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Blast Mitigation of Reinforced Concrete Structures Incorporating Shear Walls in Modern Building Designs

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Abstract: Material science advancements have resulted in the development of high-strength concrete and steel reinforcement, allowing more efficient and stable buildings against natural and manmade disasters. Increasing security concerns and the potential threat from terrorist activities have led to the safety and resilience of structures against blast loads in modern construction. The present study investigates the performance of reinforced concrete shear walls in mitigating blast-induced vibrations. The study examines four different reinforced concrete buildings based on their shapes, namely square, rectangular, C-shaped, and L-shaped, to understand the blast behaviours with and without shear walls. The study presents a methodology to protect the regular and irregular buildings equipped with shear walls against blast loads at varying standoff distances of 100 m, 200 m, 300 m, and 400 m, respectively. The study also compares the efficiency of passive control dampers and shear walls in enhancing the buildings' performance against blast vibrations. The best placement of the shear walls is also evaluated for all the selected buildings. The study also considers the effect of shear wall thickness in mitigating blast-induced vibrations in multi-storey buildings. The study also discusses the design guidelines and reinforcement detailing of shear walls to protect buildings against detrimental blast effects.

Keywords: shear walls; blast-induced vibrations; optimum placement technique; building irregularity and energy dissipation; resilience; UN SDGs

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1. Introduction

The history of shear walls dates back to the early 1960s when plywood shear walls replaced the diagonally braced wall sections. In the past, the shear walls were designed with a uniform thickness and strengthened with steel bars to resist shear and flexural pressures. To increase the performance of shear walls, the notion of boundary elements was established. Boundary elements are vertical extensions of the shear walls that are placed at the ends to disperse stresses and prevent early shear failures. This breakthrough improved the load-carrying capability and ductility of shear walls. Computational tool advancements and finite element analysis have greatly enhanced our understanding of shear wall behaviours. Shear walls have become an essential component in the design and construction of modern buildings due to the increasing demand for sustainable and resilient structures. It has been observed in the past that during high-wind events or earthquakes, shear walls provided stability and reduced excessive lateral deflections. Shear walls improve the resilience of buildings by allowing them to withstand extreme weather events such as hurricanes and typhoons [1]. The present study focussed on the implementation of finite element analysis techniques to investigate various scenarios of placement of shear walls and obtain the best results from the evaluation of shear wall systems against dynamic loadings. In the past, Frischmann and Prabhu [2] illustrated different configurations of shear walls against wind actions in the construction of suspension buildings. The study also discussed the role of shear walls in mitigating the lateral forces with the help of existing building examples in Manchester, Montreal, Milan, London, Chicago, and New York. The study was extended further to discuss the difficulties of considering the non-uniform wind effects in buildings with shear walls [3]. The study also detailed methods to estimate the shear forces and bending moments incurred in the shear walls with a brief review of the construction techniques adopted in its construction. Moroni [4] reviewed the performance of shear walls in past earthquakes and highlighted seismic strengthening technologies along with the wall reinforcement detailing as per the seismic requirements prescribed by various international standards. Cao [5] developed an effective iterative procedure for precast concrete structures to match the target responses generated from seismic ground motion histories. Cao et al. [6] also enhanced the seismic performance of an existing three-dimensional building model subjected to thirty different earthquake records by implementing a self-centring reinforced concrete buckling-resistant brace frame. Recently, Xu et al. [7] proved the seismic effectiveness of steel-reinforced concrete brace frames in reducing the axial forces of existing beams and columns. Thus, in the field of seismic-resistant structures, many vibration control techniques have been developed and reviewed, and the applicability of these techniques in the field of blast-resistant structures needs to be carefully investigated. The material advancement in the shear wall construction is highlighted in Table 1 as per the investigations conducted by various researchers. The present study also enumerated a review of the performances of shear walls installed in buildings in the vicinities of wind, earthquake, and blast-induced vibrations, as discussed in Table 2. Different types of shear walls (SW) and the configurations being constructed and designed by present structural engineers are illustrated in Figure 1a,b. The present study is restricted to solid shear walls, considering different configurations of shear walls.

Table 1. Material advancement in shear wall construction.

Sr. No.	Researcher	Material Advancement in Shear Walls	Load Applied	Behaviours of Shear Walls
1	Hung and Hsieh [8]	High-strength steel (HSS) and high-strength concrete (HSC) with steel fibres	Cyclic loading	With steel fibres of 0.75%, the drift demand was increased from 1% to 1.5%. The energy dissipation capacity of the squat shear wall increased due to the onset of inelasticity in the horizontal reinforcement.
2	Huang et al. [9]	Carbon Fiber Reinforced Polymer (CFRP) grids	Lateral cyclic loading	The lateral drift ratios of the specimens with CFRP grids were superior to the RC shear walls by 78.6%. Shear walls having horizontal CFRP bars exhibited shear failure with flexural response, and the remaining underwent typical diagonal shear crack failure.
3	Wu et al. [10]	Precast material (Average cubic strength of 43.9 MPa)	Cyclic lateral load and Axial load	Additional shear cracking, concrete spalling, and cracks appeared in precast shear walls in the precast component's core and where the precast and cast-in-place zones met. The residual displacements of both cast-in-place and precast shear walls have grown as a result of an additional increase in axial load.
4	Poul and Sruthy [11]	Coconut Fibre Reinforced Concrete (CFRC) and Flax Fibre Reinforced Concrete (FFRC)	Cyclic Load	Energy absorption capacity increased by 31% and 24% for CFRC and FFRC, respectively, compared to normal shear walls. No significant changes in frequency and base shear of structure when fibres are incorporated.
5	Peng et al. [12]	Recycled coarse aggregate concrete	Cyclic Load and axial load	According to experimental findings, increasing the axial load level improves peak loads but decreases drift capabilities.

Table 1. *Cont.*

Sr. No.	Researcher	Material Advancement in Shear Walls	Load Applied	Behaviours of Shear Walls
6	Shenton et al. [13]	Wood frame (spruce-pine-fir)	Cyclic Load	Stiffness and energy dissipation of oriented-strand boards decreased at a faster rate as compared to plywood shear walls.
7	Mo et al. [14]	Concrete-filled composite shear wall (CFCSW)	Cyclic Load	Compared to conventional RC walls, this wall has a satisfactory energy dissipation capacity, strong shear resistance, and deformation capacity. Higher reinforcement ratios contribute to higher axial stiffness and strengths but lower composite action, while higher axial load ratios reduce deformation capacity and ductility.
8	Chen et al. [15]	Cold-formed steel with plastered straw-bale sheathing	Cyclic Load	Sheathing distortion and cumulative connection deformation made up the wall's deformation, with the latter accounting for most of the damage. The sheathing materials improved the wall's shear strength.
9	Erkmen [16]	Post-tensioned precast concrete	Cyclic Load	When the steel tendons are positioned at wall ends or evenly distributed across the wall cross-section, the yielding drift decreases by around 50%.
10	Zhao and Astaneh-Asl [17]	Composite Shear Walls	Cyclic Load	The samples worked well and were able to reach an inter-storey drift of 0.05 before their shear strength fell below 80% of the highest shear force, they could withstand during testing.
11	Wu et al. [18]	Diagonally stiffened stainless-steel plate	Cyclic Load	The ability of stainless steel to dissipate energy is good. The specimens' cyclic strengthening is important.

