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# Static Stability Determination Of An Exhaust Stack Structure Using Finite Element Analysis

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## ABSTRACT

*The stability analysis of exhaust stack is generally governed by two physical factors, i.e. the intricacy of the stack shape and the height-to-diameter ratio and the nature of the the loadings it supports. In this study, an A516 Grade 70 steel cylindrical tubing exhaust stack subjected to its self-weight and wind speed of 7 m/s was analysed for static stability by applying the equilibrium of rigid body and strength of materials principles. Further analysis was conducted using the finite element simulation. Both results were then compared. The stack's stability state was assessed on the capability of the stack to withstand the maximum deflection and the maximum shear stresses. The complexity of the stack orientation caused a slight inaccuracy in the results. The computation for the volumes was slightly overestimate hence affecting the accuracy in the calculation values of the stack's own load and the determination of CG. As expected the maximum deflection occurred at the top free end of the exhaust stack. In addition the maximum shear stress was*

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*found to not exceed the maximum allowable shear stress for the studied model. Discussion on the vortex shedding was also presented. Vortex shedding developed when the wind flow passed across the cylindrical. From the FEM results, the vortex shedding had little effect to the stresses and displacement of the exhaust stack design.*

**Keywords:** *Static Stability, Deflection, Exhaust Stack, FEA.*

## Introduction

Structural stability is essential to ensure reliability and safety of a structure during operation. To achieve this condition requires in depth analysis due to the influence of numerous factors, i.e. the complexity in the structure's geometry as well as the nature of the load supported. For a structure with enormous height-to-diameter ratio, tendency for it to deflect is more severe due to lower inertia developed about its neutral axis [1]. Such structure is also prone to external force intensity attributed to its larger surface area [2].

The non-stability state of an exhaust stack may also be affected by the presence of wind induced effects such as static drag and vortex shedding [3]. A previous study has reported the effect of static drag on an exhaust stack causing it to deflect for more than 2 percent of its height when opposing wind blow of about 45 m/s [4]. Furthermore, an exhaust stack tend to experience vortex shedding causing it to oscillate in plane perpendicular to the wind direction [5, 6] as a result of alternating low pressure zones generated on downwind side of the stack, forcing it to move towards the zones [7, 8].Vortex shedding may lead to large amplitude vibration when the oscillation frequency is in resonance with the natural frequency of the structure[6]. Such occurrence has witnessed to cause severe catastrophe to tall structures [5, 9-11].The prediction on the effect of vortex shedding vibration on chimney-like structures subjected to wind flow and inertial forces has been reported in numerous studies [4-6, 12-14].The structures were observed as cantilever beams and the stability condition depend on the location of its centre of gravity (CG) [15] and the vortex shedding frequency by Reynold number and Strouhal number relation.

Exhaust stack may be manufactured with a number of turn sections which makes the analytical computation by applying the equilibrium of rigid body and strength of materials principles a bit challenging. Assumptions and some simplification sometimes are necessary but the accuracy of the outcome will be somehow affected [16]. On the other hand, numerical analysis such as finite element method (FEM) can be an alternative tool. There are many advantages using FEM in which both numerical and graphical interpretations can be obtained. Previous publications [17, 18] have shown these methods can be useful tools where comparison between their results can be used as a basis for validation.

The objective of the present work is to analyse the stability of an existing 21-meter exhaust stack supporting its own weight and transverse wind load. The effect of vortex shedding will be discussed. Comparative analysis using the analytical and finite element method (FEM) will also be presented.

## Methodology

The process flow of the stability analysis procedure is presented in Figure 1. Two methods divided into stages, i.e. the analytical approach and the finite element method were used. For both methods, the following assumptions were made:

1. The stack was made of a homogeneous material.
2. The cross section and thickness of the structure were uniform throughout the length.

