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NUMERICAL ASSESSMENT OF EXPLOSION-INDUCED STRESS AND FAILURE MODES IN VERTICAL TOWER STRUCTURES

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Industrial towers used in petrochemical and energy facilities are highly vulnerable to accidental vapor cloud explosions, yet their transient structural responses remain insufficiently understood. This study develops a detailed finite element framework to examine the deformation, stress evolution, and stability of a vertical vacuum deaeration tower subjected to explosive shock waves. A three-dimensional nonlinear model was constructed in ANSYS using shell and solid elements to capture both global and local behaviors. Explosion loading was characterized by triangular overpressure pulses following ASCE 41088 and GB/T50779-2022 guidelines, with two representative scenarios considered: a moderate far-field case (14.6 kPa) and a severe near-field case (30 kPa). The simulations reveal that deformation is dominated by displacement of the upper head, whereas maximum stress consistently concentrates at the skirt base. Increasing blast intensity leads to sharp growth in both displacement and von Mises stress, with near-yield conditions observed under the severe scenario. Parametric analyses further demonstrate that numerical damping effectively reduces peak responses, and buckling evaluations identify local ovalization at the skirt as the initial instability mode. Bolt stresses remain within allowable limits across all cases. Overall, the findings highlight the skirt region as the structural weak point and underscore the necessity of localized reinforcement strategies. The proposed methodology offers a reliable tool for safety assessment and provides practical guidance for blast-resistant design of industrial towers.

Keywords: Finite element analysis; Vapor cloud explosion; Industrial tower; Dynamic response; Buckling behavior; Blast resistance.

1. Introduction

Towers are widely employed in petrochemical, energy, and related industries as essential process equipment. Owing to their slender geometry and continuous operation under demanding conditions, these structures are particularly susceptible to extreme accidental events. Among such hazards, vapor cloud explosions represent one of the most destructive scenarios, capable of producing high-intensity pressure waves within milliseconds [1], [2]. Once a tower is exposed to these transient loads, severe deformation, instability, or even catastrophic collapse may occur, posing significant threats to personnel safety and industrial assets. Therefore, understanding the dynamic behavior of towers under blast loading is a prerequisite for improving protective design and ensuring safe plant operation.

With advances in computational mechanics, the finite element method (FEM) has become a primary tool for investigating structural response to explosions [3]. Compared with experimental testing, FEM simulations provide time-dependent distributions of stress and deformation at a fraction of the cost and risk [4]. Previous studies have addressed explosion effects on various structural forms, including buildings, tanks, and containment vessels. Bradford and Culbertson emphasized the need for designing petrochemical facilities to withstand accidental blasts [1], while Forbes highlighted protective strategies for industrial equipment [2]. More recently, Rosin et al. examined cylindrical steel tanks subjected to triangular blast loads [4], and Chinese researchers such as Chen Kai and Chen Bin analyzed container responses under oil and gas explosion environments [5], [6]. These contributions have advanced the field; however, most have focused on generalized resistance or on simple structural forms such as plates and tanks, with limited attention paid to the unique geometry and mechanical behavior of tall towers.

Distinct challenges remain in predicting the failure mechanisms of towers under vapor cloud explosions. The short-duration, high-intensity pressure pulses generate localized stress concentrations and complex buckling modes, particularly at connections and skirt regions [7], [8]. Moreover, existing studies often adopt simplified loading or material models, which may overlook critical nonlinearities. Consequently, a comprehensive finite element investigation that incorporates geometric and material nonlinear effects, realistic blast wave characterization, and failure mode evaluation is still lacking.

This work addresses these gaps by establishing a detailed nonlinear finite element model of a vacuum deaeration tower and subjecting it to blast loads consistent with ASCE 41088 [7] and GB/T50779-2022 standards [11]. Two explosion intensities are considered to represent moderate far-field and severe near-field scenarios.

2. Finite Element Simulation

The investigated structure is a vertical vacuum deaeration tower designed according to ASME Section VIII, Division 1 [10]. A three-dimensional model was developed using ANSYS SpaceClaim. To improve computational efficiency while retaining structural fidelity, secondary details such as small chamfers, weld beads,

and minor penetrations were omitted [3]. The overall configuration consists of the cylindrical shell, hemispherical heads, skirt, and foundation ring. The finite element mesh was generated with a hybrid strategy. The cylindrical shell, hemispherical heads, and skirt were modeled with Shell281 elements, while bolts were represented with Solid186 elements [3]. Boundary conditions were prescribed by fully constraining the skirt base, and contact interfaces were defined to simulate realistic load transfer.

