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Development of Blast Resistant Structural System for Critical Infrastructure

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Abstract: In recent years, the safety of structures against blast loading has become a major concern due to increasing threats from accidental explosions and terrorist activities. Blast loads are highly dynamic and impulsive in nature, which can cause severe damage to structural elements and may lead to progressive collapse if not properly considered in design. The present study focuses on the development of a blast-resistant structural system for critical infrastructure by analyzing the behavior of a multi-storey reinforced concrete (RCC) building subjected to blast loads. A G+10 RCC building is modeled and analyzed using ETABS 21 software under different blast scenarios considering TNT explosive charges of 100 kg and 150 kg with stand-off distances of 15 m and 20 m. A total of 36 models are developed by varying shear wall configurations such as bare frame, core shear walls, corner shear walls, and combined systems. The blast loads are calculated using standard methods and applied as joint loads on the structure. The structural performance is evaluated based on parameters such as story displacement, story drift, base shear, stiffness, time period, and modal participation. The results indicate that the inclusion of shear walls significantly improves the structural response under blast loading. Among all models, the structure with combined shear walls at core and corners (Model-9) shows the best performance with maximum reduction in displacement and drift and increased stiffness. The study concludes that proper placement of shear walls plays a crucial role in enhancing blast resistance and ensuring structural safety. The findings of this research can be useful for designing safer and more resilient structures against blast effects.

Keywords: *Blast Load, TNT Explosion, Shear Wall, RCC Structure, ETABS, Story Displacement, Story Drift, Base Shear, Structural Stiffness, Blast Resistant Design.*

I. INTRODUCTION

In the present era of rapid urbanization, industrial growth, and technological advancement, infrastructure development has become one of the most important aspects for the economic and social progress of any country. Critical infrastructure such as hospitals, airports, power plants, military buildings, government offices, bridges, and communication systems plays a vital role in ensuring the smooth functioning of society and the safety of the public. These structures are expected to perform efficiently not only under normal loading conditions but also under extreme and unexpected situations such as earthquakes, cyclones, fires, and explosions. Among these, blast loading is considered one of the most severe and complex types of loading because it occurs suddenly, acts for a very short duration, and produces extremely high pressure and temperature. A blast load is generated due to the rapid release of energy from an explosion, which results in the formation of a shock wave that travels through the surrounding medium, usually air, at very high speed. This shock wave exerts a high-intensity pressure on the structural elements, causing severe damage such as cracking of concrete, yielding of reinforcement, failure of columns and beams, and in extreme cases, complete collapse of the structure.

Unlike conventional loads such as dead load, live load, and even seismic load, blast loads are highly impulsive and unpredictable, making their analysis and design more challenging for engineers.

The intensity of the blast load depends on several factors such as the type and weight of explosive material (for example TNT), the stand-off distance between the explosion source and the structure, the surrounding environment, and the configuration of the building. It has been observed that as the stand-off distance increases, the intensity of the blast pressure decreases significantly, which reduces the damage to the structure; however, in densely populated urban areas, maintaining large stand-off distances is not always possible, thereby increasing the vulnerability of buildings. In India, most of the structures are designed considering only gravity loads and seismic forces as per codal provisions, while blast-resistant design is generally neglected due to lack of awareness, guidelines, and economic considerations.

II. METHODOLOGY

Structural Modeling and Simulation:

Structural modeling and simulation form the backbone of the present study, as they provide a realistic representation of how the building behaves under different loading conditions, especially blast loads. In this research, the modeling of the structure is carried out using ETABS 21 software, which is a powerful and widely used tool for the analysis and design of multi-storey buildings. The objective of structural modeling is to create a virtual model that closely resembles the actual physical structure so that its response under different loads can be accurately predicted.

The structure considered in this study is a G+10 reinforced concrete (RCC) building, which represents a typical urban building. The modeling process begins with the creation of a grid system, which defines the plan layout of the building. The grid spacing is selected based on the overall plan dimension of 36 m × 36 m, ensuring uniformity and symmetry in the structure. This regular grid layout helps in achieving a balanced distribution of loads and reduces torsional effects during dynamic loading.

After defining the grid system, the next step is to assign material properties. In this study, M30 grade concrete and Fe500 steel are used. These materials are defined in ETABS by specifying properties such as modulus of elasticity, density, Poisson's ratio, and yield strength. Accurate material definition is essential because it directly affects the stiffness and strength of the structure.