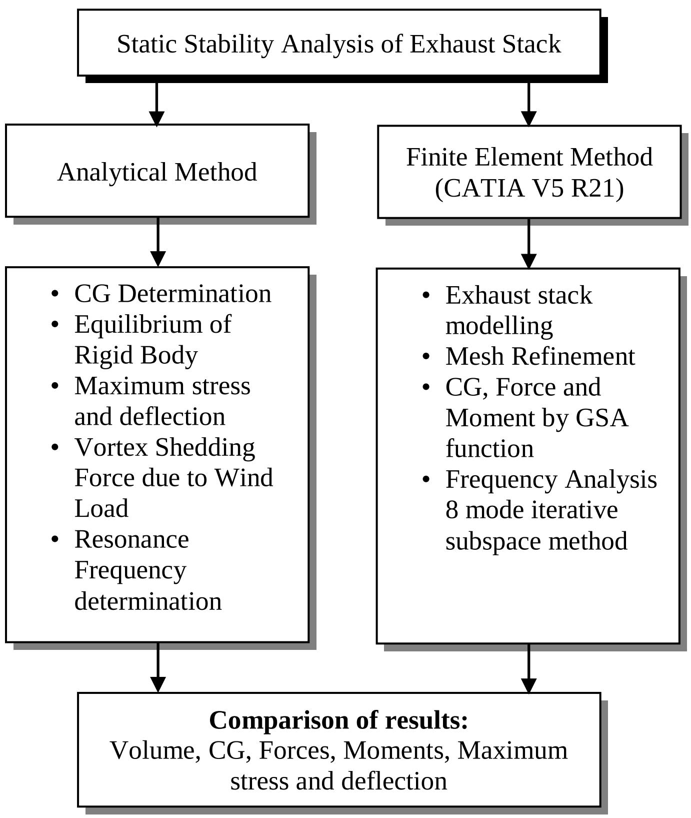

Figure 1: Process flow of static stability analyses of exhaust stack

The material of the exhaust stack was A 516 grade 70 steel and its properties are tabulated in Table 1. It was a cylindrical tube with average diameter $D_{av}$ of 1072 mm and thickness $t$ of 6.35 mm. The steel exhaust stack was modelled as three connected cylinders with 90$^o$ turn at the boundary points A and B as shown in Figure 2. The vertical length OC is 20.905 m and the length OA and AB is 6.138 m and 3.677 m respectively. The stack was clamped at end base point O and was subjected to its own body weight in negative z-direction, and wind force in x-direction. The Cartesian reference axes are shown in Figure 2.

Table 1: Material properties of A 516 grade 70 steel

| **Material Properties** | **Value** |
| --- | --- |
| Density, $\rho$ | 8000 kg/m$^3$ |
| Young's Modulus, $E$ | 207 GPa |
| Poisson's ratio | 0.3 |
| Yield Strength, $S_Y$ | 250 MPa |
| Tensile Strength, $S$ | 485 MPa |
| Damping Ratio | 0.03 |

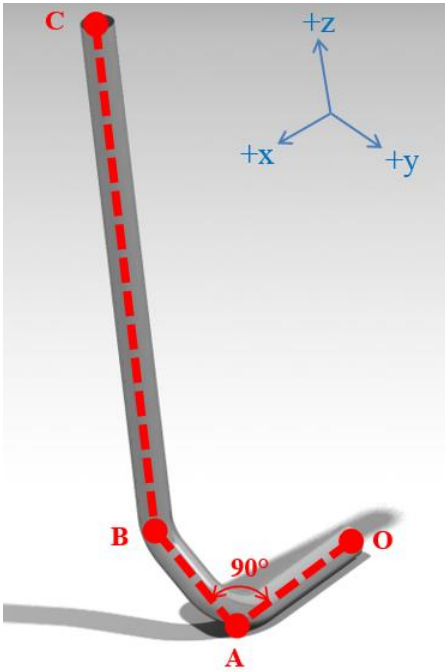


Figure 2: Exhaust stack with the respective orientation axes

## Stage 1: Stability Analysis Using Analytical Method

To establish the state of static stability of the stack, the maximum deflection and the maximum stress have to be computed and their values were compared to material's properties in Table 1. Here, the computation was carried out by applying the equilibrium of rigid body and strength of materials principles, hence this approach was considered as an analytical method. The procedure and related equations are given as follows:

### Centre of Gravity

Centre of gravity (CG) of the exhaust stack was computed based on Cartesian coordinate system with respect to the fixed point *O* (refer to Figure 2). The CG coordinate, *a*, for the structure is given by:

$$a = (X, Y, Z) \tag{1}$$

where

$$X = \sum_{i=1}^{n=3} x_i V_i / V_T \tag{2}$$

$$V_T = \sum_{i=1}^{n=3} V_i \tag{3}$$

In the above equations, $x_i$ referred to the local CG location in x-axis, and $V_i$ and $V_T$ represented the volume for each segment and the total volume respectively. Similar equation was employed to compute the value of $Y$ and $Z$ in y-axis and z-axis.

## Reaction Forces and Moments

The resultant of forces $F$ and the bending moments with respect to point $O$, $M_O$ due to the weight of the exhaust stack and the wind force were assessed as a 3-D structure. The structure was said to be in static equilibrium and hence the following equations of equilibrium of rigid bodies were used:

$$\vec{F} = F_x\vec{i} + F_y\vec{j} + F_z\vec{k} = 0 \tag{4}$$

$$\sum M_O = \sum\left(\vec{l} \times \vec{F}\right) = \begin{vmatrix} \vec{i} & \vec{j} & \vec{k} \\ l_x & l_y & l_z \\ F_x & F_y & F_z \end{vmatrix} = 0 \tag{5}$$

where $l$ is the length of the segments.

## Vortex Shedding Frequency

When air flows past over a cylinder, flow instability emerges as vortices pattern, a phenomenon known as vortex shedding. The frequency of the vortex shedding depends on the Reynolds Number, *Re*, as well as the strength of wind force experienced by a particular structure, $F_w$. The relation is given by Equation (6):

$$F_W = 0.5\rho\upsilon^2 \mathrm{Re}^2 D_O^{-1} C_L \sin(2\pi\omega t) \tag{6}$$

where $\omega$ is the frequency at particular location along the member length or height at respective period, $t$; $D_O$ is the outer diameter of the structure cross section; $\upsilon$ is the kinematic viscosity of the air; $\rho$ is the air mass density and $C_L$ is the lift force coefficient for a given cross sectional geometry as opposed to the wind direction. In this study, the value of $C_L$ was taken as 0.2 for hollow cylindrical structure.

When a body vibrates, a resonance occurs when the natural vibration frequency of a body matches the vortex shedding frequency. This phenomenon could happen in the critical range of *Re* number between $3 \times 10^5$ to $3 \times 10^6$ and wind speed of 5 to 15 m/s [8].In actual state, wind force followed cyclic load profile due to velocity variation with respect to time [7, 8]. The magnitude of wind velocity, $v$, can be computed using the formulation from Giosan's work [8]:

$$v \le 20.65 z^{0.1053} \tag{7}$$

where $z$, is the height of the cylinder above the ground level. The vortex shedding frequency, ω were determined by rearranging Strouhal number, $S$, relation:

$$\omega = S v D_O^{-1}, S = 0.25 \tag{8}$$

The natural vibration frequency can be derived from the general displacement equation with respect to the motion of nodal masses located at the middle and top point of the stack structure. The relation from [8] can be simplified as:

$$\begin{bmatrix} \dfrac{1}{m_1\omega_1^2} - \dfrac{l^3}{3EI} & -\dfrac{0.625 l^3}{6EI} \\ -\dfrac{0.625 l^3}{6EI} & \dfrac{1}{m_2\omega_2^2} - \dfrac{l^3}{3EI} \end{bmatrix} = 0 \tag{9}$$

where $E$ is the elastic modulus of the steel and $I$, the moment of inertia of the stack.

