirm the current rudder design while highlighting key areas for potential enhancement to ensure operational safety and performance efficiency.

References

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2. Hasanvand, A. & Hajivand, A. (2019). Investigating the Effect of Rudder Profile on 6DOF Ship Turning Performance. *Applied Ocean Research*, 92, 101918.

3. Su, Y., Lin, J., Zhao, D. & Guo, C. (2020). Influence of a Pre-Swirl Stator and Rudder Bulb System on the Propulsion Performance of a Large-Scale Ship Model. *Ocean Engineering*, 218, 108189.

4. Seo, D.W., Oh, J.K. & Lee, S.H. (2010).A Study for Improvement of Lift Performance of a Horn-Type Rudder with the Coanda Effect. *Journal of the Society of Naval Architects of Korea*, 47(4), pp.543-552.

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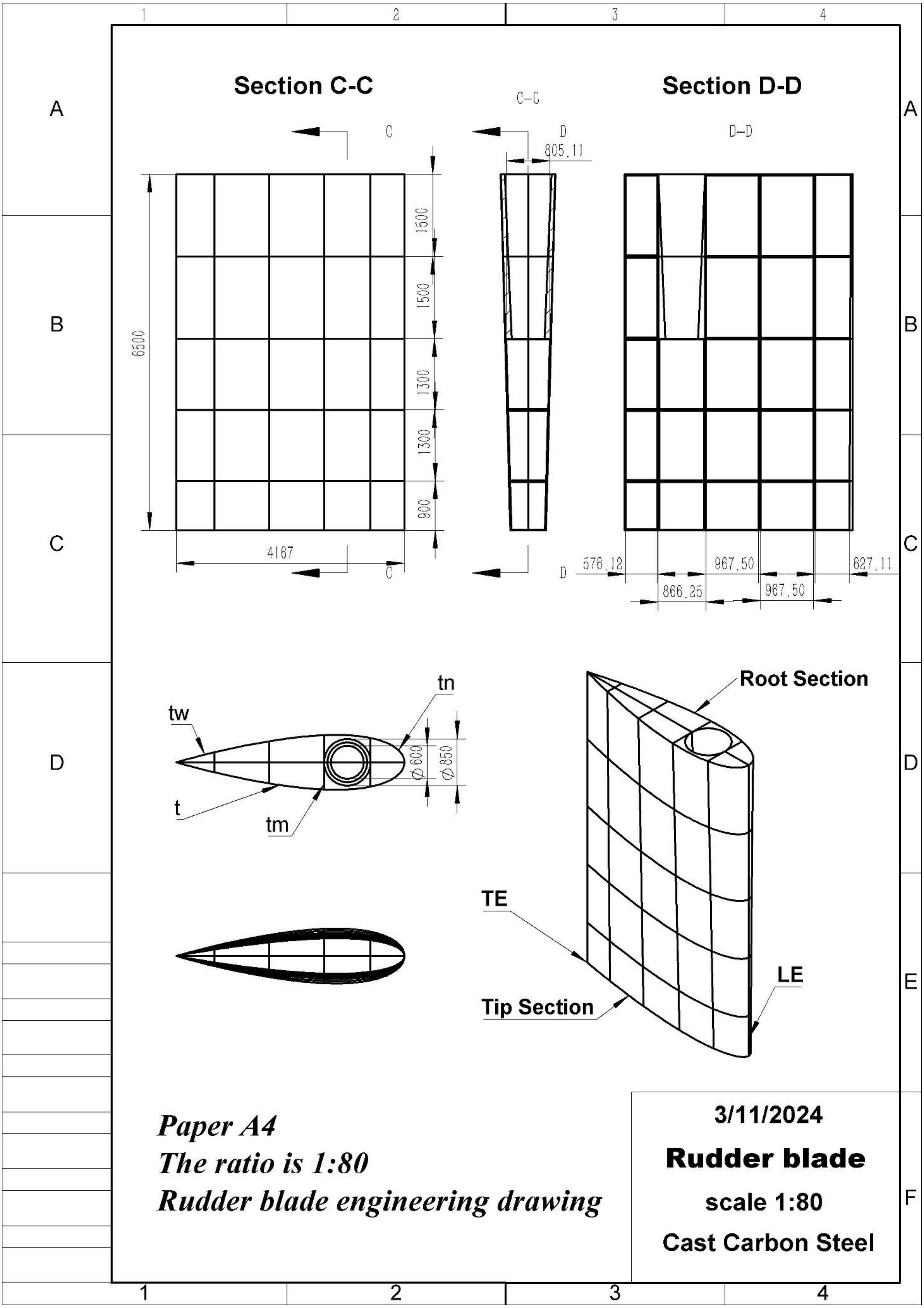
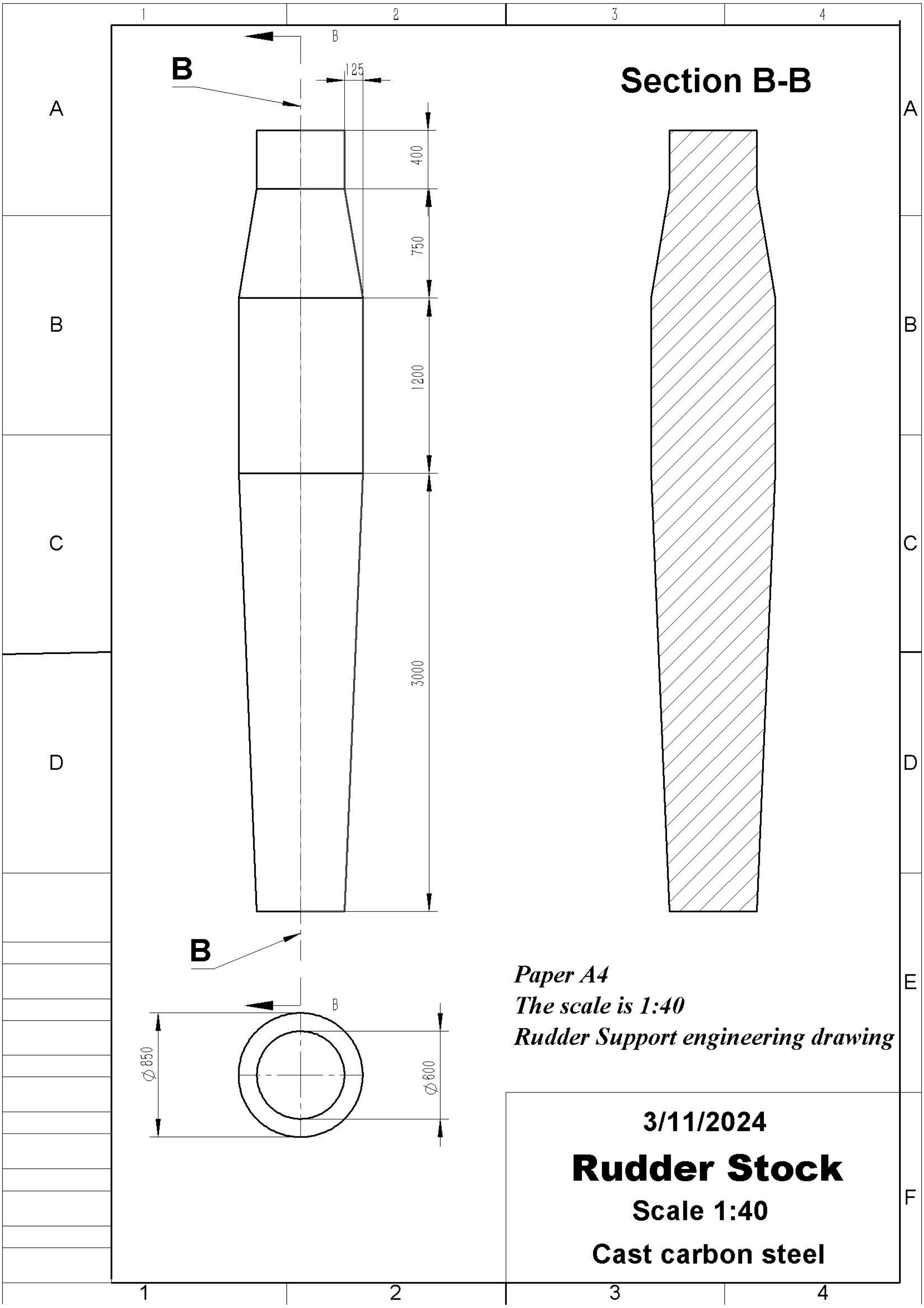
A4 scale drawings