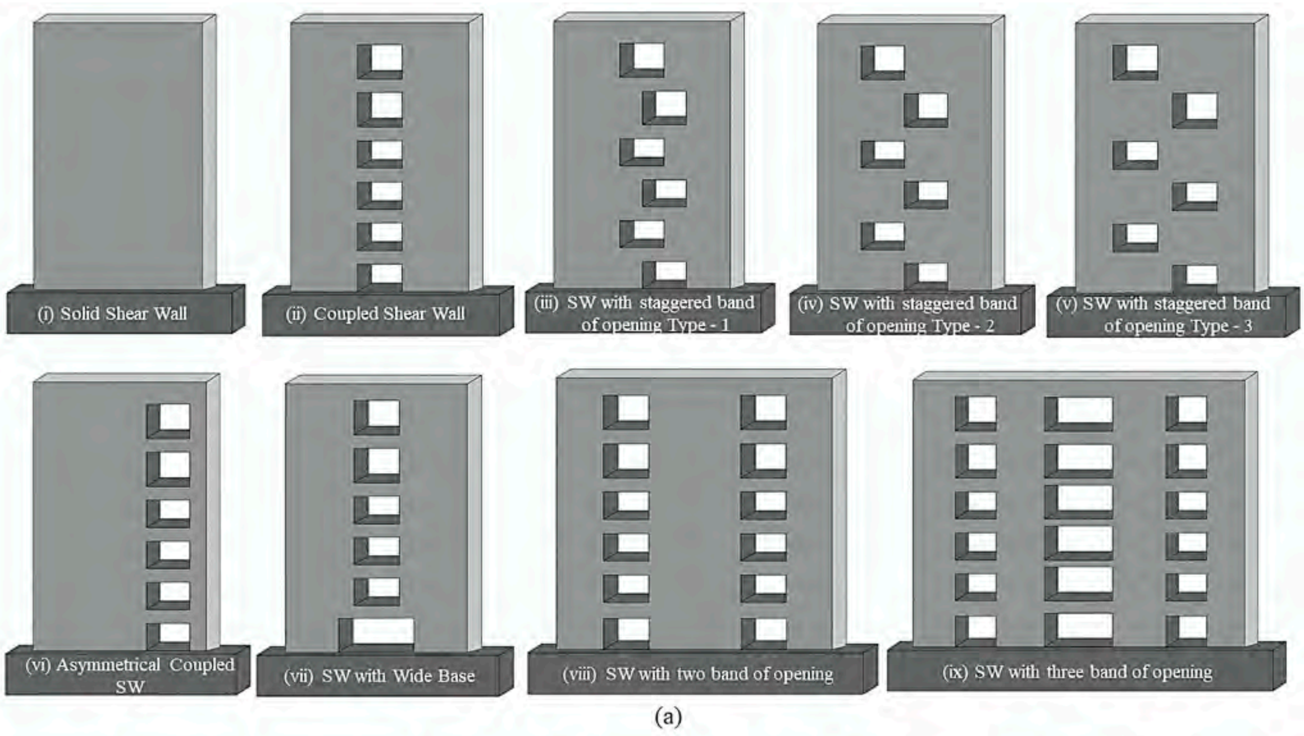


Figure 1. *Cont.*

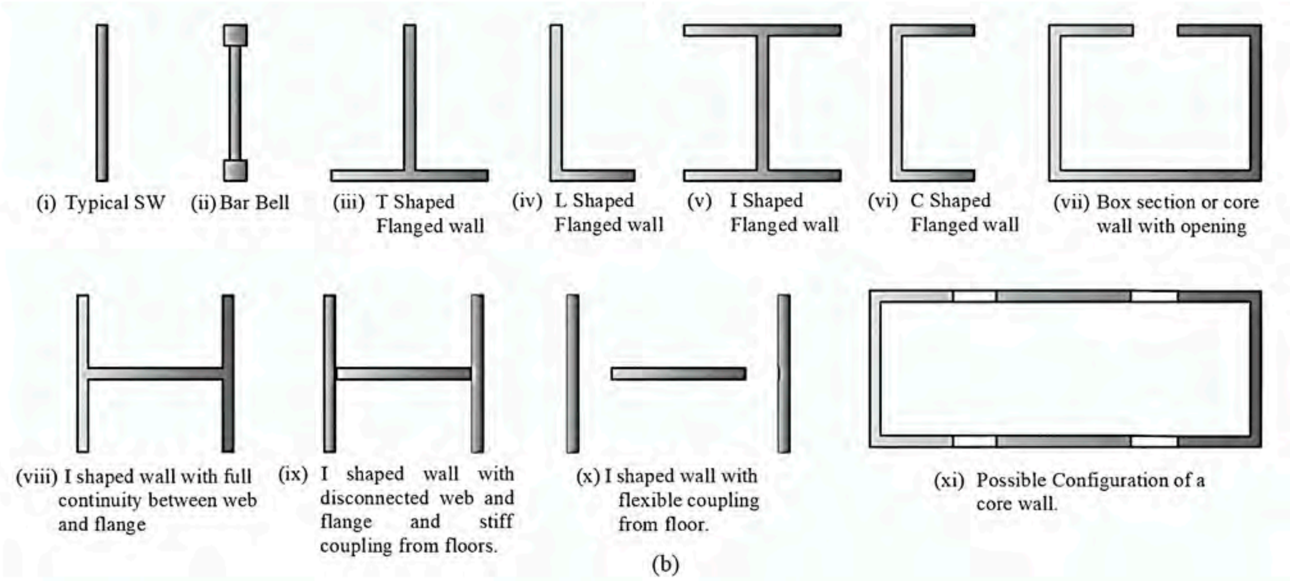


Figure 1. (**a**) Different types and (**b**) configurations of shear walls (SW) [19].

Table 2. Performance of shear walls subjected to various dynamic loadings.