## Internal Stresses and Maximum Deflection

The stack structure experienced several types of stresses including shear stress $\tau_{xy}$, tensile stress $\sigma$, and torsional shear stress $\tau_{torsion}$. These stresses can be computed using the following relations:

$$\tau_{xy} = \frac{2V_s}{A} \tag{10}$$

$$\sigma = \frac{MD_O}{I} \tag{11}$$

$$\tau_{torsion} = \frac{TD_O}{J} \tag{12}$$

Where $V_s$ is the shear force, $A$ is the cross-section area of the exhaust stack, $M$ is the bending moment of respective axis, $J$ is the polar moment of inertia and $T$ is the torque produced. Maximum in-plain stress can be calculated using:

$$\tau_{\max} = \sqrt{\left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + \tau^2} \tag{13}$$

The total (resultant) deflection of the exhaust stack as a result from the supported loads can be determined using Equations (14) and (15):

$$\delta_i = \frac{Fl^2(3l - a)}{6EI} \tag{14}$$

$$\delta_{resultant} = \sqrt{\sum \delta_i^2} \tag{15}$$

## Stage 2: Finite Element Analysis on Stability of Exhaust Stack

FEM was performed using Generative Structural Analysis, a built-in function in CATIA. The stack was modelled using the element type TE4 with 62,394 elements and 20,871 nodes with fixed boundary at point O (refer to Figure 2). The location of CG of the stack was retrieved from the constructed model using CATIA. The weight supported by the stack due to the gravitational attraction was assumed to be concentrated at the CG of the structure, acting along z-direction. The wind load was applied to the model in negative x-direction as shown in Figure 3. Iterative subspace method with 8 modes was selected after performing a series of optimization processes which resulted to lower percentage of error to the estimated results. The natural frequency of the structure was determined using Frequency Case analysis. The frequency selection was subjected to two main conditions: (1) the chosen value should not exceed the calculated vortex shedding frequency in Stage 1; and (2) the chosen value should lie within critical *Re* number.

## Results and Discussion

The results from the analyses were tabulated in Table 2. There were noticeable discrepancies between the computed volumes and the locations of CG. However, they were comparatively small with the differences of not more than 3 percent.  Such occurrence was due the simplifying assumption near the 90 degree turns where cylinders were connected in which each circumferential connectors of the stack was simply regarded as a full extension, causing extra volume being added.

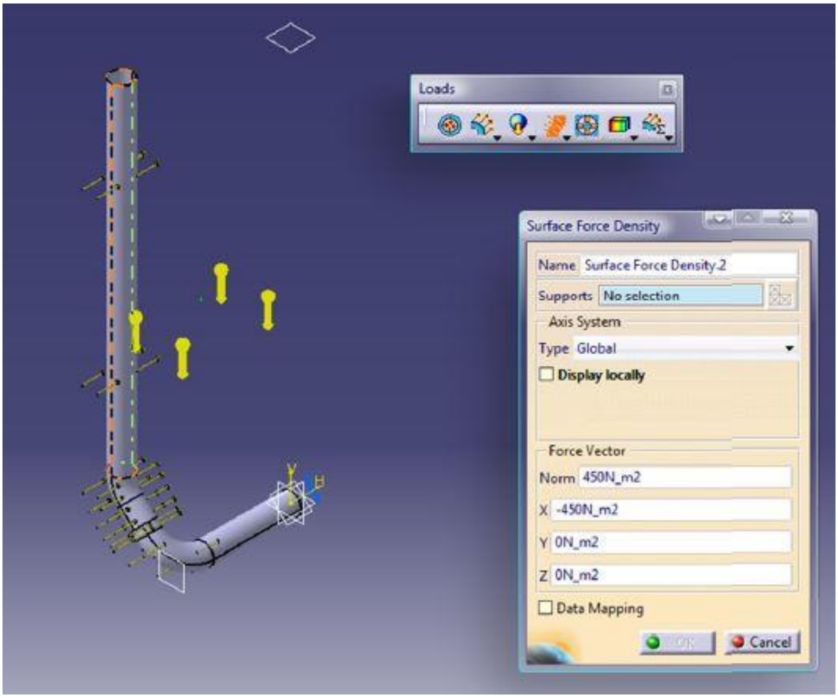

Figure 3:Self-weight and wind loading input on the stack model in z and x-directions

