Structural Strength Assessment for Unlined Steel Stack using Finite Element Analysis

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Abstract

This paper covers the minimum requirements for steel stack design. Structural design and analysis process are conducted by the use of 3-D structural finite element method. Stack structure was designed to conform to the international specifications including the ASME STS-1 (Steel Stacks), the API standard 560, and the Euro Code 1: Actions on Structures – Part 1-4: General Actions – Wind Actions.

The 30 and 35-m-tall stacks with the same flue gas volume flow rate are taken into account in the analysis. It was found that wind load acting on the structure played an important role on the tip deflection of the stack and the maximum stress was found at the base and the reducer of the middle portion. Thermal effect due to the flow of hot flue gas on structural stress and deformation was also included in the computation. Not only dynamic behavior of the structure, but also the stability analysis in terms of local buckling and stress occurring at the lower portion of stack were investigated. Finally, a common vortex shedding control method was proposed in order to minimize the structural vibration.

Keywords*:* Unlined stack, Strength analysis, Finite element method

1. Introduction

Industrial stacks are used to dissolve the concentration of the exhaust plume at the ground level by emission of this hot gas at higher position. The structural design parameters for a stack can be outlined as the stack height, the temperature of flue gas, the local annual maximum and mean wind speeds, the location of the site, and the corrosive protection requirement.

Design guideline for a steel stack is well established and documented in [1]. However, the code provides exclusively information only for the design of uniform cylindrical stack. To design the non-uniform shape stack such as a conical or stepped stack by integrating many portions, it is not feasible with the calculation guideline given in this document. It is necessary to determine an optimal member of the stack in terms of diameter and wall thickness of an individual portion.

Optimization steps regarding to strength/weight ratio and cost of fabrication are performed with care in order to meet a particular requirement of the owner along with the international codes. Therefore, the finite element method becomes an important tool in analyzing the strength of steel structure and making it possible to achieve the most appropriate design regarding the load combination.

2. Specification and Applied Loads

2.1 Structural design criteria

Design platform incorporated with the site meteorological data is given in Table. 1.

Table. 1 Data for the design of two steel stacks

Data for steel stack design		Unit
1.1 Data intake from owner		
-Height of stack	=30.00/35.00	m
-Flow rate of flue gas	=330	$m^3 min^{-1}$
-Temperature of exhaust gas	=230	°C
-Lining interior and heat insulating materials	Unlined stack	-
-Platforms and ladders	Not required	-
1.2 Meteorological data of the site – Sri Racha		
-Mean wind speed	=7.2/13.33	Knots/ $km.hr^{-1}$
-Max. wind speed in 30-yr recurrence period	=60/111	Knots/ $km.hr^{-1}$
-Design wind speed	=120	$km.hr^{-1}$
-Max ambient temp.	=40	°C

According to Table. 1, the flue gas temperature is 230°C and the flow rate is 330 m^3/s. Maximum wind speed in 30-year recurrence period of Sri Racha district is taken into account as a maximum wind loading for the lifetime of these self-supporting stacks.

The inside diameter of the stack at the tip can be determined as follows

$$D = \sqrt{\frac{4Q}{\pi . V_{exit}}} \quad (1)$$

Where

D is the inside diameter of the stack (m)

Q is the volume flow rate of the flue gas (m^3/s)

V_{exit} is the velocity (m/s) at the exit and the optimal range of velocity can be taken as 15 to 20 m/s.

Loads acting on the structure can be described as follows:

-Dead load (DL) of structure including the weight of structure, liner, refractory, platform, access ladder, and helical strakes.

-Live load (LL) during the maintenance operation for staff and equipments acting on the stack.

-Wind load (WL) on structure can be defined as [2]

$$F_w = c_s c_d . c_f . q_p(z_e) . A_{ref} \quad (2)$$

Where

-$c_s c_d$ is the structural factor

-c_f is the force coefficient for the structure

-$q_p(z_e)$ is the peak velocity pressure at reference height (Pa)

-A_{ref} is the reference area of the structure (m^2)

-Seismic load (EL) is neglected. Since the site is not located in the seismic zone.