Following material definition, the section properties of structural elements are assigned. The beams are modeled with dimensions of 400 mm × 450 mm, columns with 700 mm × 700 mm, slabs with a thickness of 150 mm, and shear walls with a thickness of 250 mm. These elements are modeled using appropriate element types in ETABS:

1. Beams and columns are modeled as frame elements
2. Slabs and shear walls are modeled as shell elements

The modeling of slabs as shell elements ensures proper distribution of loads to supporting beams and columns, while shear walls provide additional stiffness and lateral load resistance. The next important step is the assignment of boundary conditions.

The base of the structure is assumed to be fixed, which means that all degrees of freedom (translation and rotation) are restrained at the foundation level. This assumption simplifies the analysis and is commonly used for multi-storey building analysis.

After defining geometry and properties, the structural components are assembled to form a complete three-dimensional model. This 3D model allows for visualization of the entire building and helps in identifying any modeling errors before proceeding with analysis. It also ensures that load paths are correctly defined from slabs to beams, beams to columns, and columns to foundation.

The simulation part of the process involves applying different types of loads and analyzing the structural response. In this study, loads such as dead load, live load, and blast load are applied. Dead load is automatically calculated by ETABS based on the self-weight of the structure, while live load and floor finish loads are assigned manually. The blast load, which is the most critical load in this study, is applied as joint loads at beam-column intersections. The structure is divided into panels, and the blast pressure is distributed accordingly to simulate realistic loading conditions.

Once all loads are applied, the structure is analyzed using dynamic analysis methods, including Response Spectrum Analysis and Time History Analysis. The software computes the response of the structure in terms of displacement, drift, forces, and stresses. The results are then extracted and used for comparison between different structural models.

Another important aspect of structural modeling in this study is the creation of multiple models with different shear wall configurations. By changing the location and arrangement of shear walls, the study evaluates their effectiveness in improving blast resistance. Each model is analyzed under identical loading conditions to ensure a fair comparison.

The accuracy of the simulation depends on several factors, including proper modeling of geometry, correct assignment of material properties, appropriate load application, and selection of suitable analysis methods. Therefore, careful attention is given to each step of the modeling process to ensure reliable results.

The structure is modeled using **ETABS 21 software**.

Steps:
1. Create grid system
2. Define material properties
3. Define section properties
4. Assign loads
5. Run analysis

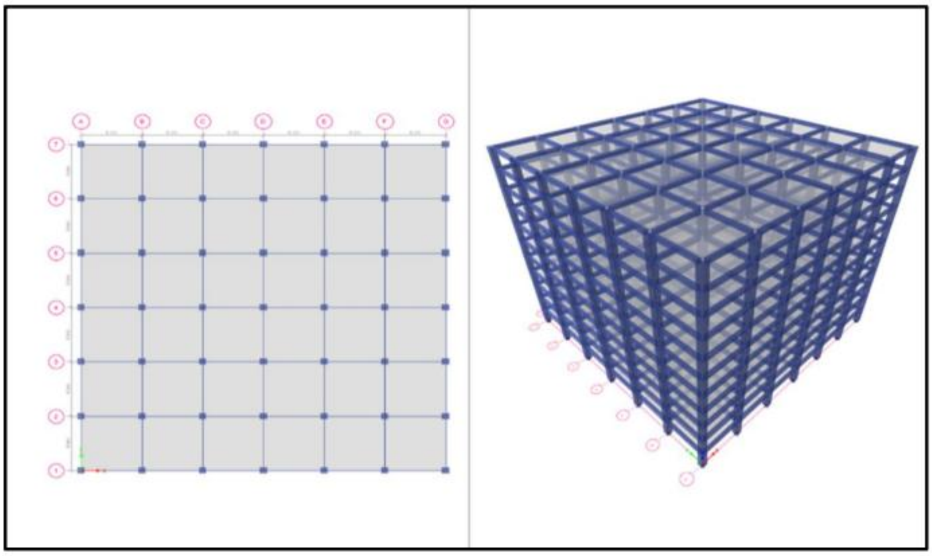


Figure 3.5 Grid and Structural Model

Figure 3.5 shows the grid layout and three-dimensional structural model of the G+10 reinforced concrete building developed in ETABS software. The grid system represents the plan arrangement of the structure, where horizontal and vertical grid lines define the exact positions of beams, columns, and structural elements. In this study, the building is modeled with a regular grid pattern corresponding to a 36 m × 36 m plan with equal spacing, which ensures uniform distribution of loads and structural symmetry.