The magnitude of the displacement was nearly 36 mm occurred at the top free end of the stack. The maximum in-plane shear stresses were 45 MPa and 42 MPa respectively from analytical and FEM results, both measured at the fixed support at O, as shown in Figure 4. The speed of the wind was set at 7 m/s which produced the vortex shedding frequency of 10.11 rad/s from analytical computation and 8.74 rad/s from FEM. The maximum bending moment was along y-direction due to the combination of the weight of the stack and the wind load. Comparing the calculated values of the maximum in-plane shear stresses to the yield strength of the A 516 grade 70 steel given in Table 1, it can be concluded that the exhaust stack was not at risk state of failure. In addition, low displacement experienced by the structure gave an indication that the exhaust stack structure was statically stable.

Table 2: Comparison of analytical calculation and FEA simulation for static stability analysis of an exhaust stack

| **Properties** | **Analytical** | **FEA** | **Error (%)** |
|---|---|---|---|

| | **Method** | **Method** | |
|---|---|---|---|
| Volume ($m^3$) | 0.6049 | 0.5890 | 2.63 |
| Center of Gravity with respect to origin *O*(mm) | | | |
| $X$ | 5468.10 | 5448.13 | 0.37 |
| $Y$ | -1862.49 | -1910.67 | 2.59 |
| $Z$ | 7820.41 | 8030.99 | 2.69 |
| Reaction Forces at origin *O* (kN) | | | |
| $F_x$ | 0.00 | 0.00 | 0.00 |
| $F_y$ | 0.00 | 0.00 | 0.00 |
| $F_z$ | 47.46 | 46.83 | 1.33 |
| Bending Moment at origin *O* (kN.m) | | | |
| $M_x$ | -88.39 | -88.92 | 0.60 |
| $M_y$ | -259.86 | -255.43 | 1.70 |
| $M_z$ | 0.00 | 0.00 | 0.00 |
| Vortex Shedding Frequency (rad/s) | 10.11 | 8.74 | 13.55 |
| Maximum In-plane Stress (MPa) | 45.12 | 42.23 | 6.41 |
| Maximum Displacement (mm) | 35.51 | 35.84 | 0.90 |

