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INCREASING THE HEIGHT OF A GUYED STEEL STACK WHICH IS SUPPORTED ON AN INDUTRIAL BUILDING

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The paper studied the rehabilitation and increase in height of an existing 30 ft tall, industrial, guyed steel stack, which was built around 1977. The stack is supported on an industrial building. Stacks are an essential part of the industrial facilities. They allow the discharge of chemical waste gases from industries to the atmosphere, under stringent pollution control guidelines. The height of the stack is increased by 40 ft to comply with the new guidelines. Analytical and numerical simulations were performed using MecaStack software (local model) and SAP2000 V.20 software (global model). Analysis and design are based on the ASME STS-1-2016 standard code. Discontinuity around the manhole at the bottom of the stack is investigated with SAP2000 V.20 finite element software. Results in terms of principle stresses, and Von-Mises stress, were used to prepare recommendations, repair and construction documents for the project.

Keywords: Dynamic wind loading, Slender structures, Stability, Analysis, Stress.

1 INTRODUCTION

Guyed steel stacks provide a more economical solution for taller stacks compared to self-supporting ones, depending on available space. The main component of these structures is usually a slender, cylindrical stack, circular in shape, which is pinned at its base. Sets of inclined guy cables support laterally the stack at several levels along its height. These guy cables are pretensioned and, generally, spaced at equal angles around the stack. The structural behavior of guyed stacks is complex due to the following reasons: geometric and material nonlinearities in conjunction with the sagging tendency of the guy cables; the interaction between the cables and the stack; the slenderness of the stack, and the boundary conditions. This paper describes the analytical and numerical research, which was carried out to increase the height of the existing steel stack, so as to comply with new pollution guidelines. The steel stack is designed in accordance with the American Society of Mechanical Engineers (ASME STS-1-2016 2016) standard. The design loads are based on the Minimum Design Loads for Buildings and Other Structures (ASCE/SEI 7-16 2016). Furthermore, the International Committee of Industrial Chimneys (CICIND 2010) model code, as well as ASCE Chimney and Stack Inspection Guidelines (ASCE 2003) provided supplemental data for the design.

The behavior of guyed structures has been investigated by several authors. Most of their work has been based on a "local model" where, the stack is independent of any adjacent or supporting structure. However, most design codes require that, structural interactions due to any supporting framework, geometric nonlinearities and potential interactions between guy wires and stack, should be taken into consideration in a detailed analysis of guyed stacks by correct modelling of inertia properties of the guy wires, the stack properties, and the boundary conditions. In essence, depending on the given geometric configuration, this amounts to determining the forces in the stack by using a global 2D or 3D model; especially, for unstiffened chimneys with a low aspect ratio. This may be explained by the fact that, the interactions between these members have a significant influence on overall performance of the whole system. A nonlinear analysis should be performed, if it is determined that the magnitude of cable displacements is such that the equilibrium equation for the structure should be based on the geometry of the displaced structure (P-Delta effect). Cables should maintain a minimum tensile force under all loading conditions to minimize visible sag and potential for induced vibrations.

Prinz and Roels (1998) performed the design of strengthening of a brick-built chimney structure by adding a guyed steel stack onto the structure. The added steel section was guyed with three steel ropes. During a period of four years, in which the system was in use, routine maintenance inspection, every two months revealed no defects. Bhowmik and Custodis (2001) performed a challenging chimney retrofit project for a steel producing company in Ontario, Canada. The stack was 160 ft tall with ten ft ten in inside diameter, and with approximately the bottom 30 ft inside a building. The authors used a Beam model to help retrofit the chimney.

This paper deals with analysis, design and rehabilitation of a guyed steel stack. The most important parameters considered in the evaluation and practical design of the stack will be presented. The performance of the stack is examined by using MecaStack software (2016) and through the finite element computer program SAP2000 V. 20 (2018). The effects of some important structural and material parameters on the guyed steel stack are evaluated and discussed.