3.8 Blast Load Application in ETABS

The application of blast load in ETABS is carried out by converting calculated blast pressures into equivalent joint loads acting on the structure. In this study, the blast load is applied on the exposed surfaces of the building, mainly the front face, and is distributed to beam-column joints by dividing the elevation into 3 m × 3 m panels. The magnitude of the load is determined based on TNT equivalent weight and stand-off distance, and it varies for each joint depending on its distance from the blast source. The blast loads are applied in global X and Y directions to simulate realistic impact conditions, including front, side, and rear face effects. The loads are defined as dynamic loads and assigned to appropriate load cases in ETABS. This method ensures proper representation of pressure distribution over the structure. By applying blast loads in this manner, the structural response such as displacement, drift, and internal forces can be accurately evaluated under extreme loading conditions.

Blast loads are applied in different directions:

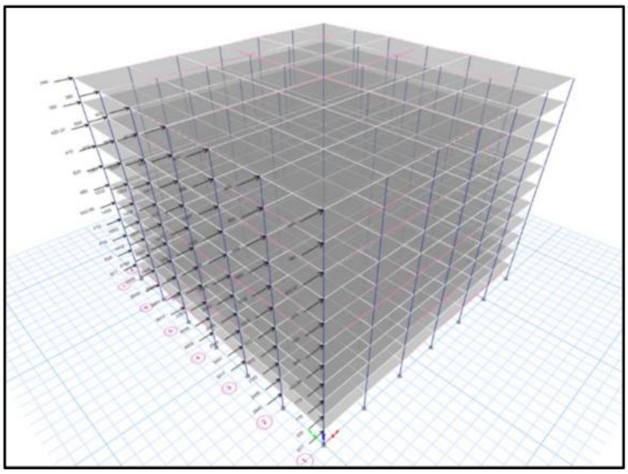


Figure 3.6 Blast Load in X Direction (Front Face)

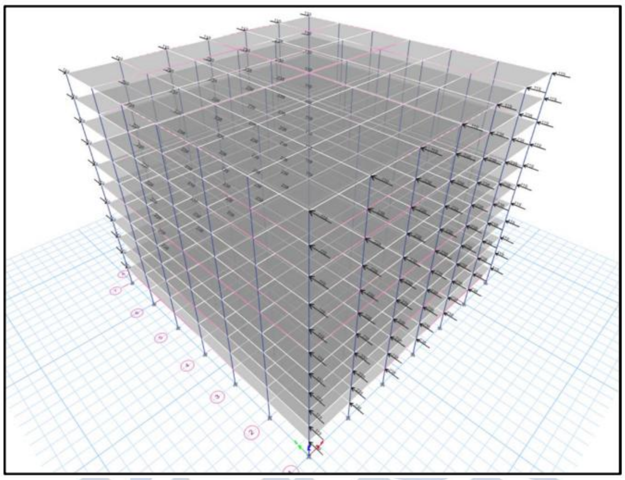


Figure 3.7 Blast Load in Y Direction (Side Face)

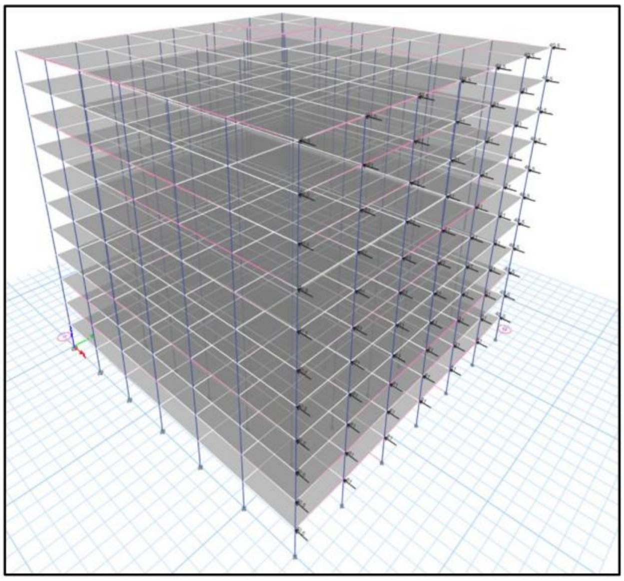


Figure 3.8 Blast Load in Rear Face

3.9 Structural Details

The structural details of the building considered in this study are defined to represent a typical reinforced concrete multi-storey structure. The building is a G+10 RCC frame structure with a plan dimension of 36 m × 36 m and a storey height of 3 m. The structural elements include beams of size 400 mm × 450 mm, columns of 700 mm × 700 mm, and slab thickness of 150 mm. Shear walls of 250 mm thickness are provided in different configurations to study their effectiveness. The materials used are M30 grade concrete and Fe500 steel, ensuring adequate strength and durability.