-Thermal load (TL) at operating temperature is included in the calculation.

-Corrosion allowance for steel shell and base plates is 3 mm for entire design lifetime of the stack. Stress analysis in stack wall and base plate is done in considering actual thickness of the wall less the corrosion allowance. The minimum stack shell thickness is 6 mm as recommended in [1].

-Minimum safety factor in [1] for stack design is 1.50.

The combination of multiple load cases is applied simultaneously as the extreme load condition for stack design. Combined loading used in the computation is

$$Load_{design} = DL + LL + WL + TL \tag{3}$$

3. Methodology of Finite Element Analysis

3.1 Model construction and mesh topology

Mesh topology for two models shown in Fig. 1 is the shell element type defined for the stack wall and solid element type employed for the opening frame and the base plate of the shaft.

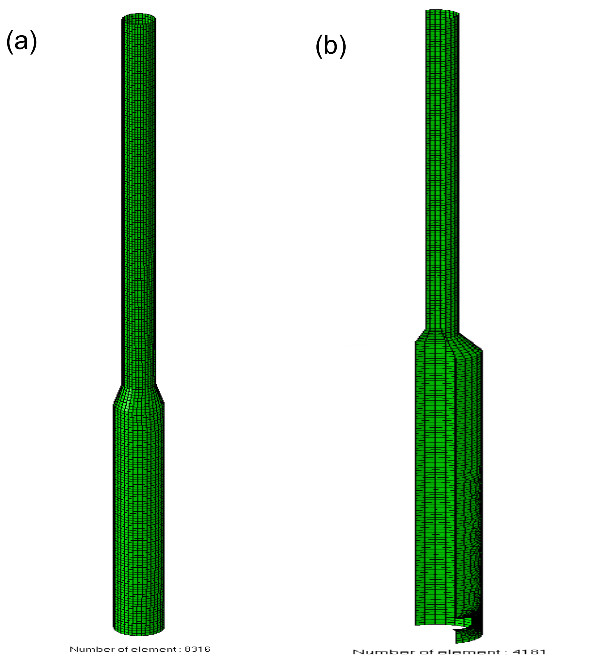


Fig. 1 Mesh topology applied to stack structure *(a)* 8316 elements for full-scale model of 30-m stack *(b)* 4181 elements for half-scale model of 35-m stack

It is obvious that that deformation of the stack is in the similar manner to a cantilever beam subjected to a lateral distributed load. Design aiming for stack structure is to reduce the stress and deflection in the structure associating with the overall cost of the stack. A better design is also for saving the cost of fabrication and it is more economic to fabricate the stack member in cylindrical shape than in conical shape. Typically, stack structure is divided into three portions and the length of each portion is 10 meters. The assembly of each portion is done by fastening two flange plates at the ends of individual portion. The lower and the upper portions are designed in the cylindrical shape. Intermediate portion with a small tapered reducer assists the continuous gas flow inside the shaft.

3.2 Boundary conditions

Since main stack structure is fixed to the concrete foundation by anchor bolts. Fixing conditions at stack base plate for the model must be corresponded to the application and can be presented as follows:

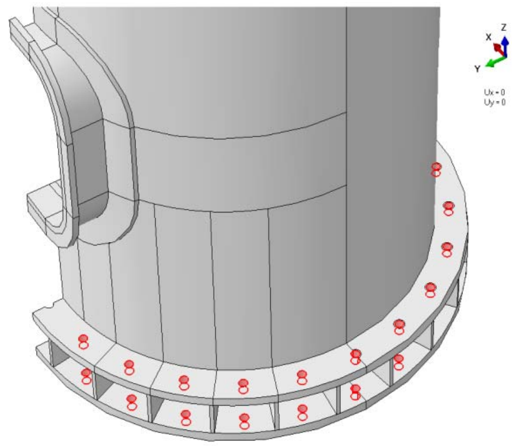


Fig. 2 Typical boundary condition is applied at the base plate of stack

- All interior surfaces of the bolt holes are fixed, thus preventing planar motion of the base plate
- The upper surface around the bolt hole with the same annulus size as that of washer are fixed and preventing the vertical displacement of the base plate

3.3 Material data

Mechanical properties of materials used are given in Table. 2.

