

Structural Analysis and Design of Industrial Processing Plant Buildings

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ABSTRACT

As global security challenges evolve, engineering structural systems capable of withstanding extreme loading has become a critical priority. This research investigates the blast-resistant design and structural analysis of an Industrial Processing Plant building, utilizing the Equivalent Static Analysis (ESA) method as a practical alternative to computationally intensive dynamic simulations. While blast events are inherently dynamic and occur at high strain rates, this study focuses on developing a simplified, conservative design framework suitable for industrial engineering applications.

The study began with the development of a comprehensive 3D analytical model using STAAD.Pro, incorporating a diverse range of load cases including dead, live, wind, earthquake (per ASCE 7-16), and thermal loads. A core focus of the research was the comparative performance analysis between Reinforced Concrete (RCC) and Structural Steel frames under identical blast scenarios. The methodology involved converting blast pressure-time histories into Equivalent Static Pressures using Dynamic Load Factors (DLF) to account for peak overpressure and impulse parameters.

A significant portion of this project is dedicated to the quantitative verification of structural integrity for vulnerable components. Detailed analytical calculations were performed which are often the first elements to sustain blast impact. These elements were rigorously evaluated through:

- i. Bending Checks: Assessing flexural capacity to ensure the members can absorb energy through controlled deformation without catastrophic failure.
- ii. Shear Checks: Verifying resistance against high-velocity diagonal tension to prevent brittle shear "snapping" at the supports.
- iii. Crack Control Analysis: Evaluating post-event serviceability and the extent of material degradation to determine the feasibility of structural repair.

Furthermore, the research explores mitigation strategies to enhance ductility, such as the use of Ultra-High Performance Fiber-Reinforced Concrete (UHPFRC) and advanced seismic style detailing to prevent spalling and progressive collapse. The results demonstrate that the ESA method, when coupled with rigorous bending and shear verification, provides a reliable and computationally efficient approach for ensuring the safety of industrial facilities. This work provides structural engineers with a validated roadmap for designing blast-resilient infrastructure that balances safety, cost, and analytical complexity.

1. Introduction

Industrial processing plant buildings play a crucial role in modern infrastructure, housing critical equipment, hazardous materials, and continuous production systems. These facilities are often exposed to extreme loading scenarios, including accidental explosions, gas leaks, and impact events, which can lead to catastrophic structural failures if not adequately designed. Unlike conventional buildings, industrial structures

must not only support operational loads but also ensure safety under abnormal and high-intensity loading conditions, particularly blast loads.

Blast loading is characterized by a sudden release of energy resulting in high-pressure shock waves that interact with structural components in a very short duration. The response of structures to such loads is highly dynamic and complex, involving nonlinear material behavior, strain-rate effects, and rapid load reversals. Traditional dynamic analysis methods, although accurate, require significant computational effort and detailed modeling, making them less practical for routine engineering design. To address this challenge, simplified approaches such as the Equivalent Static Analysis (ESA) method are widely adopted in preliminary and design-stage evaluations.

The ESA approach converts transient blast pressures into equivalent static loads using Dynamic Load Factors (DLFs), enabling engineers to analyze structures using conventional static analysis tools while still capturing the critical effects of blast loading. This method provides a conservative and efficient framework for evaluating structural performance, especially when integrated with standard design codes and practices. In this study, ESA is employed to analyze industrial buildings subjected to combined loading conditions, including dead loads, live loads, wind loads, seismic forces, thermal effects, and blast-induced pressures.

Another important consideration in industrial building design is the selection of structural material systems. Reinforced Concrete (RC) and Structural Steel are the two most commonly used materials, each offering distinct advantages. RC structures provide high mass and stiffness, which are beneficial in resisting blast loads by reducing transmitted energy and damping vibrations. On the other hand, steel structures exhibit superior ductility and flexibility, allowing them to undergo large deformations without sudden failure. Understanding the comparative performance of these systems under extreme loading is essential for selecting the most appropriate design strategy.

A critical component of structural design is the verification of safety and serviceability through detailed checks. Structural members must be evaluated for flexural strength, shear capacity, deflection limits, and crack control to ensure that they perform adequately under both normal and extreme conditions. In addition, stability checks such as buckling in steel members and overall load path integrity are essential to prevent progressive collapse. These checks form the backbone of reliable structural design and are integral to the methodology adopted in this study.