B
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Section B-B
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The scale is 1:40
Rudder Support engineering drawing
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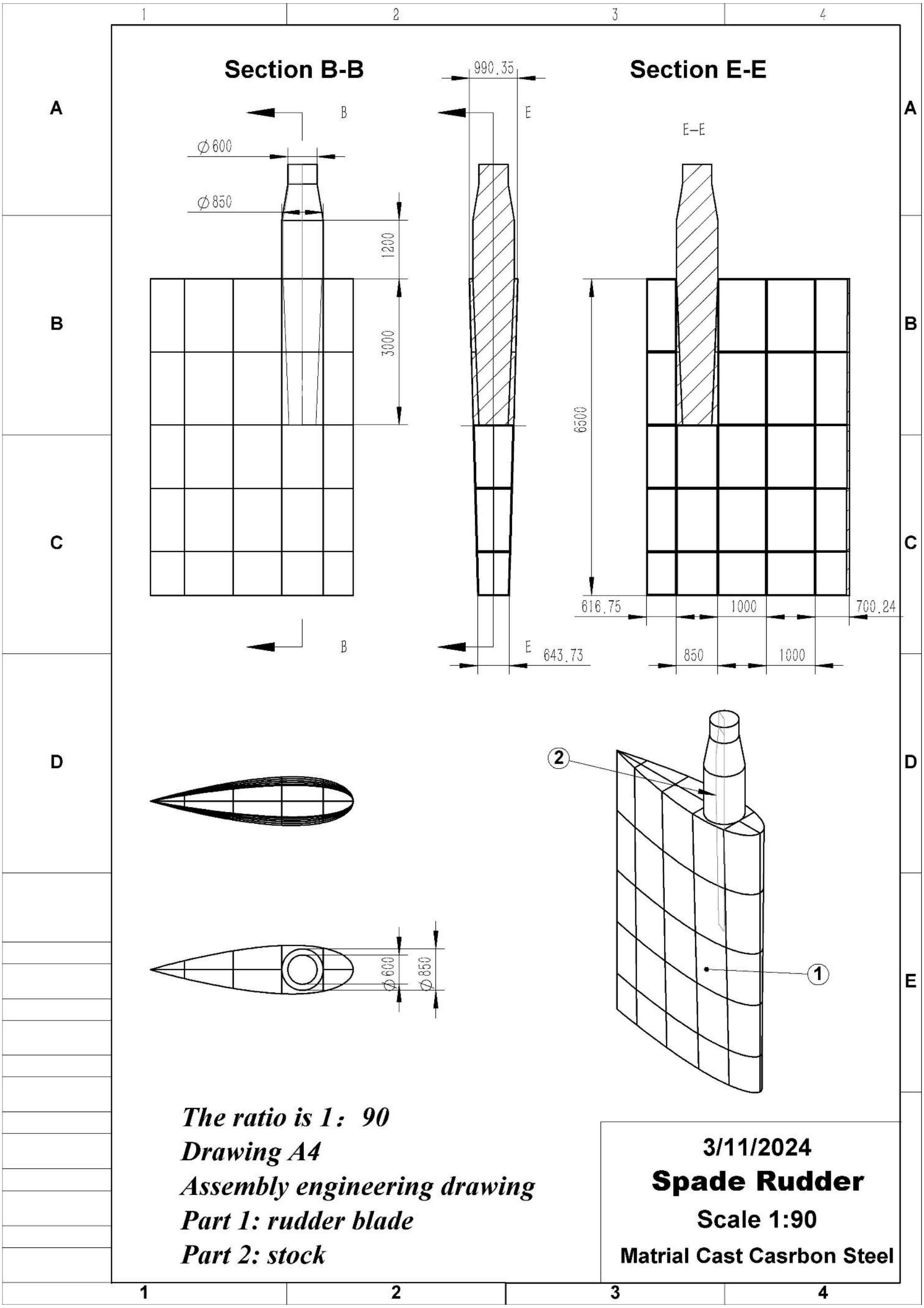
Rudder Stock
Scale 1:40
Cast carbon steel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The ratio is 1： 90
Drawing A4
Assembly engineering drawing
Part 1: rudder blade
Part 2: stock
3/11/2024
Spade Rudder
Scale 1:90
Matrial Cast Casrbon Steel