Table. 2 Mechanical properties of materials

Properties of materials		Unit
1.Structural steel-JIS grade 3101 - SS400 properties		
-Yield strength of steel	=215	MPa
-Specific weight of steel	=7,850	$kg.m^{-3}$
-Modulus of elasticity	=200	GPa
2. Others		
-Yield strength of bolt	=235.4	MPa
-Tensile strength of welding rod (for E60-xx only)	=412	MPa
-Min. corrosion allowance of unlined stack	=3.0	mm

Note *Wall thickness in the numerical model equals the thickness of new sheet less minimum corrosion allowance of 3.0 mm*

Stress-strain relationship describing thermo-elastic behavior of isotropic material, e.g. steel, can be written as

$$\sigma_{ij} = \frac{E}{1+\nu}\left\{\varepsilon_{ij} + \frac{\nu}{1-2\nu}\varepsilon_{kk}\delta_{ij}\right\} - \frac{E\alpha\Delta T}{1-2\nu}\delta_{ij} \quad (3)$$

Where

σ_{ij} is the stress tensor (Pa)

E is the Young's modulus (Pa)

ν is the poisson ratio

ε_{ij}, ε_{kk} are the strain tensor

δ_{ij} is the Kronecker delta

α is the dilatation coefficient ($^{\circ}C^{-1}$)

ΔT is the temperature gradient ($^{\circ}C$)

4. Results and Discussion

It is widely agreed that the most important issue in design of a steel structure is to determine an optimal structural member in terms of strength and weight, e.g. strength/weight ratio. To achieve this purpose, twenty five models are constructed and analyzed in the static structural module. This is to create a relationship between these design parameters while trying to lower the cost of material used. It is noted that deflection and stress in the stack structure is generally decreased with the larger base diameter but this typical design results in higher the mass of steel in the structure as in Fig. 3. According to the design guideline and the code of practice [1], the most effective design is with the minimum local safety factor equally to 1.5 as a design criterion. Results of structural analysis are presented in Fig. 4 and 5.