Table 3.2: Material Properties

Material	Value
Concrete	M30
Steel	Fe500
Density of Concrete	25 kN/m³
Density of Steel	78.5 kN/m³

Table 3.3: Structural Specifications

Parameter	Value
Building Type	RCC
Plan Size	36m × 36m
Storey Height	3 m
Beam Size	400×450 mm
Column Size	700×700 mm
Slab Thickness	150 mm
Shear Wall Thickness	250 mm

3.10 Loading Details

Loading details form the foundation of any structural analysis, as they define the types and magnitudes of forces acting on the structure during its service life. In the present study, the loading on the G+10 reinforced concrete building is carefully defined to simulate realistic conditions, including both conventional loads and extreme blast loading. The loads considered in this analysis include dead load, live load, floor finish load, wall load, and blast load, which together represent the actual forces acting on the structure.

The dead load consists of the self-weight of all structural components such as beams, columns, slabs, and shear walls, and is automatically calculated by the software based on material properties. The live load, taken as 7 kN/m², represents the imposed loads due to occupancy and usage of the building, as per standard codal provisions. Additional loads such as floor finish load (1.5 kN/m²) and wall loads (external and internal walls) are also included to ensure realistic modeling of the structure.

The most significant load in this study is the blast load, which is applied as a dynamic load on the structure. The blast load is calculated based on TNT equivalent weight and stand-off distance and is applied as joint loads in both X and Y directions. This approach ensures proper distribution of blast forces over the structure.

Wind load is not considered in this study, as the focus is primarily on blast and seismic effects. The combination of all these loads helps in evaluating the structural performance under both normal and extreme conditions, ensuring a comprehensive analysis of the building behavior.

Table 3.4 Loading

Load Type	Value

Dead Load	Self-weight
Live Load	7 kN/m²
Floor Finish	1.5 kN/m²
External Wall	14 kN/m
Internal Wall	7 kN/m

Strength Combinations:

1. DL+1.5LL
2. 1.2 DL+1.2 LL+1.2RSX
3. 1.2 DL+1.2LL+ 1.2RSY
4. 1.2 DL+1.2 LL-1.2RSX
5. 1.2 DL+1.2LL- 1.2RSY
6. 1.2 DL+1.2LL+1.2 BLAST
7. DL+1.5RSX
8. DL+1.5RSY

Serviceability:

1. 1 DL+1 LL
2. 1 DL+1 BL
3. 1 DL+0.8 LL+0.8BL
4. 0.9 DL+1.5RSX
5. 0.9 DL+1.5RSY
6. 0.9 DL-1.5RSX
7. 0.9 DL-1.5RSY

3.12 Structural Models

In the present study, multiple structural models are developed to evaluate and compare the performance of reinforced concrete buildings under blast loading. The main objective of creating different models is to study the effect of shear wall location, orientation, and configuration on the overall structural response. A total of 36 models are considered, which include variations in blast load cases as well as different shear wall arrangements.

1. Total Models = **36 models**
2. Includes:
    - Bare frame
    - Core shear wall
    - Corner shear wall
    - Combined system