Appendices of calculations

NACA Airfoil Sections - Thickness Calculation at 25% Chord

The thickness at 25% of the chord length (t_r) is calculated using the formula:

$$t_r = D_L + 2(50) + 2(t_M)$$

Substituting the values, we find: t_r = 999.65mm

The shape of the NACA 00XX foil can be defined by the equation:

$$y_t = 5t[0.2969\sqrt{x} - 0.1260x - 0.3516x^2 + 0.2843x^3 - 0.1015x^4]$$

Where y_t represents the half-thickness at a given position along the chord. For x=0.25,

the half-thickness is calculated as:

$$y_t = \frac{t_r}{2} = 499.825\text{mm},$$

which gives a thickness ratio of:

$$\frac{t}{c} = 0.2$$

Hand Calculations for Finite Element Analysis (FEA)

Maximum Stress

The maximum stress is calculated as follows:

$$\sigma_{max} = -\frac{\theta_1 q b^2}{t^2} = 9.967e + 08$$

Maximum Deflection

The maximum deflection is calculated using:

$$y_{max} = \frac{\alpha q b^4}{t^3} = 8.42e - 3$$

Table 3A: Results from CFD of the lift and drag coefficient for the tapered and un-tapered blade run at inflow velocity V=10m/sec. Final column shows ratio of resultant forces.

Rudder angle (deg)	Rudder forces for rudder t/c = 0.2 and no taper			Rudder forces for rudder t/c =0.2 and 65% taper			
	Cl	Cd	C_R	Cl	Cd	C_{Rtaper}	C_{Rtaper}/C_R
0	-0.038	0.081	0.089	0.003	0.02	0.02	0.225
5	0.736	0.119	0.745	0.122	0.025	0.125	0.168
10	1.116	0.201	1.134	0.188	0.043	0.193	0.17
15	1.358	0.387	1.413	0.289	0.081	0.3	0.212
20	1.483	0.568	1.584	0.402	0.111	0.416	0.263
25	1.722	0.869	1.929	0.455	0.196	0.496	0.257
30	2.288	1.317	2.639	0.318	0.223	0.389	0.147
35	1.887	1.4	2.348	0.336	0.264	0.426	0.182