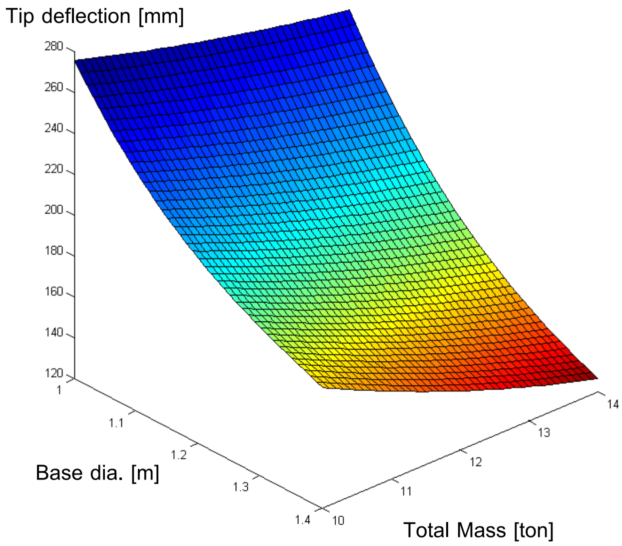
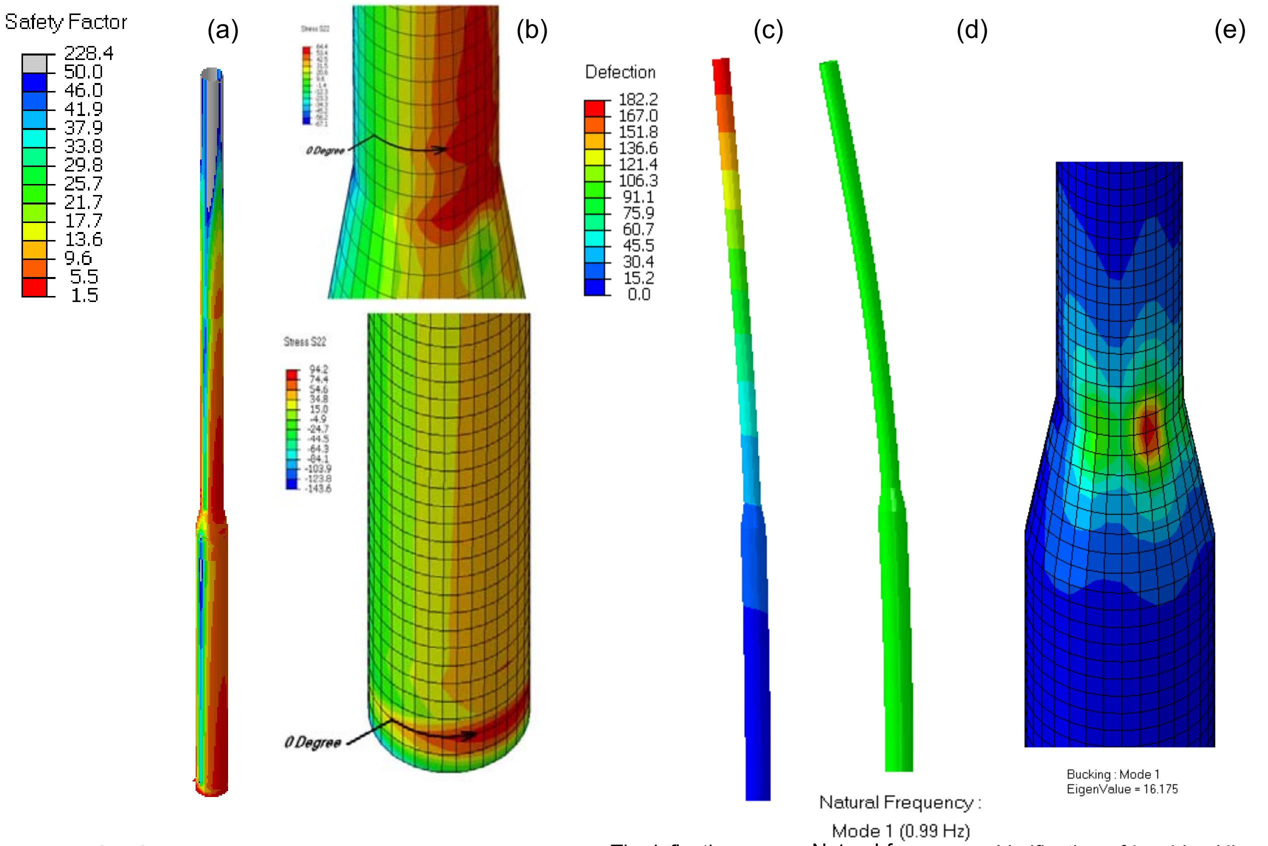