Researcher	Wind Load	Seismic Load	Blast Load	Parameters Considered	Effect on Shear Walls
Ettouney et al. [20]	–	Zone 1 (As per ASCE 7-05)	Surface ground blast	Trinitrotoluene (TNT) weight and standoff distance	Shear walls combined with moment-resisting frames provided more ductility to undergo large deformation by protecting the structure.
Wang et al. [21]	NA	EI Centro ground motion	NA	Height of shear wall	Inclusion of shear walls reduced the top displacement of the structure.
Wen et al. [22]	NA	Zones as per Chinese code GB 50011-2001	NA	Different seismic zones, soil types, and epicentre distances	When exposed to distant field earthquakes, tall flexible constructions with longer natural periods are more vivid.
Saatcioglu et al. [23]	NA	NA	Surface ground blast	Different charge weights and standoff distances.	High degrees of lateral rigidity offered by the shear walls shield brittle structural and non-structural elements from blast stresses.
Kim et al. [24]	Wind-acceleration	NA	NA	Different grades of concrete and modelling of floor Slabs.	Shear walls provided a better serviceability level than normal buildings.
Faghihmaleki et al. [25]	NA	Magnitude of 6.5 to 7.5 (European Seismic Guidelines)	Surface ground blast	Different charge weights.	Progressive collapse can be delayed with shear wall provision.
Baral and Yajdani [26]	NA	Zone V as per IS 1893: 2002	NA	Position of shear wall.	Drift reduction with proper positioning of shear walls.
Kaveh and Zakian [27]	NA	American Concrete Institute Seismic Criteria	NA	Width and thickness of shear wall are varied.	Shear walls are designed according to optimized design procedures to reduce cost and achieve better performance.

Table 2. *Cont.*

Researcher	Wind Load	Seismic Load	Blast Load	Parameters Considered	Effect on Shear Walls
Xue et al. [28]	NA	Nonlinear time history analysis	Underground blast	Different seismic zones and TNT weights.	Damage state of shear walls went from level 1 under seismic load to level 3 under blast load. Shear walls require proper design required for to resist blast load.
Pendem and Chandana [29]	NA	NA	Surface blast	Different TNT weights and standoff distances.	Both regular and irregular buildings in plans with shear walls performed better under blast load with shear walls.
Kadhum and Razzaq [30]	NA	American Concrete Institute Seismic Criteria	Surface blast	Different TNT weights.	Storey drifts of shear walls increased under blast load as compared to seismic load.
Chehab et al. [31]	NA	NA	Surface blast	Building with different numbers of bays and blast positions inside and outside of structure.	Dispersed shear walls performed well to reduce progressive collapse.
Çavdar et al. [32]	NA	Bingöl earthquake (nonlinear analysis)	NA	Case study of reinforced concrete shear wall building in Turkey.	The pushover analysis technique underestimates the performance of the building as compared to nonlinear dynamic analysis.
Esmaeilnia et al. [33]	NA	NA	Surface blast	Height of the building is varied with and without shear walls.	Shear walls mitigate the blast effects as compared to reinforced concrete buildings without shear walls.

The present study also reviewed the failure patterns of shear walls subjected to various dynamic loadings, namely wind, seismic, and blast loading, as illustrated in Figure 2. The major reinforced concrete shear wall failure patterns are classified as shear failure [34], flexure failure [35,36], sliding failure [37], and out-of-plane failure [38] subjected to seismic loading. The blast load majorly caused localized failures [39–41], namely, the crushing of concrete, yielding of reinforcement, and spalling of concrete, along with the above-mentioned failures. In the case of wind loading, the shear walls failed primarily due to excessive overturning, tension and compression, and excessive deflections [42,43]. Studies also show extensive research investigating the stress distribution [44], deformation, and failure [45,46] mechanisms of shear walls under different loading conditions, with no research evaluating the macro performances of regular and irregular buildings equipped with shear walls subjected to blast-induced vibrations. The present research investigated the structural blast behaviours of regular (square and rectangular buildings) and irregular buildings (L and C-shaped buildings) classified as per provisions drafted in Table 5 of IS 1893:2016 [47]. The analysis was carried out using ETABS software version 20, which facilitates the modelling of these building shapes. The main objective is to analyse and design the selected buildings with G + 10 elevation in the seismic safe zone along with dead and live loads, and subsequently subject them to underground accidental blasts having a charge weight of 50 tons at four distinct standoff distances, namely 100 m, 200 m, 300 m, and 400 m. The prime focus of this investigation is to assess the vulnerability of the building members when subjected to such blast events with a brief flow chart of the methodology adopted in the present study enumerated in Figure 3.

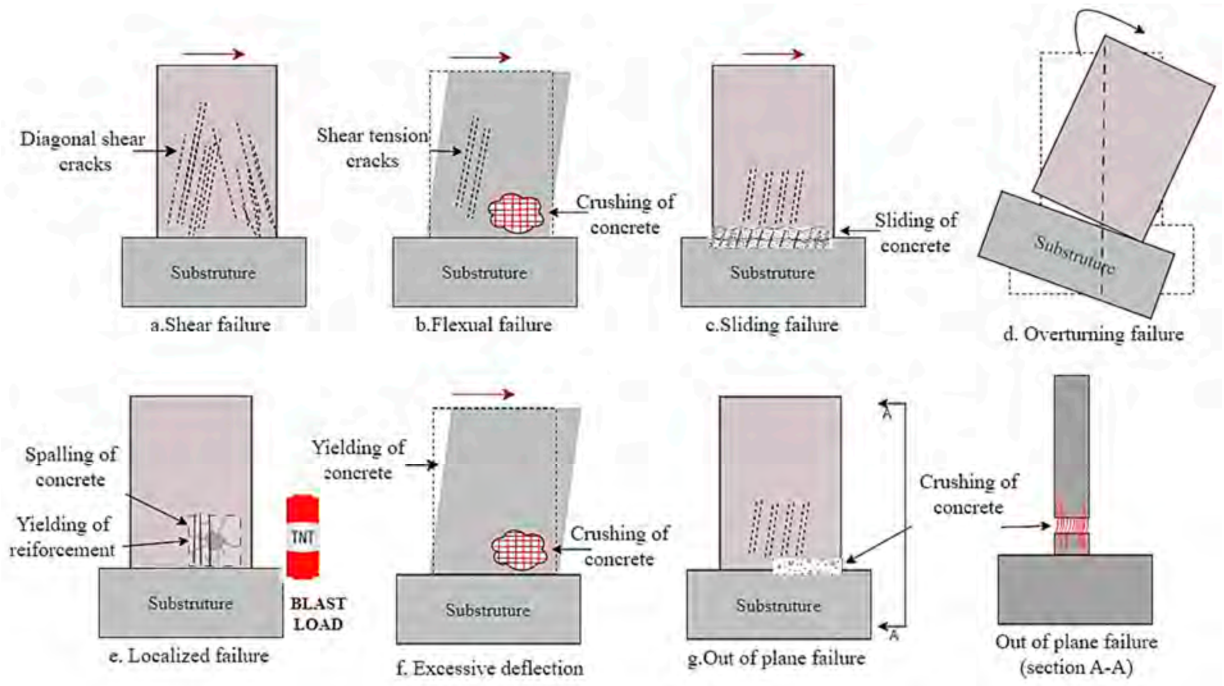


Figure 2. Typical types of shear failures in shear walls subjected to dynamic loadings.