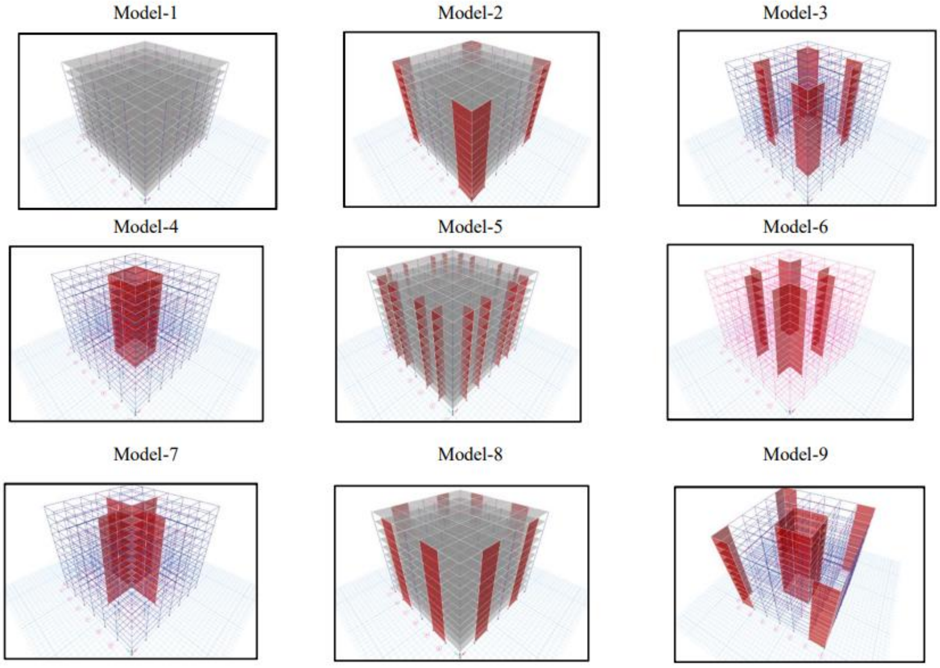


Figure 3.9: Structural Models

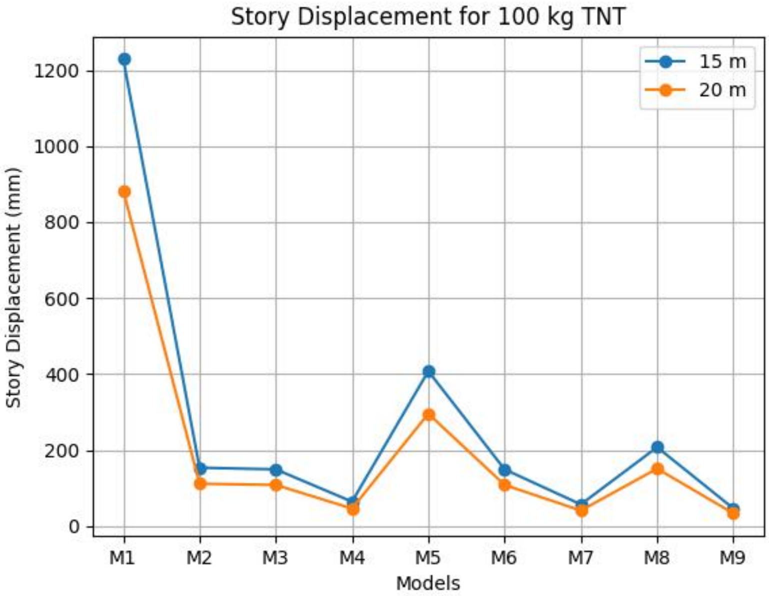
III. RESULTS

4.2 Story Displacement

Story displacement is defined as the maximum lateral movement of each storey under the action of applied loads. It is one of the most important parameters to evaluate structural performance under blast loading.

Table 4.1 Story Displacement for 100 kg TNT

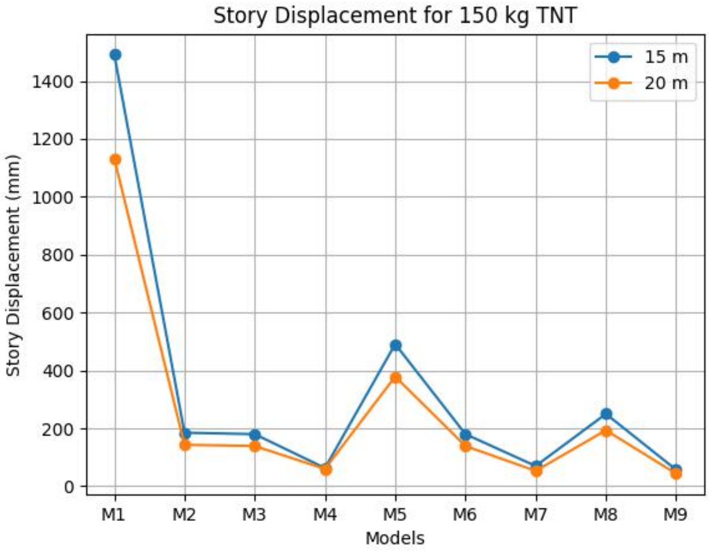
Model	15 m (mm)	20 m (mm)
Model-1	1228.90	883.24
Model-2	154.14	111.98
Model-3	149.75	108.76
Model-4	64.78	46.71
Model-5	408.00	296.11
Model-6	149.77	108.76
Model-7	57.53	41.42
Model-8	207.98	151.61
Model-9	46.93	33.95



Graph 4.1 Story Displacement for 100 kg TNT

Table 4.2 Story Displacement for 150 kg TNT

Model	15 m (mm)	20 m (mm)
Model-1	1491	1132.71
Model-2	185	143.13
Model-3	180	139.02
Model-4	63	59.82
Model-5	491	378.66
Model-6	180	139.03
Model-7	70	53.06
Model-8	250	193.32
Model-9	57	43.44



Graph 4.2 Story Displacement for 150 kg TNT

Discussion:

From the above results, the following observations are made:

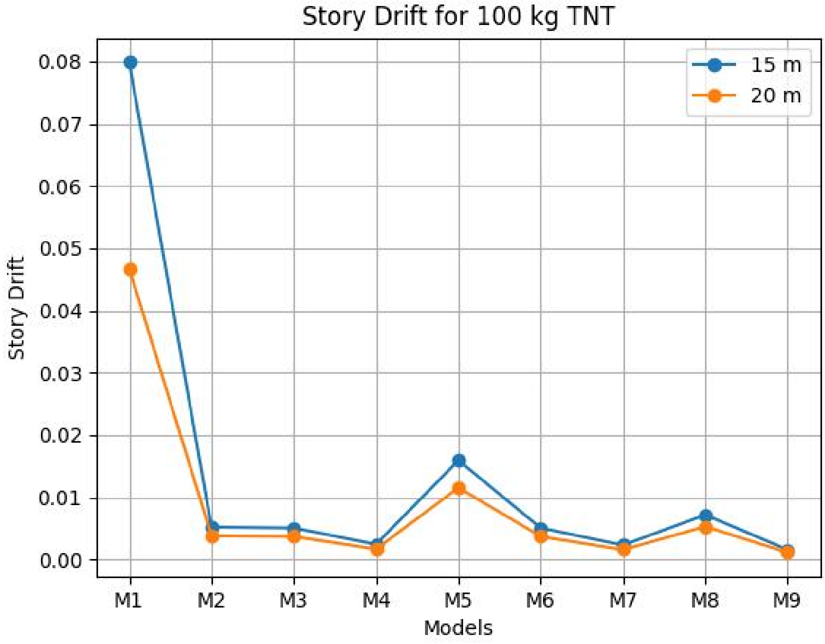
1. Maximum displacement is observed at the top storey, which is expected due to accumulation of lateral effects.
2. Increase in stand-off distance from 15 m to 20 m reduces displacement by about 21–24%.
3. Increase in TNT weight from 100 kg to 150 kg increases displacement by about 17–22%.
4. Model-1 (bare frame) shows extremely high displacement, indicating poor performance.
5. Model-9 shows minimum displacement, proving it is the most efficient configuration.
6. Models with core shear walls (Model-4, 7, 9) perform significantly better.

4.3 Story Drift

Story drift is the relative displacement between two consecutive storeys. It is important for checking structural safety and serviceability.

Table 4.3 Story Drift for 100 kg TNT

Model	15 m	20 m
Model-1	0.079893	0.046732
Model-2	0.005229	0.003839
Model-3	0.00508	0.003729
Model-4	0.002474	0.001702
Model-5	0.015942	0.01155
Model-6	0.00508	0.003729
Model-7	0.00234	0.001607
Model-8	0.007201	0.00531
Model-9	0.001602	0.001158

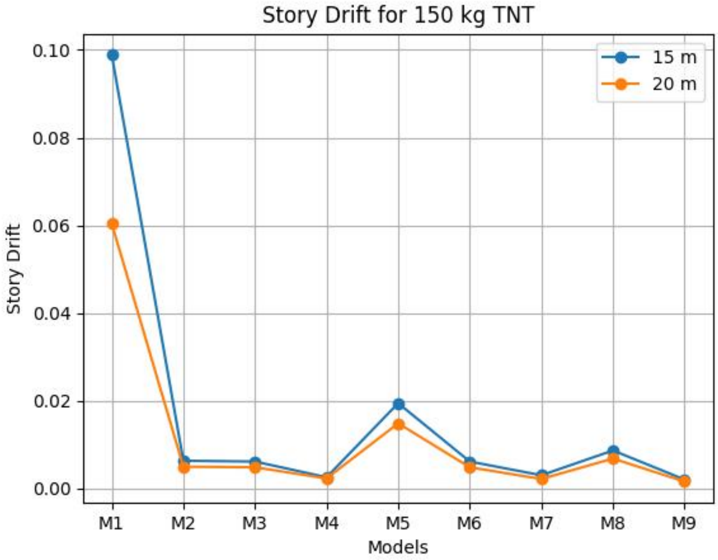


Graph 4.3 Story Drift for 100 kg TNT

Table 4.4 Story Drift for 150 kg TNT

Model	15 m	20 m
Model-1	0.098869	0.060371

Model-2	0.006242	0.004895
Model-3	0.006063	0.004756
Model-4	0.002476	0.002208
Model-5	0.01938	0.014784
Model-6	0.006064	0.004756
Model-7	0.002931	0.002085
Model-8	0.008588	0.006747
Model-9	0.001942	0.001485



Graph 4.4 Story Drift for 150 kg TNT

Discussion:
1. Story drift reduces significantly with the introduction of shear walls.
2. Model-9 shows maximum reduction (~98%) compared to bare frame.
3. Increase in stand-off distance reduces drift.
4. Higher TNT weight increases drift values.
5. Core shear walls provide the best drift control.