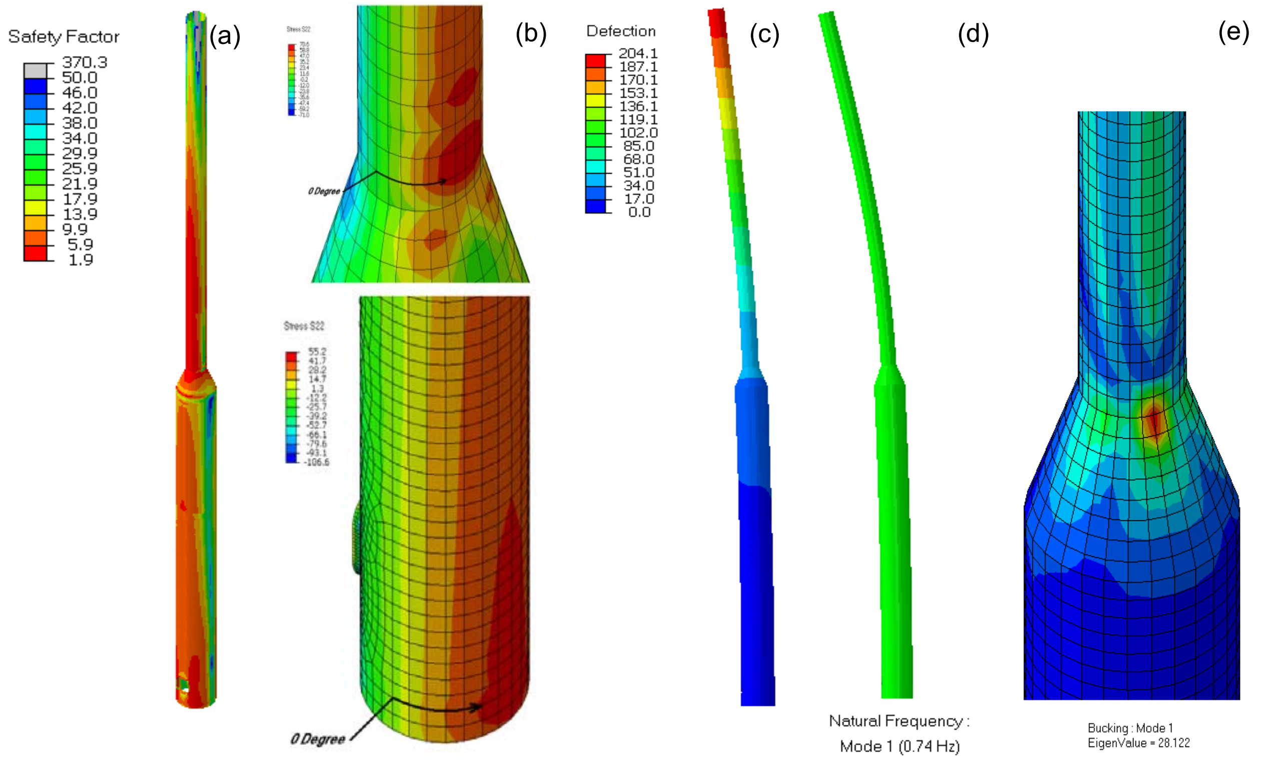