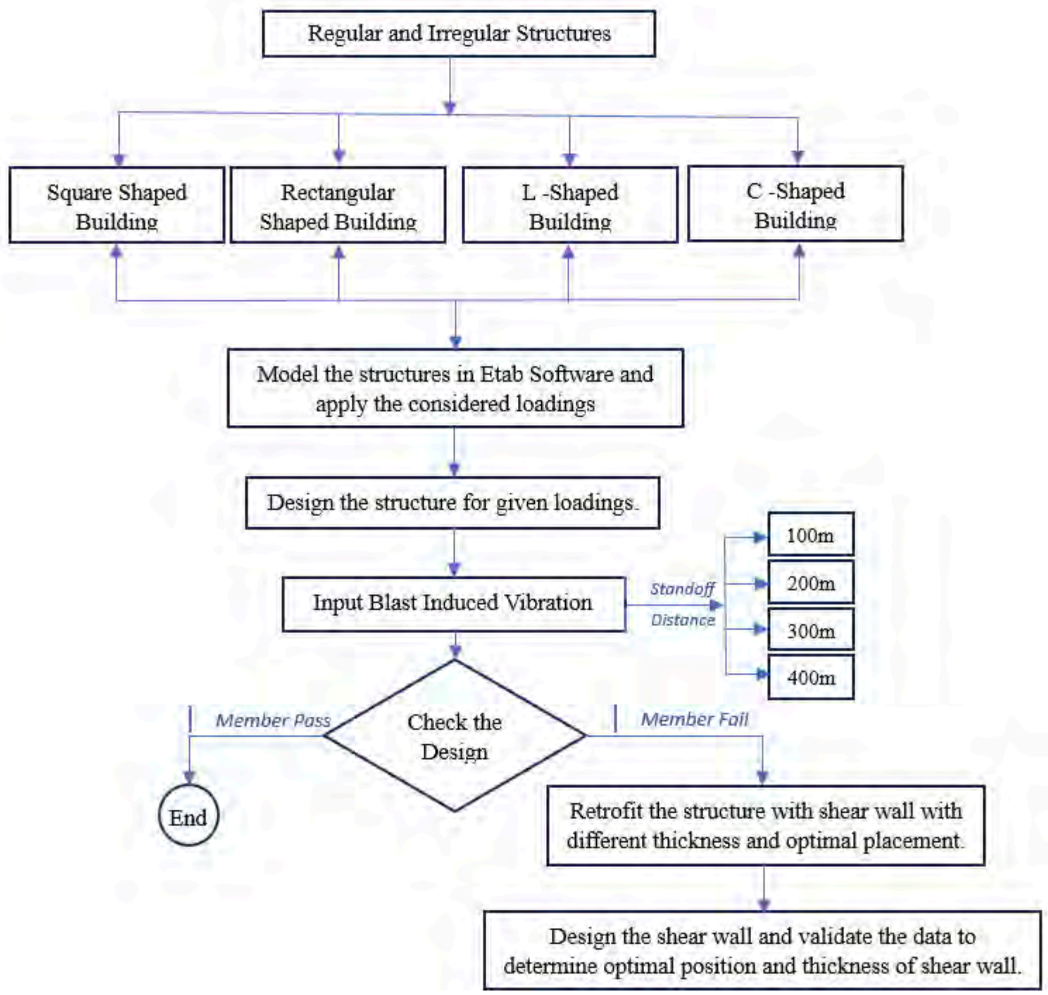


Figure 3. Schematic representation of the retrofitting methodology adopted for blast protection.

The analysis aimed to determine structural members prone to failure under the given dynamic loading conditions. In the event of member failure, a retrofitting technique involving the integration of shear walls with different wall thicknesses, such as 200 mm, 300 mm, 400 mm, and 500 mm, is investigated to strengthen the structural performances of the selected buildings. The study also reviewed the best possible shear wall placement locations after a detailed investigation of various placement strategies adopted to mitigate the performance of buildings with shear walls. The subsequent sections present a comprehensive comparison of the obtained results, leading to a thorough assessment of the efficiency of different retrofitting approaches implemented in the past to mitigate blast vibrations. The study validated the design guidelines presented in IS 13920:2016 [48] to design the shear walls subjected to various blast loadings. The design steps adopted and reinforcement detailing of shear walls required to protect the regular and irregular buildings from collapse are also presented.

2. Methodology

The current study compares the performances of four reinforced concrete structures, each with G + 10 stories, to evaluate the structural performances under blast loads. The goal is to evaluate the responses of structures with and without shear walls subjected to accidental underground blast forces. The regular plan buildings in this study have square and rectangular geometries, and the irregular plan structures have C-shaped and L-shaped layouts. The investigated structures are buildings with G + 10 stories, having a plinth height of 1.5 m and floor-to-floor height of 3 m. All the buildings in the study share the same concrete material properties, including a Poisson's ratio of 0.2 and an elastic modulus of 25 GPa.