2 AS-BUILT STRUCTURE

The project is located in Dallas, Texas, U.S. The as-built steel stack has a diameter of 4.25 ft, and a current height of 30 ft. It is supported on a platform, 20 ft x 15 ft, at an elevation of about 44 ft from the pavement, in conjunction with a set of three guy wires, with a diameter of 3/8 inches at about 120 degrees around the stack. The thickness of the shell is 0.167 in along the whole height; and the steel plate on the platform is 5/8 in thick. It is a single wall construction with fixed ladders. A steel-braced frame supports the platform and transfers the loads over four columns to the 30-in diameter, nine ft deep concrete shafts. The shafts are reinforced with eight #7 vertical rebars, and #3 stirrups at 18 in on center. The platform configuration consists of typical wide-flange beams: W16x26 sections in the north-south direction, at four ft spacing (approx.); and W12x16 in the east-west direction, at three ft spacing (approx.). The columns are square, hollow structural sections, HSS8x8x1/4 at the lower levels and HSS5x5x1/4 section at upper levels. X-diagonal bracings are ¾ in dia. steel rods. Additionally, some W16x26 beam sections are used as horizontal bracings below the platform level. There is a two ft by 7.5 ft flue opening at the bottom of the stack. The stack was built around 1977. The as-built steel is assumed to be A-36.

3 REHABILITATION

Based on the evaluation of the inspection reports, and the need to increase the height of the existing stack, a retrofit of the supporting steel frame was deemed necessary. Thus, the exiting stack shell is reinforced with a total of eight WT4x5 sections as vertical stiffeners. Additionally, two WT7x11 sections are welded adjacent to the flue opening. In the east-west direction, the platform is reinforced with three additional beams, W16x26, reducing the spacing of the beams to about two ft; and, the existing W8x10 beams are reinforced with WT4x5 section. The perimeter beams, W12x16 in the north-south direction are reinforced with WT6x7. These built-up beams are then boxed-up with two 1/8 in thick plates, one on each side. Furthermore, in the north-south direction, W16x26 and W12x14 beams have been added. The bracing configuration, just beneath the platform has been retrofitted with pipe sections PIPE 4, in combination with ¾ in diameter diagonal rods. The structural system is supported additionally by four new columns, HSS5x5x3/8 at the top and HSS8x8x3/8 below. The load from each column is transferred to a 40-ft deep, 30-in diameter concrete drilled shafts, with an embedment of seven ft into rock. The shafts are reinforced with eight #9 vertical rebars, and #3 spirals at 6 in pitch. The new steel is one of the following: A36, A53, A475 (7 Wire), A500, A572. Concrete has a minimum compressive strength of 3 ksi.

4 INCREASING THE STACK HEIGHT

The stack height has been increased by 40 ft, using ¼ in thick steel cylinder sections. The diameter is kept constant as in the as-built section, at a value of 4.25 ft. Angle sections, L3x3x1/4, at five ft spacing are used as horizontal rings. The whole rehabilitated stack, including the new section, is tied onto the platform by three sets of four, 1.5 in. diameter guy wires at different heights of 20 ft; 40 ft and 60 ft above the platform. The guy wire is attached onto the stack and onto the platform by using eye lug and a dead man. This is done in conjunction with turnbuckle, which allows the adjustment to the pretension force. Additional platform has been added to the stack.