Fig. 3 Tip deflection as a function of total mass and the base diameter



Local safety factor | Locations of maximum stress | Tip deflection | Natural frequency | Verification of local buckling

Fig. 4 Analysis features for 30-m stack



Local safety factor | Locations of maximum stress | Tip deflection | Natural frequency | Verification of local buckling

Fig. 5 Analysis features for 35-m stack

Local minimum safety factor found in both designed stacks are well agreed with the design criteria in the above mention. The value obtained from the computation is 1.5 as shown in Fig. 4a and 5a. Since the stack is subjected to a bending moment which is produced by wind pressure. The side of stack against the wind pressure is under the tension and the opposite side is under the compression. Stress distribution along the circumference of the shaft located by a line on Fig. 5b is plotted in Fig. 6. It is observed that maximum axial stress in tension occurs at 90 degrees. This is the case for the stack side against the wind pressure. For the opposite side or the position at 270 degrees, the maximum axial compressive stress is found. Magnitude of axial stress along the circumference of the middle portion is globally lower than that found near the base of stack. However, the intermediate portion experiences higher compressive stress than the stack wall near the base.

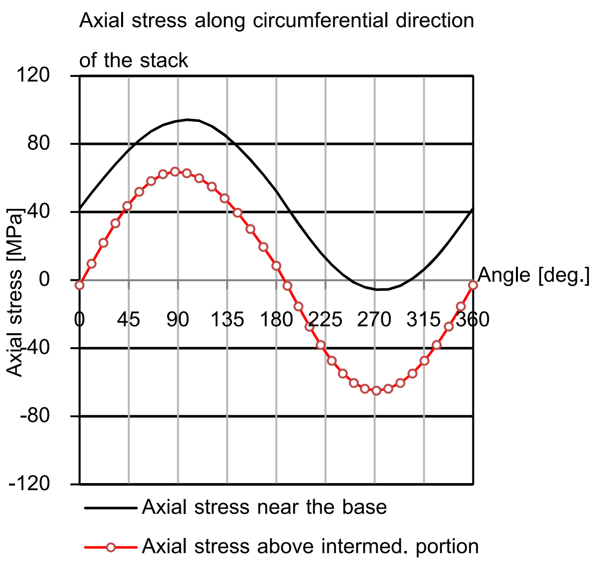


Fig. 6 Distribution of maximum axial stress along the circumference of the 35-m stack

There are two techniques to minimize the stress occurring in the lower portion. First technique is to increase the wall thickness of the shaft which is often practically impossible by using a single sheet. Personal experience can be shared from fabricating such structure is that two rounded sheets after hydraulic press forming must be internally welded together to produce a hollow cylinder with required thickness of the lower portion. This technique is quite complicated since it is necessary not only to control the welding distortion but also require skill shop fabrication, and thus more costly than second technique. In addition, it is also possible to reinforce the lower portion with the vertical and ring stiffeners or liners by welding.

Second technique seems more conventional and popular in terms of cost and work due but need more installation space for the stack and the piping system. It is to design with larger base diameter. This results in the increase of the moment of inertia of cross sectional area of the wall near the base and thus overcoming the stress due to bending moment. However, the permissible largest diameter of a cylindrical structure is approximately 3.5-4.0 meters for the trailer transport according to a traffic regulation for road transportation in Thailand.

Tip deflection is also presented in Fig. 4c and 5c for two stacks involved. Allowable tip deflection is also a design matter and mentioned as a criterion for high mast structure which is of 1 per 180 or more strictly 1 per 200 [3]. Guy wires or cables can also economically help improving the tip deflection.

In this paper, the minimum safety factor criterion is maintained as a stress and deflection control parameter [1]. Furthermore, it is not mentioned in the owner's specification for the stack installation site.

It is understood that this analysis is for the final phase of the stack lifetime, e.g. approximately 20-25 years. Since thickness of corroded wall being the shell thickness of new sheet less 3 mm due to corrosion is taken into account through the analysis.

Results of modal analysis for the first mode resonance are shown in Fig. 4d and 5d for both stacks. Vibration control can be considered as an important topic in high mast and tower design. In order to minimize the structural vibration due to gust or namely vortex shedding control method, helical strakes, fins or shroud cover are commonly mounted to the tip portion of the stack. These are countermeasures for vortex-induced vibration control for a cylindrical structure. The length of strake is approximately one third of the stack height.

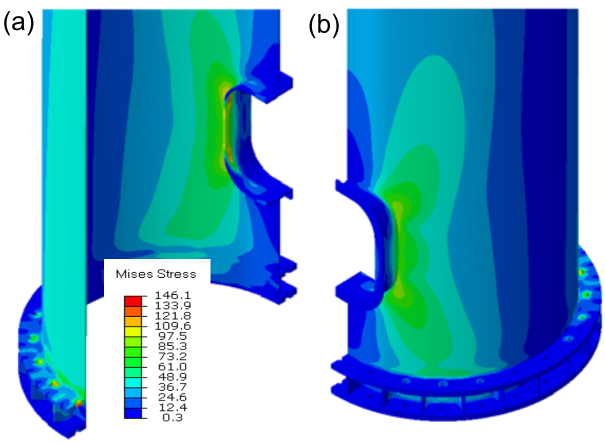


Fig. 7 Distribution of equivalent or Mises stress occurring around the opening frame *(a)* stress on internal wall *(b)* stress on external wall