The structural elements possess specific dimensions, such as a slab thickness of 125 mm, an external wall thickness of 230 mm, and an internal wall thickness of 150 mm. In accordance with the guidelines provided by IS 875 Part 1 [49] and Part 2 [50], the structures are subjected to both dead loads and live loads. The applied loads include a live load of 2 kN/m^2, a live load on the terrace of 0.75 kN/m^2, a floor finish load of 1.5 kN/m^2, and wall loads of 13.156 kN/m for main walls, 8.58 kN/m for partition walls, and 3.3 kN/m for parapet walls. Initially, careful consideration is given to both regular and irregular building structures for detailed analysis. These structures are accurately modelled using ETABS version 20. Subsequently, the structures are designed and checked to withstand the above-mentioned loads. In the next phase, the structures undergo blast load testing at various standoff distances, namely 100 m, 200 m, 300 m, and 400 m. Blasting is a common practice in mines and tunnels to fragment large rocks. This creates ground motion and has an influence on neighbouring structures. The resulting ground vibrations cannot be ignored since they cause considerable structural damage and create earthquake-like effects. The blast-generated acceleration ($\ddot{x}_g$) is a function of the peak particle velocity (v) in m/s and the time of arrival (t_a) in seconds (s), which is computed as a ratio of the radial distance (R) in metres (m) the wave propagation velocity of soil (c) in m/s. The blast time history is depicted in Figure 4 and evaluated by Equation (1), which was developed using the blast load parameters and explored by Kangda and Bakre [51] in the past.

$$\ddot{x}_g(t) = -\frac{1}{t_a} v e^{\frac{-t}{t_a}} \tag{1}$$

The peak particle velocity of rock particles is determined by the empirical equation suggested by Kumar et al. [52] as given by Equation (2). The formulation is a function of the average mass density (γ_d) of rock particles having a value equal to 26.5 kN/m^3, the uniaxial compressive strength (f_c = 70 MPa) of rock particles, and scaled distance (SD) in $m/kg^{1/2}$ and determined as the ratio of the distance from charge point, R (m), to the square root of the charge mass Q (kg). The granite rock particle characteristics investigated in this work are derived from [53]. The standoff distance of 100 m is represented by R1, 200 m by R2, 300 m by R3, and 400 m by R4.

$$v = \frac{f_c{}^{0.642}\ SD^{-1.463}}{\gamma_d} \tag{2}$$

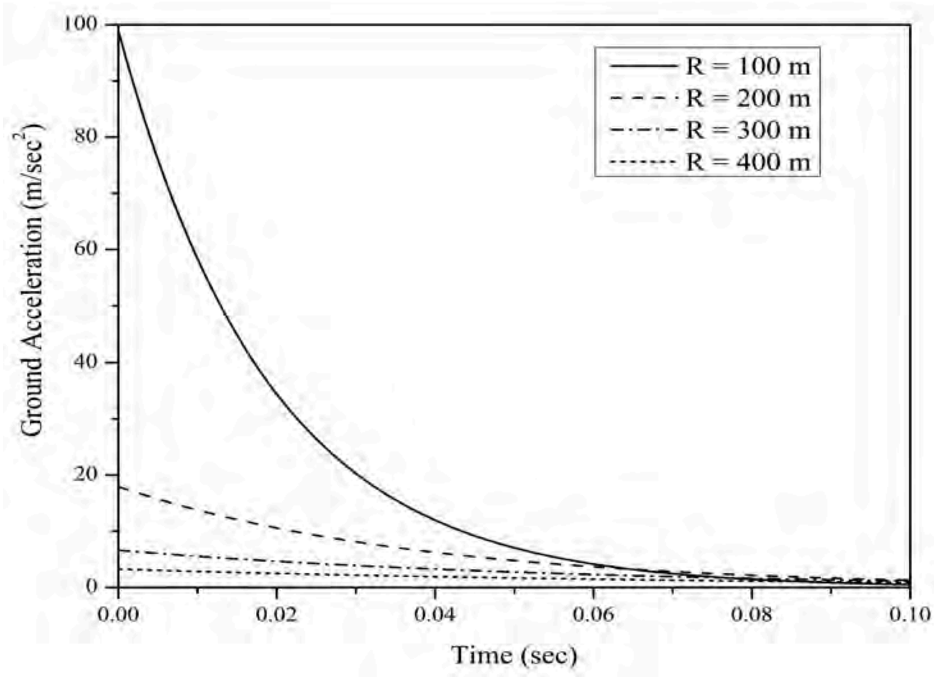


Figure 4. Blast-induced ground acceleration.

Ten different shear wall placement positions were examined in the present study. The structures were evaluated for critical parameters such as displacement, shear force, and bending moment to compare the efficiency of shear walls in mitigating the blast-induced vibrations of reinforced concrete buildings. The efficiency of shear walls in mitigating the blast loads was also compared with the passive control techniques adopted by various researchers in the past to protect the failure of regular and irregular buildings against blast loading. The simulation of the critical blast loads was carried out by an advanced numerical method called finite element analysis (FEA). The material properties of the reinforced concrete structures, such as their strength and stiffness, were incorporated into the FEA model to accurately predict the response of the buildings to blast forces. Additionally, the blast loading is modelled as an acceleration-time function developed from the empirical data reviewed in the above section. Strategic placement of shear walls at the critical locations enhanced the structural responses significantly. The addition of shear walls increased the stiffness and strength of the buildings, reducing their vulnerability to blast-induced vibrations and potential collapse. The placement cases of shear walls in square, rectangular, L, and C-shaped buildings are classified as S0 to S9, R0 to R9, L0 to L9, and C0 to C9, respectively. The structural properties of beams and columns designed using the conventional loads are also depicted in Table 3 for both regular and irregular plan buildings. The shear walls are modelled as a thin shell element having a compressive strength of 30 MPa and modulus elasticity of 30 GPa. The study showcased the number of shear walls modelled in the regular and irregular buildings as W1, W2, W3, W4, W5, W6, W7, and W8. The shear walls are numbered W1 to W8, with a minimum of four (W1–W4) shear walls placed in case 1 and a maximum of eight shear walls installed in case 8 of the C-shaped building model. The study also reviewed the effectiveness of the area of shear walls (As) in reducing the blast effects of regular and irregular buildings. The study optimized the positions of shear walls and presented detailed structural drawings of the shear walls to be provided for varying thicknesses of shear walls subjected to blast-induced vibrations. The shear walls were modelled using the software tool ETABS Version 20 (extended three-dimensional analysis of building systems) launched by Computers and Structures Inc. (CSI). The steps to be followed in the modelling of shear walls included defining the section properties and wall sections. The wall was modelled as a thin shell element available in the software tool and the thickness of the wall was 300 mm. This was followed by creating three-dimensional building models with and without shear walls. Next, the selected loads are applied at their respective sections along with the underground blast-induced vibrations. The regular and irregular building models discussed in this section follow the guidelines prescribed by Raikar and Kangda [54]. The study also conducted free vibration and nonlinear time history analysis to obtain the results as discussed in the next section.

Table 3. Shear wall placements in regular and irregular buildings.