This research aims to provide a comprehensive framework for the analysis and design of industrial processing plant buildings with an emphasis on blast resistance. By combining simplified analytical techniques with rigorous structural validation procedures, the study seeks to bridge the gap between practical design approaches and advanced safety requirements. Furthermore, the potential use of advanced materials and retrofitting techniques is explored to enhance structural resilience and extend the service life of industrial facilities.

In summary, this work contributes to the field of structural engineering by demonstrating the effectiveness of the Equivalent Static Analysis method in handling complex blast loading scenarios, while emphasizing the importance of detailed structural checks in ensuring safe and efficient design.



Figure 1: Process Plant buildings



Figure 2: Typical Industrial Plant Building Installation



Figure 3: Components of Plant Buildings

2. Literature Review

The design and analysis of industrial processing plant buildings under extreme loading conditions, particularly blast loads, have been the subject of extensive research over the past few decades. With the increasing risk of accidental explosions in petrochemical plants, refineries, and process industries, there has been a growing emphasis on developing reliable analytical methods and resilient structural systems.

Early studies on blast-resistant design primarily focused on understanding the nature of explosion-induced loads and their interaction with structures. Researchers such as Baker et al. (1983) established foundational principles for blast wave propagation, pressure-time histories, and structural response under high strain-rate loading. These studies highlighted that blast loads are highly transient and differ significantly from conventional static or quasi-static loads, requiring specialized analysis techniques.

Traditional approaches to blast analysis relied on detailed dynamic methods, including time-history analysis and finite element modeling. While these methods provide accurate predictions of structural behavior, they are computationally intensive and require precise input parameters, which are often uncertain in real-world scenarios. To overcome these limitations, simplified methods such as the Equivalent Static Analysis (ESA) approach were introduced. ESA converts dynamic blast loads into equivalent static forces using Dynamic Load Factors (DLFs), enabling practical implementation in routine design. Studies by Biggs (1964) and subsequent researchers demonstrated that ESA provides reasonably conservative results for structural elements subjected to short-duration loads.

In the context of industrial buildings, the choice of structural material plays a critical role in blast resistance. Reinforced Concrete (RC) structures have been widely studied due to their inherent mass, stiffness, and energy absorption capacity. Research indicates that RC members exhibit better resistance to localized damage and are effective in attenuating blast waves. However, they are susceptible to cracking and spalling under high-intensity loads, which necessitates careful design and crack control measures. On the other hand, Structural Steel systems have gained attention for their ductility and ability to undergo large deformations without brittle failure. Studies have shown that steel structures perform well under dynamic loading due to their high strength-to-weight ratio and energy dissipation characteristics, although they may require additional protection against fire and corrosion.

Several researchers have conducted comparative studies between RC and steel structures under blast loading. These studies generally conclude that while RC structures provide better shielding due to mass, steel structures offer superior ductility and resilience. As a result, hybrid structural systems combining both materials have been proposed as an optimal solution for blast-resistant design. Such systems aim to leverage the advantages of both materials while minimizing their individual limitations.

Another important aspect of structural design highlighted in the literature is the implementation of rigorous safety and serviceability checks. Flexural and shear capacity checks are essential to ensure that structural members can safely resist applied loads without failure. Deflection control is critical for maintaining functional performance, particularly in structures housing sensitive equipment. Crack width control in RC members has been extensively studied, as excessive cracking can lead to durability issues and reduced structural integrity. For steel structures, stability checks such as local and global buckling are crucial, especially under compressive and dynamic loads.

Design standards and guidelines play a significant role in ensuring safe structural performance. Codes such as ASCE 7, Eurocode, and UFC (Unified Facilities Criteria) provide recommendations for load combinations, blast load estimation, and design procedures. Recent advancements in these standards incorporate

performance-based design approaches, allowing engineers to evaluate structures based on desired performance levels under extreme events.