Port located at the lower portion of stack is for the gas inlet and the accessibility of service operation during shut-down period. Stresses in the frame and stiffeners around the opening are illustrated in Fig. 7a and 7b. Configuration of the frame or stiffeners must be designed with a great care in order to avoid the stress concentration around the corner and the periphery of the opening. The oval or circular cutout results in lower the stress concentration.

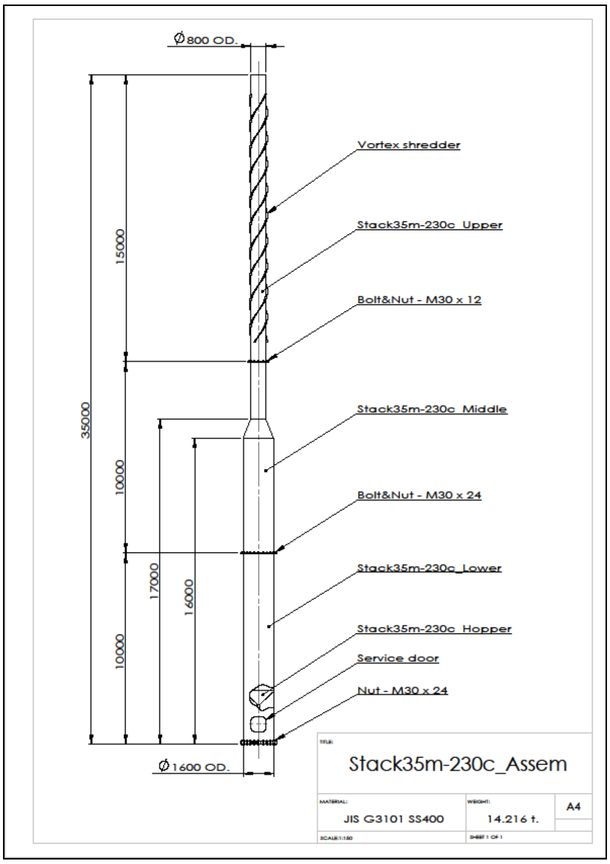


Fig. 8 Shop drawing of the 35-m stack

An elaborate study on the opening reinforcement and design in a wind turbine tower using numerical analysis can be found in [4].

Proposed shop drawing for the 35-m stack mounted with three strakes at the upper portion is illustrated in Fig. 8. It is evident that the design of a high vertical structure is the state-of-the-art and requires multi-step analysis procedure.

Recent challenge in this research area is to design and construct the stack structure with the height up to approximately 100-meter where the vortex induced vibration is the most concern in the design framework [5].

5. Conclusions

Conclusions can be drawn from the result of this study as follows:

1) Finite element method is an effective tool to analyze the integrated structural members associating with multi-physic aspects in terms of static structural, modal, and stability analysis. It is also possible to determine an optimal relationship among several design parameters including strength of structure and material used. Owner or subcontractor can select the most suitable engineered structure regarding to a given specification and cost of construction.

2) It was observed that the maximum stress occurs at the structure wall near the base of the stack and also appeared above the reducing member where the discontinuity of structural profile located. In addition, local stress analysis was important at the place of cutout, e.g. the gas inlet port at the lower portion. An optimal frame and stiffener configuration for the opening can effectively minimize the stress concentration around the port periphery.

3) In order to countermeasure the vortex induced vibration, three strake liners were mounted on the upper surface exposure of the stack. This is a common successful technique used in low or intermediate height in the stack design against the gust.

6. Acknowledgement

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7. References

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