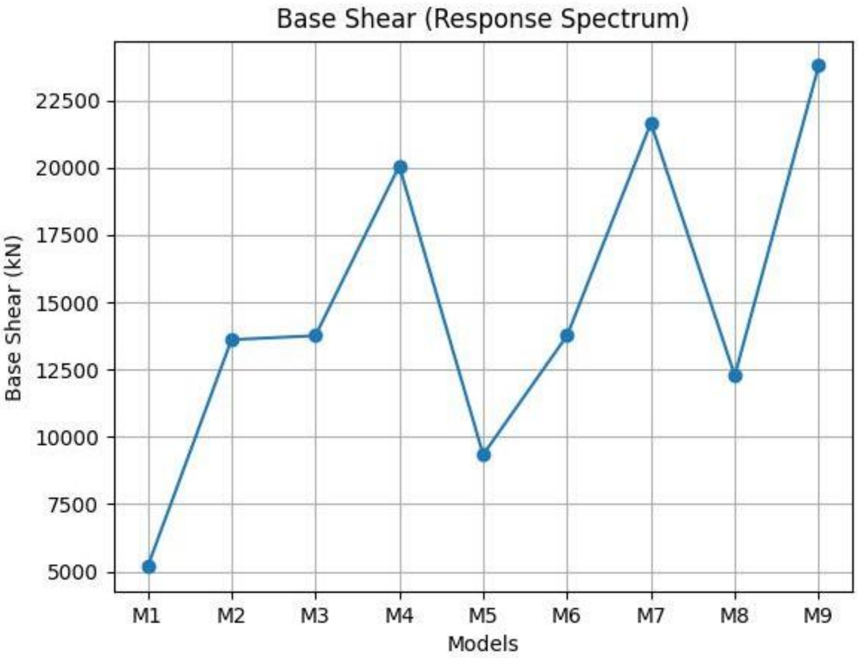
4.4 Base Shear

Base shear represents total lateral force acting at the base.

Table 4.5 Base Shear (Response Spectrum)

Model	**Base Shear (kN)**
Model-1	5173.69
Model-2	13609.97
Model-3	13757.94
Model-4	20066.08
Model-5	9338.25
Model-6	13757.6

Model-7	21657.27
Model-8	12276.6
Model-9	23791.55



Graph 4.5 Base Shear (Response Spectrum)

Discussion:

1. Base shear increases with stiffness.
2. Model-9 shows maximum base shear (78.25% increase).
3. Increase in stand-off distance reduces base shear by 32–34%.
4. Increase in TNT weight increases base shear by 20–22%.

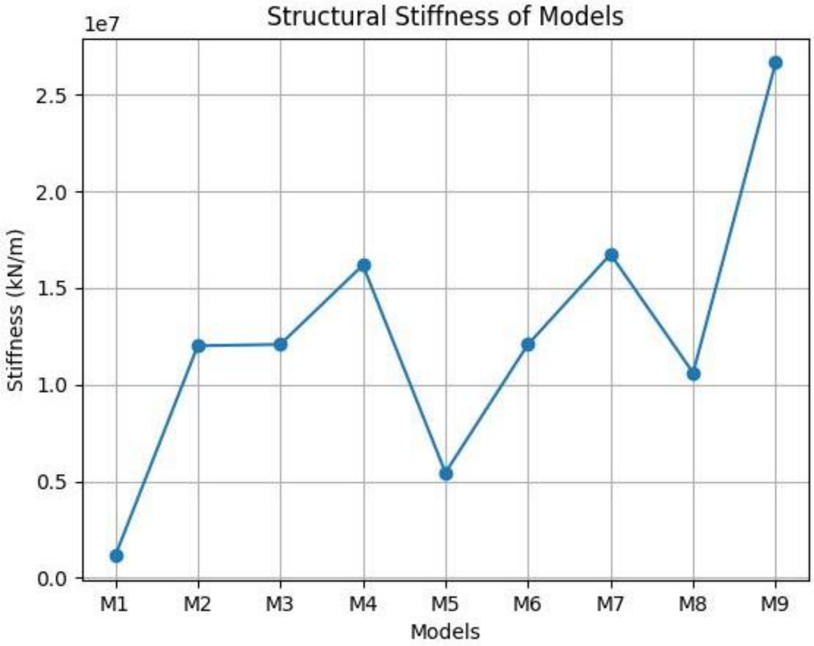
4.5 Structural Stiffness

Structural stiffness is the ability to resist deformation.