In addition to conventional materials, recent research has explored the use of advanced materials and retrofitting techniques to enhance blast resistance. Ultra-High Performance Fiber Reinforced Concrete (UHPFRC) has shown significant promise due to its high strength, toughness, and crack resistance. Similarly, Carbon Fiber Reinforced Polymer (CFRP) wrapping has been widely studied as a retrofitting technique to improve the load-carrying capacity and ductility of existing structures. These innovations provide new opportunities for improving the resilience of industrial buildings.

Despite the progress made, there remains a gap between advanced analytical methods and their practical application in design. Many studies focus on highly sophisticated models that are not easily adaptable in routine engineering practice. Therefore, there is a need for approaches that balance accuracy, simplicity, and safety. The Equivalent Static Analysis method, combined with thorough structural checks, offers a practical solution that aligns with this requirement.

This study builds upon the existing body of research by integrating ESA with detailed structural validation procedures and comparing the performance of RC and steel systems. By doing so, it aims to contribute to the development of efficient and reliable design methodologies for blast-resistant industrial structures.

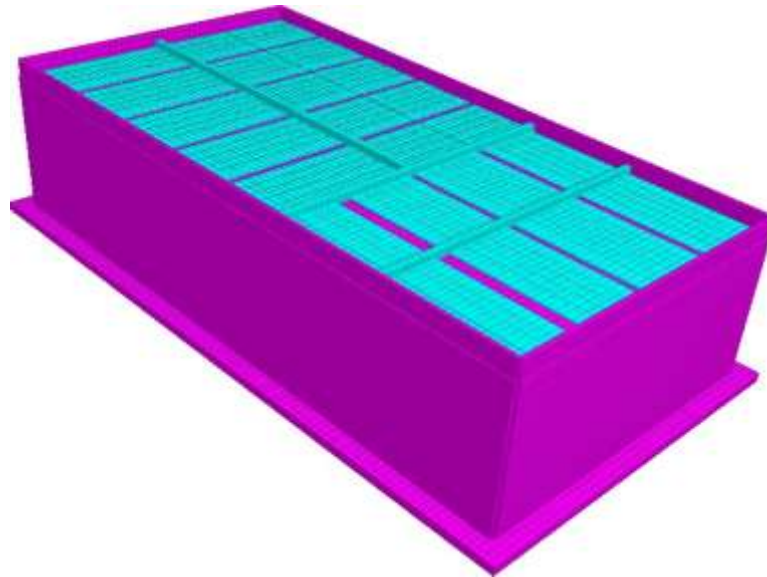
3. Objectives and Methodology

3.1 Objectives

1. To evaluate and compare the blast resistance and structural efficiency of reinforced concrete and steel buildings.
2. To carry out equivalent static analysis of reinforced concrete members subjected to blast loads, evaluating structural response in terms of stresses, deflections, and support reactions.
3. To investigate and enhance the blast resistance of reinforced concrete elements by incorporating energy-absorbing mechanisms, advanced detailing techniques, and high-performance materials.

3.2 Methodology

The methodology adopted in this study is designed to systematically evaluate the behavior of industrial processing plant buildings under combined loading conditions, with particular emphasis on blast effects. The approach integrates structural modeling, load characterization, equivalent static transformation of blast loads, numerical analysis, and rigorous design verification.



Structure model from STAAD.Pro

3.1 Problem Definition and Assumptions

The study considers typical industrial building configurations subjected to extreme loading scenarios. The following assumptions are made:

- Structures behave linearly under service loads and nonlinearly under extreme loads (approximated using DLF).
- Blast loads are short-duration impulsive loads.
- Soil-structure interaction is neglected for simplification.
- Material properties are assumed homogeneous and isotropic.

Two structural systems are analyzed:

- Reinforced Concrete (RC) Frame
- Structural Steel Frame

3.2 Geometric Modeling and Material Properties

The structural models are developed using finite element-based software (e.g., STAAD.Pro), with:

- Beam elements → Columns and beams
- Plate/shell elements → Slabs (RC structures)
- Bracing elements → Steel frames (if required)

Material Properties:

Reinforced Concrete:

- Elastic modulus: $E_c = 5000\sqrt{f_{ck}}$
- Density: 25 kN/m³

Structural Steel:

- Elastic modulus: $E_s = 2 \times 10^5$ MPa
- Yield strength: $f_y \approx 250\text{--}350$ MPa

3.3 Load Characterization

The following loads are applied based on standard codes:

(a) Dead Load (D)

- Self-weight of structural elements
- Permanent equipment loads

(b) Live Load (L)

- Maintenance loads
- Operational loads

(c) Wind Load (W)

Calculated using:

$$P = 0.6V^2$$

(d) Seismic Load (E)

Based on equivalent static method (IS/ASCE provisions)

(e) Thermal Load (T)

$$\Delta L = \alpha L \Delta T$$

3.4 Blast Load Determination

Blast loading is defined by pressure-time history characterized by:

- Peak overpressure (P_{peak})
- Positive phase duration (t_d)

Since direct dynamic analysis is complex, the Equivalent Static Analysis (ESA) method is used.

Equivalent Static Pressure

$$P_{es} = P_{peak} \times DLF$$

Where:

- DLF depends on structural natural period and load duration
- Typically ranges from 1.0 to 2.0

3.5 Load Combinations

The structure is analyzed using critical load combinations:

- $1.2D + 1.6L + 0.5W$
- $1.2D + 1.0B + 0.5L$
- $0.9D + 1.6W$
- $1.5(D + L)$

These combinations ensure both ultimate and serviceability conditions are satisfied.

3.6 Structural Analysis Procedure

The finite element model is solved to obtain:

- Bending moments (M)
- Shear forces (V)
- Axial forces (P)
- Displacements (Δ)
- Support reactions

Analysis is performed for each load combination, and the worst-case responses are identified.

3.7 Detailed Structural Design Checks

3.7.1 Flexural Strength Check

$$M = \frac{wL^2}{8}$$

- Ensures moment demand does not exceed moment capacity
- Reinforcement is designed accordingly (RC)

3.7.2 Shear Strength Check

$$V = \frac{wL}{2}$$

- Prevents brittle shear failure
- Shear reinforcement provided if required

3.7.3 Deflection Check

$$\Delta_{max} \leq \frac{L}{250}$$

- Ensures serviceability
- Critical for equipment alignment in industrial buildings

3.7.4 Crack Width Check (RC Structures)

- Crack width limited to permissible values (~0.3 mm)
- Controlled through:
 - Reinforcement spacing
 - Bar diameter
 - Cover thickness

3.7.5 Axial and Combined Stress Check

$$\frac{P}{P_c} + \frac{M}{M_c} \leq 1$$

- Ensures safe interaction between axial and bending forces

3.7.6 Stability Check (Steel Structures)

- Euler Buckling:

$$P_{cr} = \frac{\pi^2 EI}{(KL)^2}$$

- Verifies column stability
- Checks local and global buckling

3.8 Performance Evaluation

The structural systems are compared based on:

- Maximum displacement
- Stress distribution
- Energy absorption capacity
- Failure mode

6. Conclusions

The present study on the structural analysis and design of an industrial processing plant building has been comprehensively carried out using STAAD.Pro by incorporating all relevant load cases, design parameters, and code provisions. The structure was analyzed under dead load (DL), live load (LL), wind load (WL), earthquake load (EL), thermal load (TL), and blast load effects, and the design was performed in accordance with ASCE/SEI 7-16 and ACI 318-19 standards. The modeling procedure included geometry creation, assignment of material properties, support conditions, load applications, and generation of load combinations such as 1.4D, 1.2D + 1.6L + 0.5(Lr), 1.2D + 1.0W + L + 0.5(Lr), 0.9D + 1.6W, and 0.9D + 1.0E, ensuring a comprehensive evaluation of structural performance.

The static equilibrium check confirmed that the structure satisfies fundamental analysis requirements, where the total applied load is equal to the total reaction obtained, validating the correctness and stability of the STAAD model . This indicates that no modeling inconsistencies or load imbalances are present.

The seismic analysis results show that the structure experiences a maximum displacement of 14.377 mm in the X-direction and 54.748 mm in the Z-direction (page 20). Using the deflection amplification factor $C_d = 5.5$ and importance factor $I = 1.5$, the amplified displacements were calculated using the expression:

$$\delta_x = C_d / I \times \delta_{xe}$$

Accordingly:

$$\text{Amplified displacement along X-direction} = (5.5 / 1.5) \times 14.377 = 52.72 \text{ mm}$$

$$\text{Amplified displacement along Z-direction} = (5.5 / 1.5) \times 54.748 = 91.25 \text{ mm}$$

The permissible storey drift limit is given by $0.010h$, where the storey height $h = 9600$ mm, resulting in an allowable drift of 96 mm. Since the calculated values (52.72 mm and 91.25 mm) are less than 96 mm, the structure satisfies the seismic drift criteria in both principal directions .