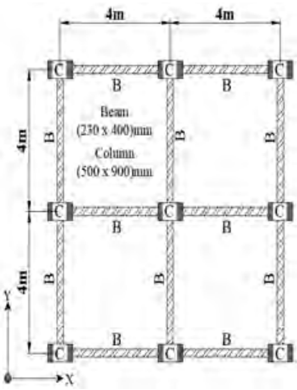
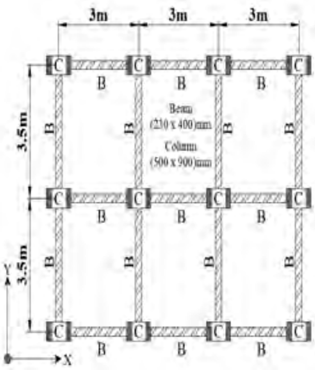
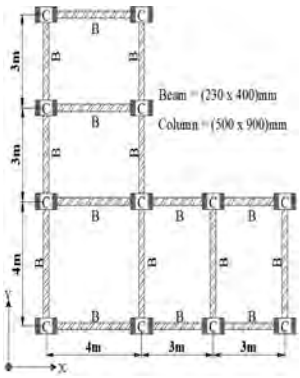
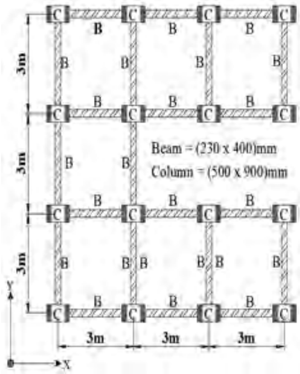
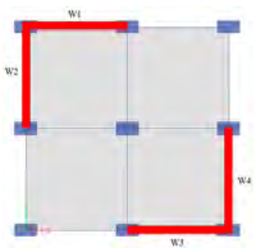
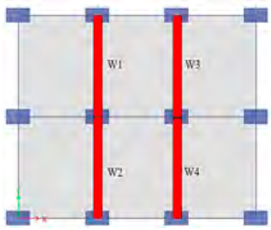
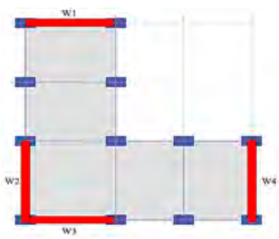
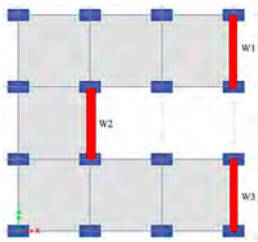
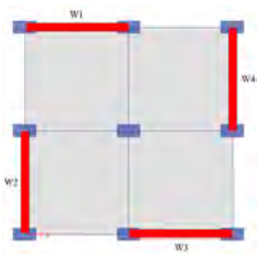
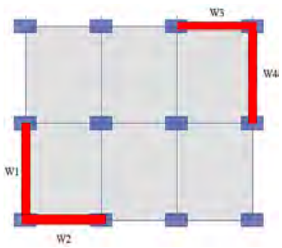
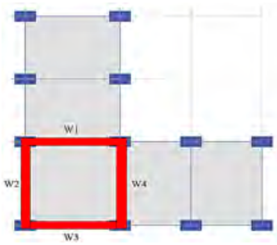
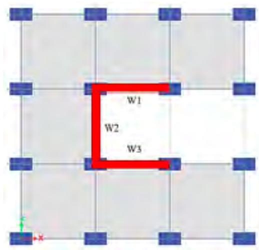
Member	Square	Rectangle	L-Shaped	C-Shaped
Without Shear Wall				
		With Shear Walls		
Case 1	 S0, A_S = 504 m^2	 R0, A_S = 441 m^2	 L0, A_S = 504 m^2	 C0, A_S = 283.5 m^2
Case 2	 S1, A_S = 504 m^2	 R1, A_S = 409.5 m^2	 L1, A_S = 504 m^2	 C1, A_S = 283.5 m^2