Table 4.6 Stiffness

Model	**Stiffness (kN/m)**
Model-1	1131785
Model-2	12010967
Model-3	12082411
Model-4	16184761
Model-5	5439825
Model-6	12082282
Model-7	16754108
Model-8	10612505

Model-9	26675047



Graph 4.6 Stiffness

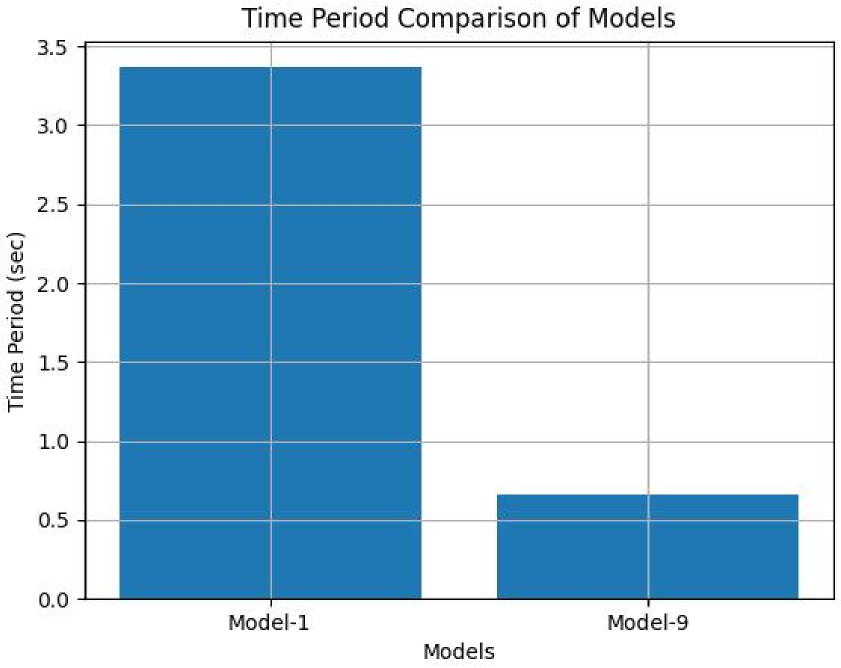
Discussion:

1. Model-9 shows highest stiffness (95.76% increase).
2. Core shear walls provide best stiffness.
3. Periphery walls are less effective.

4.6 Time Period

Table 4.7 Time Period

Model	Time Period (sec)
Model-1	3.366
Model-9	0.666



Graph 4.7 Time Period

Discussion:

1. Time period decreases with increase in stiffness.
2. Model-9 has lowest time period (best performance).
3. Lower time period indicates higher stability.

CONCLUSION

Based on the detailed analysis and results obtained from the study on blast-resistant structural systems, the following conclusions are drawn:

i. Bare frame structure (Model-1) is highly vulnerable to blast loading and shows excessive displacement and drift, indicating poor performance.
ii. Introduction of shear walls significantly improves structural performance by increasing stiffness and reducing displacement and drift.
iii. Model-9 (shear walls at core + corners) is found to be the most effective structural configuration for blast resistance.
iv. Maximum story displacement is observed at the top storey in all models.
v. Increasing the stand-off distance from 15 m to 20 m reduces displacement by about 20–26%, indicating that blast intensity decreases with distance.

vi. Increasing TNT charge from 100 kg to 150 kg increases displacement by about 17–22%, showing direct relation between explosive weight and structural response.
vii. There is a significant reduction in story drift (up to 98%) in shear wall models compared to the bare frame.
viii. Base shear increases with stiffness, and Model-9 shows approximately 78% higher base shear compared to Model-1, indicating better resistance.
ix. Increase in stand-off distance reduces base shear by 32–34%, while increase in TNT weight increases base shear by 20–22%.
x. Structural stiffness increases significantly (about 95.76% increase) from bare frame to optimized shear wall model.
xi. Time period reduces with increase in stiffness; Model-9 shows lowest time period (about 80% reduction), indicating better structural stability.
xii. Models with core shear walls (Model-4, 7, 9) perform better in controlling displacement and drift.
xiii. Periphery shear wall models are less effective compared to core and combined configurations.
xiv. Modal analysis shows that mass participation is greater than 65% in the first three modes for all models.

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