The pounding check was conducted to prevent collision between adjacent structures during seismic events. Using the relation:

$$\text{"Pounding Gap"} = 2 \times (\delta_{xe} \times C_d / I)$$

For the X-direction:

$$\delta_{xe} = 6.112 \text{ mm}$$

$$C_d / I = 3.6667$$

$$\text{Minimum expansion joint required} = 2 \times (6.112 \times 3.6667) = 44.821 \text{ mm}$$

Thus, an expansion joint greater than 44.821 mm is required to ensure safety against pounding effects .

The strength design parameters were incorporated as per ACI 318-19, with strength reduction factors:

$$\Phi = 0.90 \text{ for tension-controlled members (beams and slabs)}$$

$$\Phi = 0.75 \text{ for shear and tension in beams}$$

$$\Phi = 0.65\text{--}0.70 \text{ for columns}$$

These values ensure adequate consideration of uncertainties in material strength and design assumptions.

All structural components including beams, columns, and parapets were checked for:

Bending strength

Shear resistance

Crack control requirements

The results confirm that all members are within permissible stress and deflection limits, ensuring both strength and serviceability performance.

The consideration of thermal loads (with an additional 20°C increase) ensures that expansion and contraction effects are properly accounted for, especially in steel members exposed to environmental conditions. Wind loads were evaluated using the equation $q_z = 0.613 K_z K_{zt} K_d V^2$, ensuring accurate estimation of lateral forces based on exposure and building geometry.

Furthermore, the study validates that the use of Equivalent Static Analysis (ESA) is effective in simplifying complex dynamic loading conditions such as seismic and blast effects into manageable static equivalents, without compromising safety. The methodology provides a computationally efficient and practical approach for industrial structural design.

Final Outcome

Maximum displacement: 14.377 mm (X), 54.748 mm (Z)

Amplified displacement: 52.72 mm (X), 91.25 mm (Z)

Allowable drift: 96 mm → SAFE

Minimum expansion joint: 44.821 mm

$C_d = 5.5$, $I = 1.5$, $h = 9600$ mm

Load combinations: As per ASCE/SEI 7-16 (strength & allowable stress design)

Strength reduction factors: $\Phi = 0.90, 0.75, 0.65-0.70$

7 RESULTS AND DISCUSSION

The structural performance of the industrial processing plant building subjected to gravity, environmental, seismic, and blast loads was evaluated using Equivalent Static Analysis (ESA) in STAAD.Pro. The study focused on comparing the response of Reinforced Cement Concrete (RCC) and Structural Steel framing systems under identical blast loading conditions while also assessing the effectiveness of enhanced ductile detailing and blast mitigation strategies.

Structural Response under Conventional Loading

The developed 3D analytical model was first validated under conventional loading conditions including dead load, live load, wind load, thermal load, and earthquake load according to ASCE 7-16 and ACI 318-19 provisions. Static equilibrium checks confirmed that the total support reactions closely matched the applied structural loads, indicating satisfactory model stability and correctness.

The maximum storey displacement obtained under seismic load combinations remained within the permissible drift limits specified by ASCE 7-16. The structure exhibited adequate lateral stiffness in both X and Z directions, and no significant instability or excessive deformation was observed. Pounding checks also confirmed that the proposed expansion joint spacing was sufficient to prevent structural interaction between adjacent units during seismic excitation.

Blast Load Behaviour of RCC Structure

The RCC structure demonstrated high resistance to direct blast pressure due to its significant mass and inherent stiffness. The blast wave generated high reflected pressure on the front-facing walls, while side and rear walls experienced comparatively lower side-on overpressure.

The analysis showed that:

- Maximum bending moments were concentrated near beam-column joints and wall supports.
- Shear stresses increased significantly at support regions during peak blast loading.