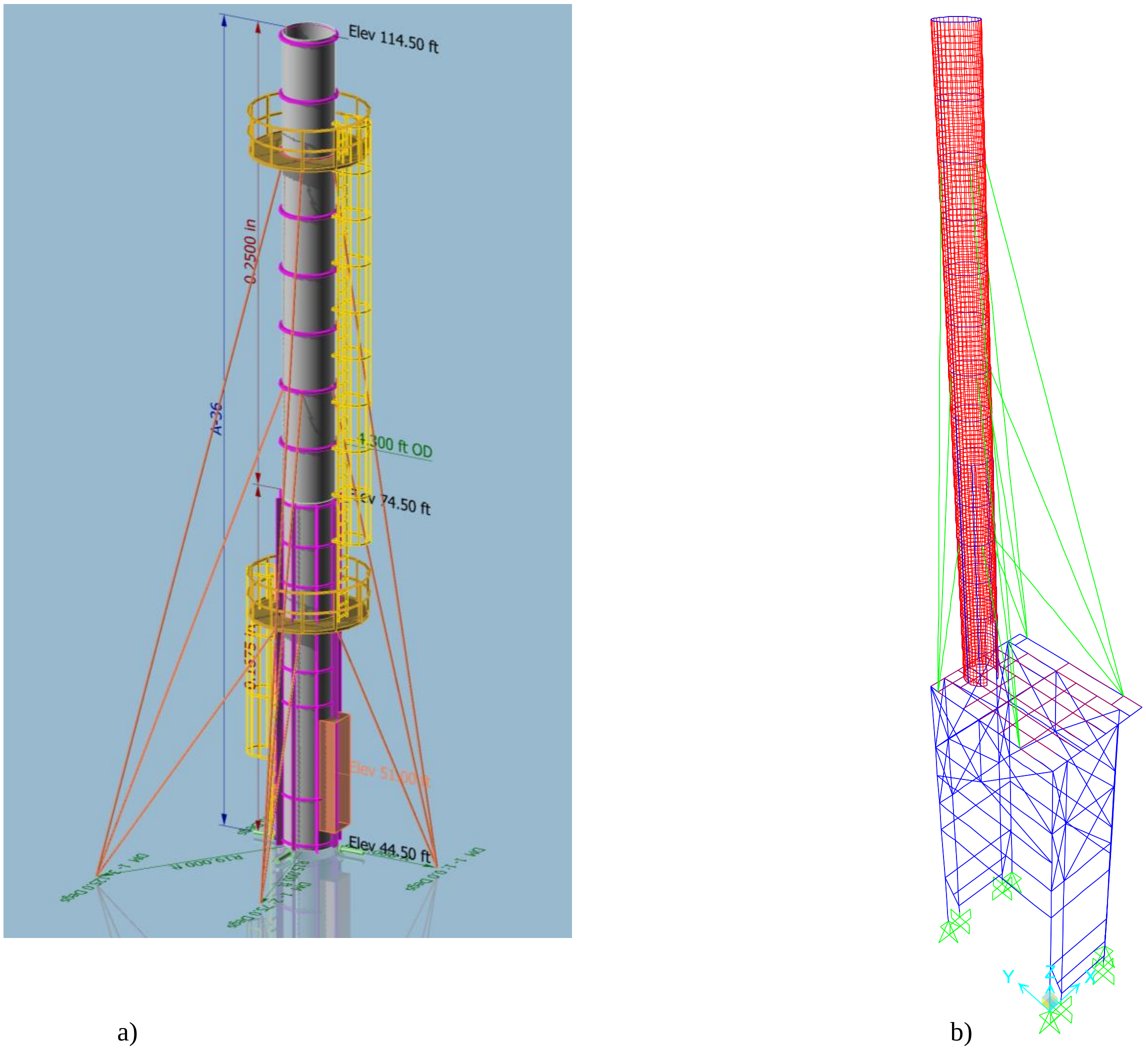
5 LOCAL ANALYSIS WITH MECASTACK SOFTWARE

A local analysis has been carried out using MecaStack software (2016), in accordance with ASME STS-1-2016 and the Minimum Design Loads for Buildings and other Structures, ASCE/SEI 7-16. Fig. 1a) shows the model used for the analysis. All geometric configuration described above is included in the model. The stack has been analyzed under constant wind load of 41 psf. The platform live load is 50 psf. The pretension guy wire force at the platform is normally a value between 6% and 15% of the wire breaking strength. This analysis used a value of 6%. Furthermore, the analysis takes the following parameters into consideration: a) nonlinear cable effects; b) wind loads in different directions; c) thermal expansion of the stack; d) vortex shedding of guyed stack, and e) fatigue.

The results of the local analysis, in terms of guy wire tension, F; axial compression stress, σ_a; bending stress, $\sigma_{b;}$ circumferential stress, σ_c, in the stack shell are provided in Table 1. The table also includes the allowable design values per ASME STS-1-2016. It can be seen that, for the proposed configuration, the calculated values are less than the allowable values. Thus, the design is safe.

6 GLOBAL ANALYSIS WITH SAP2000 V. 20 (2018) – FEA MODELLING

A 3D finite element model has been developed using SAP2000 V.20 (2018) commercial software, for the steel stack, as shown in Fig. 1b. This model is used to capture any other features of the structure, which could not be effectively simulated with the local model, including the supporting steel-braced frames. The ladders and platforms are not simulated in this global model. However, the dead and live loads due to the platform are included in the model. The guy wires are modelled as tension-only elements. The shell element SHELL is used in modelling the stack wall and platform plates. This is a three- or four node formulation that combines membrane and plate bending behavior. There is a rigid connection between the stack shell and the platform plates.



a) b)

Figure 1. Analysis models: a) Local model with MecaStack; b) Global model with SAP2000 V.20 (2018).

Table 1. Comparison of analysis results with allowable values (ASD).