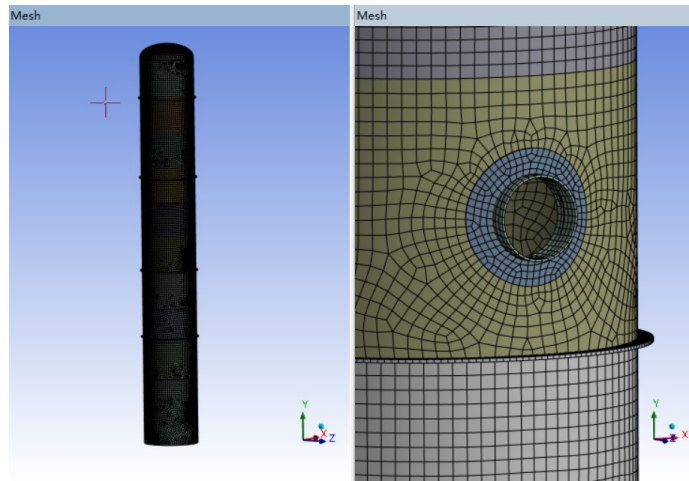


Figure 1. Finite element mesh of the vacuum deaeration tower: (a) global model, (b) refined mesh at skirt region.

The finite element mesh of the tower model was carefully generated to balance accuracy and computational efficiency. Global mesh density was adopted for the cylindrical shell and heads, while local refinement was applied near bolt holes and skirt transitions to capture stress concentrations. Figure 2 illustrates the overall mesh distribution and a close-up view around the skirt connection, confirming that the model can represent both global deformation and localized effects.

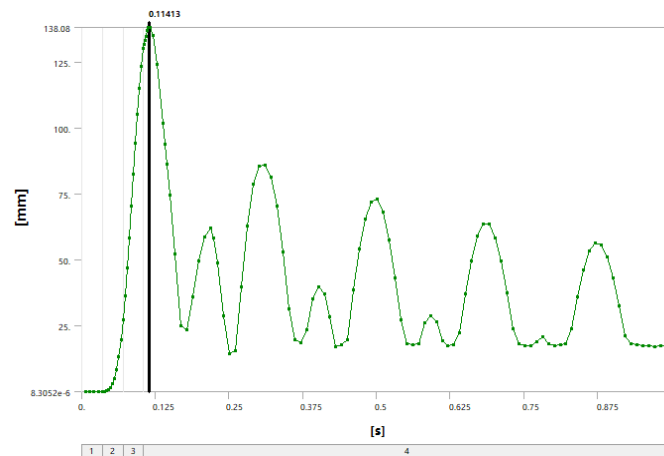


Figure 2. Time history of top displacement under explosion loading, showing peak response and subsequent oscillatory behavior.

To evaluate the transient dynamic behavior, the tower was subjected to triangular blast pulses defined by ASCE 41088 and GB/T50779-2022. Figure 3 presents the time history of the top displacement under explosion loading. The results indicate that the maximum displacement occurs shortly after load application, followed by oscillations due to structural vibration and energy dissipation. These patterns provide important insights into dynamic response characteristics and potential failure modes.

Explosion loading was modeled according to ASCE 41088 [7] and GB/T50779-2022 [11]. The pressure-time history was approximated by triangular pulses, and reflection coefficients were calculated using the method of Newmark [13]. Structural performance was assessed using ductility ratio and support rotation angle as evaluation metrics [7].

3. Results and Discussion

Transient simulations confirmed that deformation concentrated at the tower head while stresses localized at the skirt [12], [14]. Under moderate blast loading (14.6 kPa), results showed displacements and stresses remained within safe limits [15]. Under severe blast loading (30 kPa), stresses in the skirt region approached yield and buckling analysis revealed local ovalization as the critical failure mode, consistent with observations in cylindrical tank studies [4], [18].

The inclusion of damping demonstrated significant mitigation effects under severe blast loads, in line with previous findings on energy dissipation [9]. Bolted connections remained within allowable stress limits, confirming that global shell instability, rather than fastener failure, governs the vulnerability [16], [17].

4. Conclusions and Future Work

This study applied nonlinear finite element simulations to investigate the dynamic performance of a vacuum deaeration tower exposed to vapor cloud explosion loads. Key findings include,

1) The skirt-to-shell transition zone is the most vulnerable region, showing consistent stress concentration [4], [18].

Under moderate blasts (14.6 kPa), displacements and stresses remain below critical thresholds, consistent with ASCE 41088 [7].

Severe blasts (30 kPa) cause near-yield stress and marginal stability, in line with prior studies [5], [6].

Energy dissipation mechanisms proved effective under severe conditions [9].

Bolted connections remained safe, indicating that global shell response dominates failure risks [16], [17].

Future research should include strain-rate sensitive constitutive laws such as Cowper–Symonds or Johnson–Cook [8], [17], and account for thermal softening, progressive damage, and multi-physics effects for improved predictive accuracy.