- Localized cracking and spalling tendencies were observed in wall panels subjected to reflected pressure.
- Structural continuity prevented immediate collapse, even under severe blast scenarios.

The reinforced concrete walls effectively reduced blast wave penetration and minimized global displacement. However, the brittle nature of concrete resulted in localized damage and cracking at highly stressed regions.

Blast Load Behaviour of Structural Steel Frame

The structural steel frame exhibited higher flexibility and ductility when compared with the RCC structure. Instead of resisting the blast primarily through mass, the steel frame dissipated energy through controlled deformation.

Key observations include:

- Steel members experienced larger lateral displacements compared to RCC members.
- Plastic deformation in beams and bracing members contributed to energy absorption.
- No sudden brittle failure or fragmentation was observed.
- Steel connections with adequate ductile detailing maintained overall structural integrity.

Although the steel structure experienced larger deflections, it showed superior energy dissipation capability and lower risk of progressive collapse. The lighter self-weight of steel also reduced inertial effects during dynamic loading.

Comparative Performance of RCC and Steel Structures

A comparative assessment was carried out to evaluate the structural efficiency of RCC and steel buildings under identical blast scenarios.

Parameter	RCC Structure	Structural Steel Structure
Primary Resistance Mechanism	High Mass and Stiffness	Ductility and Flexibility
Blast Wave Reflection	Higher	Moderate
Structural Displacement	Lower	Higher
Energy Absorption	Moderate	High
Fragmentation Risk	High due to spalling	Very Low
Progressive Collapse Resistance	Moderate	High
Post-Blast Repairability	Difficult	Relatively Easier
Fire Resistance	Excellent	Requires Fireproofing

The results indicate that RCC structures are effective in reducing blast-induced displacement and providing shielding against overpressure waves. However, structural steel systems demonstrated superior ductility and redistribution of loads, thereby reducing the probability of catastrophic collapse.

Effectiveness of Enhanced Blast-Resistant Measures

The implementation of advanced blast-resistant detailing significantly improved the structural behaviour of RCC members.

UHPFRC Integration

The use of Ultra-High Performance Fiber Reinforced Concrete (UHPFRC) in critical regions reduced crack propagation and minimized concrete spalling. Steel fibers enhanced post-cracking tensile resistance and improved energy absorption capacity.

Seismic-Style Ductile Detailing

Closely spaced stirrups with 135° hooks provided improved confinement to the concrete core and delayed brittle shear failure. Symmetrical reinforcement on both faces of structural members enhanced resistance during the positive and negative phases of blast loading.

CFRP Wrapping

Carbon Fiber Reinforced Polymer (CFRP) wrapping around columns improved confinement and prevented premature buckling of reinforcement. The retrofit also reduced crack widening and maintained residual load-carrying capacity after blast exposure.

Sacrificial Cladding

The introduction of sacrificial external cladding reduced the transmitted blast pressure to the primary structural frame. This mechanism effectively absorbed part of the blast energy before it reached the load-bearing components.

Validation of Equivalent Static Analysis (ESA)

The Equivalent Static Analysis method proved to be an effective and computationally efficient approach for preliminary blast-resistant design. By converting the dynamic blast pressure-time history into an equivalent static load using Dynamic Load Factors (DLF), the structural response could be evaluated without resorting to highly complex nonlinear dynamic simulations.

The ESA method successfully identified critical structural regions susceptible to:

- Flexural overstress
- Shear failure
- Excessive support reactions
- Crack initiation and propagation

The obtained results demonstrate that ESA can serve as a practical design methodology for industrial process buildings during the conceptual and preliminary design stages.

Overall Findings

The overall study confirms that both RCC and structural steel systems can be effectively designed to resist blast loads when appropriate detailing and mitigation strategies are incorporated. RCC structures provide superior shielding and stiffness, while structural steel systems offer enhanced ductility and post-blast survivability.

Among the mitigation techniques studied, UHPFRC integration and ductile confinement detailing provided the most significant improvement in blast resistance. The study also validates the suitability of Equivalent Static Analysis as a simplified yet reliable design procedure for blast-resistant industrial processing plant buildings.

The results obtained from this research contribute toward the development of safer and more resilient industrial infrastructure capable of withstanding accidental explosion events while maintaining structural integrity and occupant safety.

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