Table 3. *Cont.*

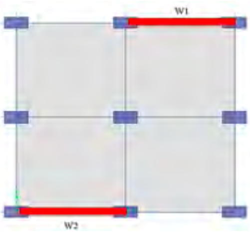
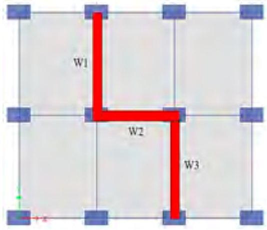
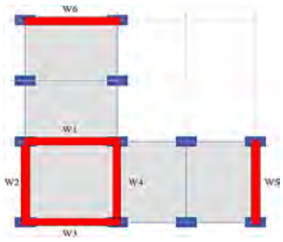
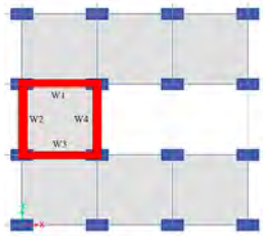
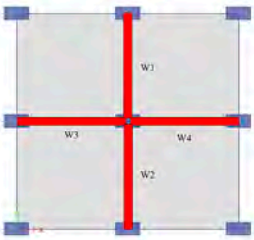
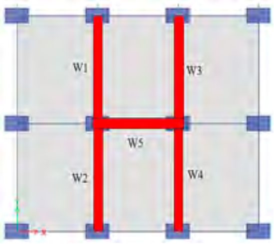
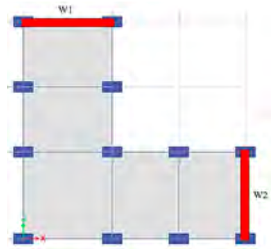
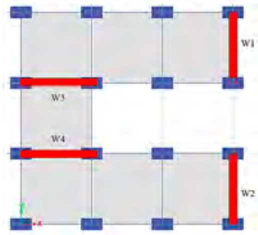
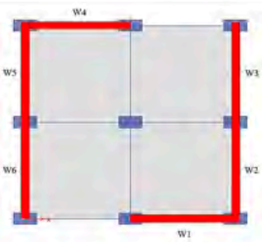
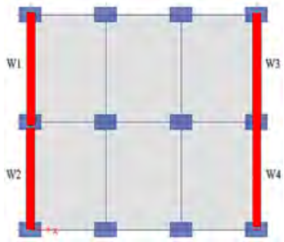
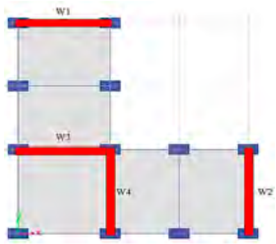
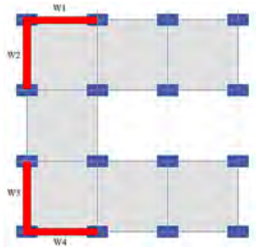
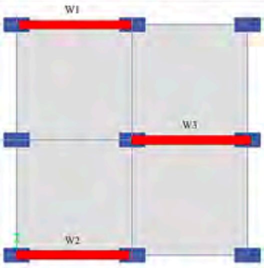
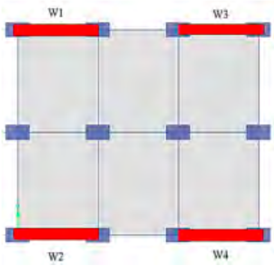
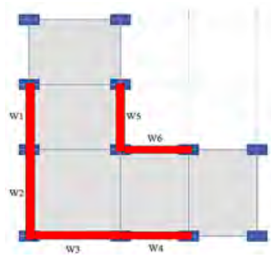
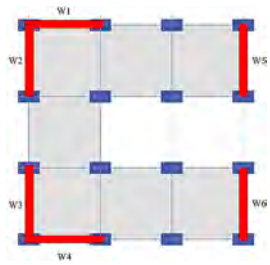
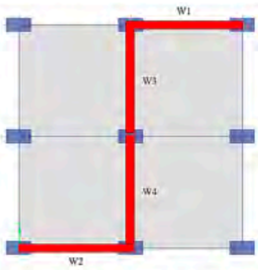
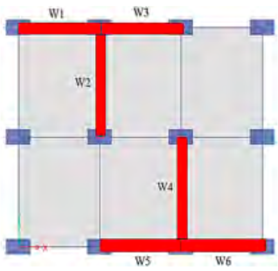
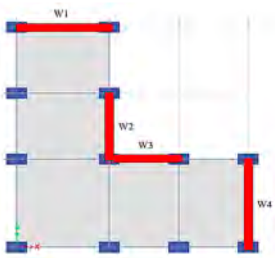
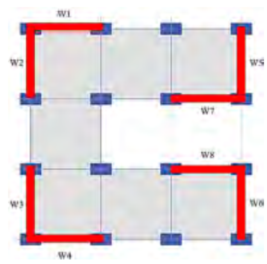
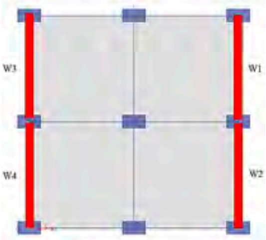
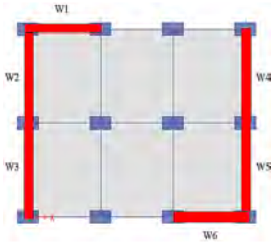
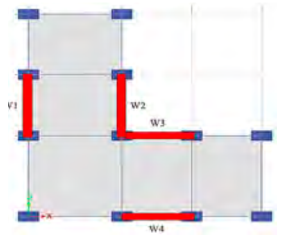
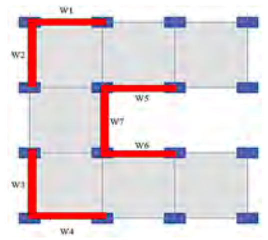
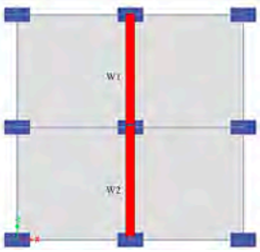
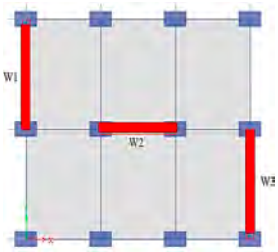
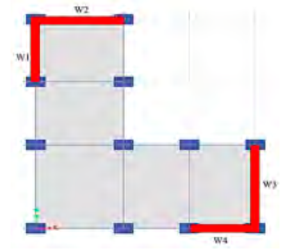
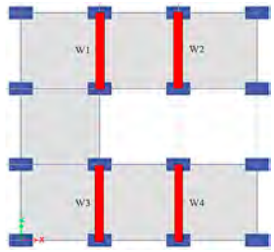
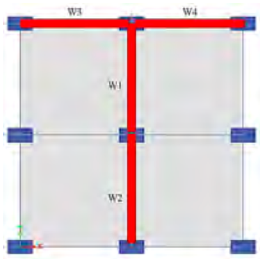
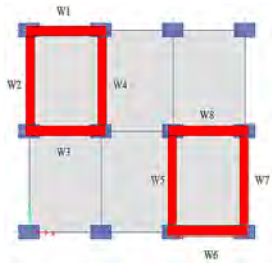
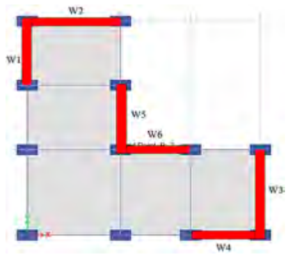
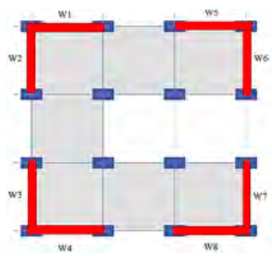
Member	Square	Rectangle	L-Shaped	C-Shaped
Case 3	 S2, $A_S = 252$ m^2	 R2, $A_S = 315$ m^2	 L2, $A_S = 756$ m^2	 C2, $A_S = 378$ m^2
Case 4	 S3, $A_S = 504$ m^2	 R3, $A_S = 535.5$ m^2	 L2, $A_S = 252$ m^2	 C2, $A_S = 378$ m^2
Case 5	 S4, $A_S = 756$ m^2	 R4, $A_S = 441$ m^2	 L4, $A_S = 504$ m^2	 C4, $A_S = 378$ m^2
Case 6	 S5, $A_S = 378$ m^2	 R5, $A_S = 378$ m^2	 L5, $A_S = 630$ m^2	 C5, $A_S = 756$ m^2
Case 7	 S6, $A_S = 504$ m^2	 R6, $A_S = 598.5$ m^2	 L6, $A_S = 441$ m^2	 C6, $A_S = 756$ m^2

Table 3. *Cont.*

Member	Square	Rectangle	L-Shaped	C-Shaped
Case 8	 S7, A_S = 504 m^2	 R7, A_S = 630 m^2	 L7, A_S = 378 m^2	 C7, A_S = 661.5 m^2
Case 9 (S8)	 S8, A_S = 252 m^2	 R8, A_S = 315 m^2	 L8, A_S = 441 m^2	 C8, A_S = 378 m^2
Case 10 (S9)	 S9, A_S = 504 m^2	 R9, A_S = 819 m^2	 L9, A_S = 630 m^2	 C9, A_S = 756 m^2

Optimal locations in square-shaped building, S2. Optimal locations in rectangular-shaped building, R6. Optimal locations in L-shaped building, L1. Optimal locations in C-shaped building, C2.