Item	MecaStack		SAP2000	
	Calc.	Allow.	Calc.	Yield
Guy Wire Force, [kips]	37.74	54.72	17.4	54.72
Shell Stress at 44.5 ft				
Axial Compr., σ_a [ksi]	4.22	9.88		
Bending, σ_b [ksi]	0	9.88		
Circumferential, σ_c [ksi]	0.10	19.9		
Von-Mises, σ_{vM}			26.0	36.0
Shell Stress at 74.2 ft				
Axial Compr., σ_a [ksi]	6.6	9.88		
Bending, σ_b [ksi]	2.49	9.88		
Circumferential, σ_c [ksi]	0.1	19.9		
Von-Mises, σ_{vM}			5.9	36.0

Wind loading is a constant value of 41 psf., as determined under section 5. Additional dead and live loads due to the upper platforms, as well as the loads on the lower platform have been included. Thus, wind, live and dead loads have been considered in this model. As depicted on Figure 1b), a fixed boundary condition is used at the pavement level. The analysis is based on allowable stress as per code AISC 325-05 (2006). SAP2000 (2018) takes the following parameters into consideration: a) nonlinear cable effects, b) P-Delta effects with small and large deformations; and c) wind loads in different directions.

The results show plausible distribution of the principle stresses, and the need for the retrofitting of the bracing system configurations. Generally, the maximum principal stresses and Von-mises stress are used to evaluate the capacity of shell structures. The results presented in Figure 2, show realistic distribution of the Von-Mises stress, σ_{vM} [ksi] on the stack shell and on the platform plate.

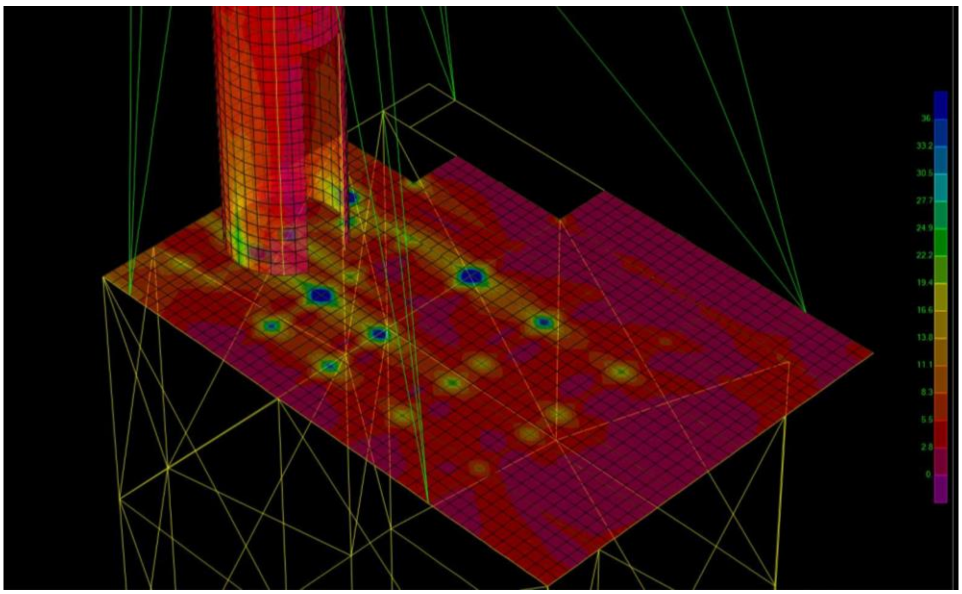


Figure 2. Global model analysis results – computed Von-Mises stress [ksi].

Due to the flue opening at the bottom of the stack, the stiffness of the cross-section is reduced significantly, and high concentration of stresses could be expected, when no reinforcement is provided. However, the reinforcement provided section 3 above seems to be adequate. Except for singularity cases, the plotted values are less than the yield strength, which is 36 ksi. Furthermore, the results of the combined stress in the frame members show that their maximum stress ratios are less than unity. The additional outputs of the analysis are not presented in this paper due to space limit; but, they will be presented in the conference. Therefore, the selected geometric configuration meets the design safety requirements.

As shown in Table 1, the local analysis provides stresses that are lower than the ones based on the global model. However, the results from both models are used to determine the necessary stack shell thickness to resist flexural loading; the need, size and spacing of ring and vertical stiffeners; the size and location of any additional bracings, and the size and number of guy wire cables. Furthermore, in adherence to ASME STS-1-2016, section 4.11.3.1 [2], this study took into consideration the “structural interaction between the guyed steel stack and its supporting structure.”

7 CONCLUSIONS

Simplified, local models may not be adequate for slender stacks with large opening. Geometric and material nonlinearities and cable-stack-framework interactions are important and should be simulated properly by using appropriate type and number of elements in the cable model, suitable formulation, and also correct modelling of inertia properties of the guy cables, the stack and any supporting framework. Thus, it can be concluded that, the analysis, design and performance of a guyed steel stack may be accurately predicted by the use of an efficient and effective software such as MecaStack (2016) and SAP2000 V.20 (2018).

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