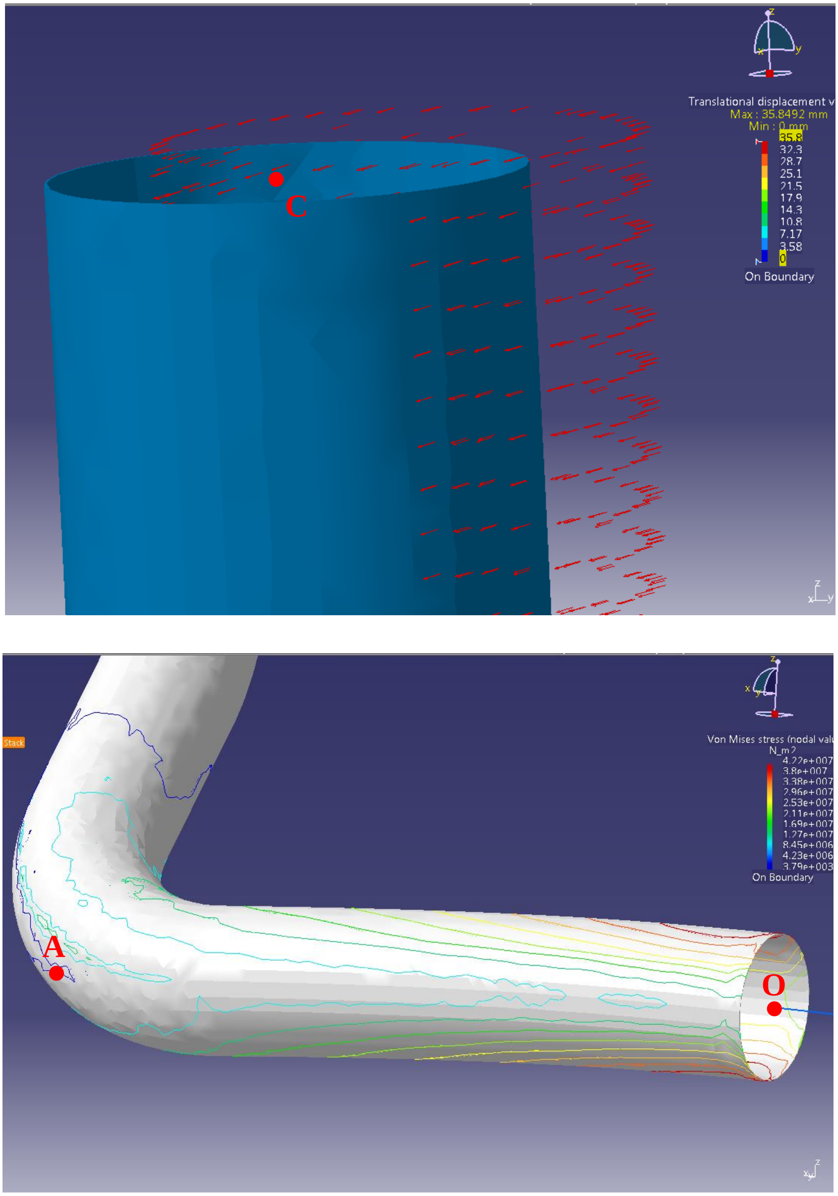


Figure 4: FEA simulation translational displacement at tip of the exhaust stack (above) and stress distribution along member OA (below)

Comparing between the analytical and FEM results, the exhaust stack static stability was not affected by the vortex shedding for the chosen wind load. This was clearly observed in small difference in maximum stress and displacement computed using both methods. As stated in [8], if a cyclic wind loading was to be imposed then it would be advisable to further analyse the effect of vortex shedding with respect to time. The cyclic loading would generate cumulative stress over time and the maximum stress limit will no longer depends on the material ultimate strength but endurance limit [19].

Nonetheless, the stability of the structure can be further improved by reducing the structure effective area and the diameter of the stack [4]. As a result, lower obstruction will be experienced by the exhaust stack. To some extent, this proposition might compromise thermodynamic aspect of an exhaust stack which may cause back flow, lack of thrust and etc. [3-6, 20]. For tall structures with restriction to its geometrical aspect, increment to the total mass may reduce the effect of vortex shedding [11]. A direct relation can be seen through Equation (9) – slight increase in mass leads to reduction of displacement. Strengthening or stiffening the member are also useful to reduce vortex shedding induced effect as being reported in [6, 10].

## Conclusion

The process of stability assessment on the exhaust stack due to its own weight and the wind load effect has been fully presented. The stability of the stack was assessed on the capability of the stack to support the loadings. As expected the maximum deflection occurred at the top free end and the total deflection of 37 mm was considered not critical in comparison to the stack's total length of 21 m. In addition the maximum shear stress was found to not exceed the maximum allowable shear stress for the studied model. Vortex shedding developed when the wind flow across the cylindrical stack but the induced vibration was not severe. The vortex frequencies were 10.11 rad/s and 8.74 rad/s computed analytically and FEM, respectively, and they had little effect to the stresses and displacement of the exhaust stack design. Hence it can be concluded that the exhaust stack structure was statically stable

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