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ЧИСЛЕННЫЙ АНАЛИЗ НАПРЯЖЕНИЙ И ФОРМ РАЗРУШЕНИЯ В ВЕРТИКАЛЬНЫХ БАШЕННЫХ КОНСТРУКЦИЯХ, ВЫЗВАННЫХ ВЗРЫВОМ

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Промышленные башни, используемые на нефтехимических и энергетических объектах, чрезвычайно уязвимы перед случайными взрывами паровоздушных облаков, однако их кратковременные динамические отклики до сих пор изучены недостаточно. В данном исследовании разработана детализированная конечно-элементная модель для анализа деформации, эволюции напряжений и устойчивости вертикальной вакуумной деаэрационной башни, подвергнутой воздействию ударных волн взрыва. Трёхмерная нелинейная модель была построена в ANSYS с использованием оболочечных и твердотельных элементов для учёта как глобального, так и локального поведения конструкции. Нагрузка от взрыва моделировалась в виде треугольных импульсов избыточного давления в соответствии со стандартами ASCE 41088 и GB/T50779-2022, при этом рассматривались два сценария: умеренный (дальнее воздействие, 14,6 кПа) и сильный (близкое воздействие, 30 кПа). Результаты моделирования показали, что основная деформация происходит за счёт смещения верхней части башни, в то время как максимальные напряжения стабильно концентрируются у основания юбки. С увеличением интенсивности взрыва наблюдается резкий рост как смещений, так и напряжений по Мизесу, при этом в случае сильного сценария достигаются значения, близкие к пределу текучести. Параметрический анализ показал, что численное демпфирование эффективно снижает пиковые реакции, а оценка устойчивости выявила локальную овальность юбки как начальный режим потери устойчивости. Напряжения в болтовых соединениях оставались в допустимых пределах во всех сценариях. Предложенная методика представляет собой надёжный инструмент для оценки безопасности и даёт практические рекомендации по проектированию промышленных башен, устойчивых к взрывным нагрузкам.

Ключевые слова: конечно-элементный анализ, взрыв паровоздушного облака, промышленная башня, динамический отклик, потеря устойчивости, взрывоустойчивость.

ТІК МҰНАРАЛЫҚ ҚҰРЫЛЫМДАРДА ЖАРЫЛЫСТАН ТУЫНДАЙТЫН КЕРНЕУЛЕР МЕН БҰЗЫЛУ ТҮРЛЕРІНІҢ САНДЫҚ ТАЛДАУЫ

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Мұнай-химия және энергетика салаларында қолданылатын өнеркәсіптік мұнаралар бу-ауа қоспаларының кездейсоқ жарылыстарына өте осал, алайда олардың қысқа мерзімді құрылымдық реакциялары әлі де жеткілікті зерттелмеген. Бұл зерттеуде жарылыс толқындарының әсеріне ұшыраған тік вакуумды деаэрациялық мұнараның деформациясын, кернеудің таралуын және тұрақтылығын зерттеу үшін егжей-тегжейлі соңғы элементтік (finite element) модель әзірленді. Үш өлшемді бейсызық модель ANSYS бағдарламасында қабықшалы және көлемдік элементтерді пайдалану арқылы жасалды, бұл ғаламдық және жергілікті мінез-құлықты қамтуға мүмкіндік берді. Жарылыс жүктемесі ASCE 41088 және GB/T50779-2022 стандарттарына сәйкес үшбұрышты артық қысым импульстері түрінде сипатталды. Екі сценарий қарастырылды: орташа (алыс өріс, 14,6 кПа) және күшті (жақын өріс, 30 кПа). Модельдеу нәтижелері негізгі деформация мұнараның жоғарғы бөлігінің ығысуымен анықталатынын, ал ең жоғары кернеулер әрдайым юбка негізінде шоғырланатынын көрсетті. Жарылыс қарқындылығы артқан сайын ығысу мен Мизес бойынша кернеулердің айтарлықтай өсуі байқалды, ал күшті сценарий кезінде материалдың ағу шегіне жақын мәндер тіркелді. Параметрлік талдау сандық демпфирлеудің пиковая реакцияны тиімді азайтатынын көрсетті, ал орнықтылықты бағалау юбка аймағындағы жергілікті сопақтануды бастапқы тұрақсыздық режимі ретінде анықтады. Болттардағы кернеулер барлық жағдайларда рұқсат етілген шектерде қалды. Ұсынылған әдістеме қауіпсіздікті бағалау үшін сенімді құрал болып табылады және жарылысқа төзімді өнеркәсіптік мұнараларды жобалау бойынша практикалық нұсқаулық ұсынады.

Кілт сөздер: соңғы элементтік талдау, бу-ауа жарылысы, өнеркәсіптік мұнара, динамикалық әсер, орнықтылықтың бұзылуы, жарылысқа төзімділік.