During free vibration analysis, the structural behaviours of buildings, whether regular or irregular, provide vital insights into their dynamic properties and responsiveness to external pressures and are tabulated in Table 4. The study of the natural frequencies and mode shapes of a building without any external excitation, such as wind, seismic, or blast, is known as free vibration analysis. Regular buildings have a constant and symmetrical distribution of structural parts throughout their height. Regular buildings comprise rectangular or square-shaped structures with a regular grid of columns and shear walls. It is observed from the analysis that the presence of shear walls reduces the structural period and modal mass excited in the selected building models, with an exception observed for square buildings wherein the period increased due to the presence of shear walls. It is interesting to note that increasing the thickness of shear walls results in a decrease in the mass excited. The modal periods presented in Table 4 are obtained for the best possible shear wall locations highlighted at the bottom of Table 3. These optimal locations are determined from the results discussed in Section 3 of the present research. The building properties are assigned such that the first two modes in both regular and irregular buildings show translational modes of vibration, whereas the third and fourth modes are torsional and depicted in Figures 5, 6, 7, and 8 for square, rectangular, L, and C-shaped buildings without shear walls, respectively. The presence of shear walls resulted in reduced mass excitations in the first four modes of vibration (shown in Figures 9, 10, 11, and 12) for square, rectangular, L, and C-shaped buildings, respectively. The results show that keeping the loading and elevation conditions similar, the square-shaped buildings generate the highest period, followed by rectangular, L, and C-shaped buildings. The plan area of all the selected building models is kept constant, and the values are 64 m^2, 63 m^2, 64 m^2, and 63 m^2 for square, rectangular, L, and C-shaped buildings.

Table 4. Modal properties of the selected buildings with and without shear walls.

Geometry	Thickness of SW in mm	Mode Number	Modal Period in s	Modal Participating Mass in %	Angular Frequency in rad/s
Square-Shaped Building	Without SW	1	2.05	74.65	3.06
		2	1.82	71.54	3.45
	200	1	2.16	74.86	2.91
		2	0.86	64.08	7.30
	400	1	2.21	74.05	2.84
		2	0.83	63.48	7.53
	500	1	2.22	73.26	2.84
		2	0.83	63.34	7.61
Rectangular-Shaped Building	Without SW	1	1.83	74.77	3.44
		2	1.48	65.34	4.24
	200	1	0.81	66.04	7.78
		2	0.64	64.89	9.80
	400	1	0.78	64.95	8.06
		2	0.62	64.04	10.11
	500	1	0.77	64.67	8.13
		2	0.62	63.85	10.20
L-Shaped Building	Without SW	1	1.83	73.08	3.36
		2	1.67	66.81	3.76
	200	1	0.78	44.03	7.88
		2	0.77	44.17	8.19
	400	1	0.71	46.36	8.82
		2	0.70	46.28	9.00
	500	1	0.69	47.25	9.13
		2	0.68	47.16	9.28
C-Shaped Building	Without SW	1	1.75	73.39	3.59
		2	1.43	72.47	4.40
	200	1	1.01	64.17	6.21
		2	0.94	65.91	6.71
	400	1	0.92	64.82	6.80
		2	0.88	64.87	7.13
	500	1	0.90	64.74	7.01
		2	0.86	64.58	7.29

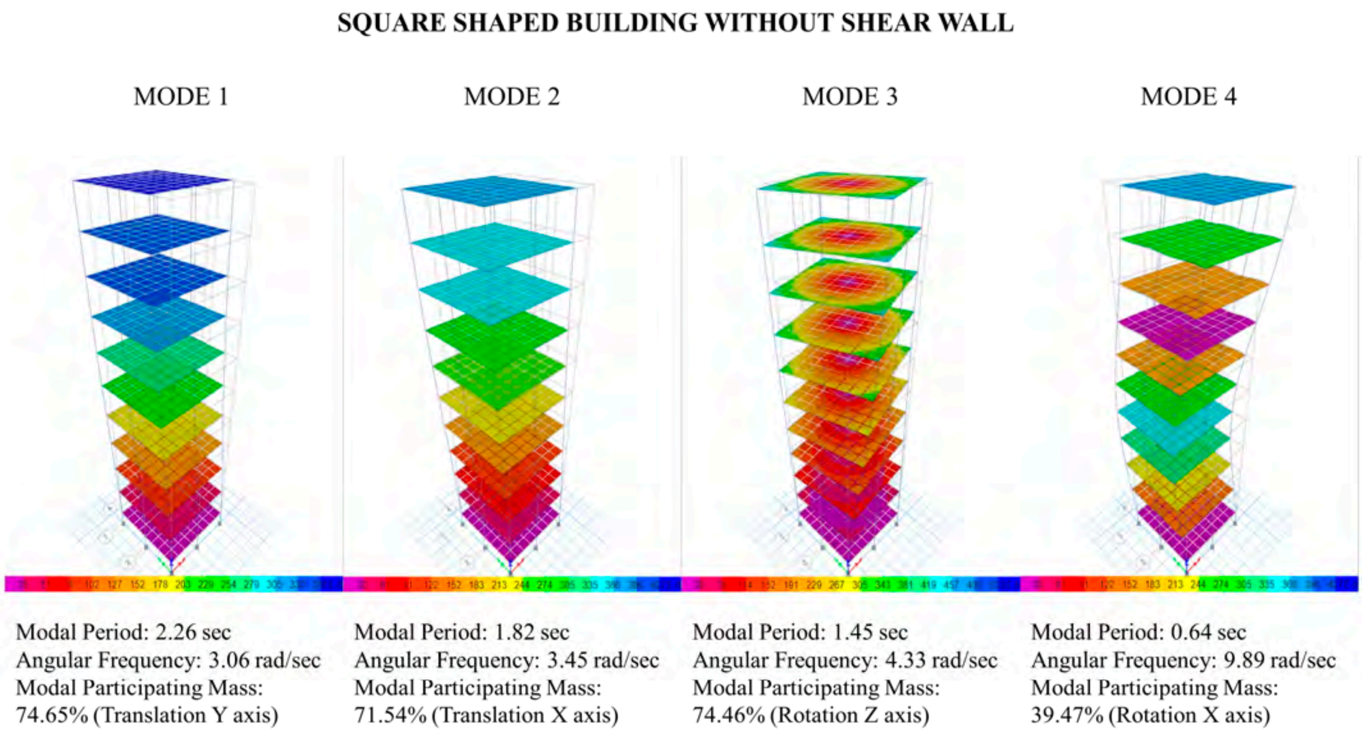


Figure 5. Modal periods and Modal Participation Masses of the square-shaped building without shear walls.

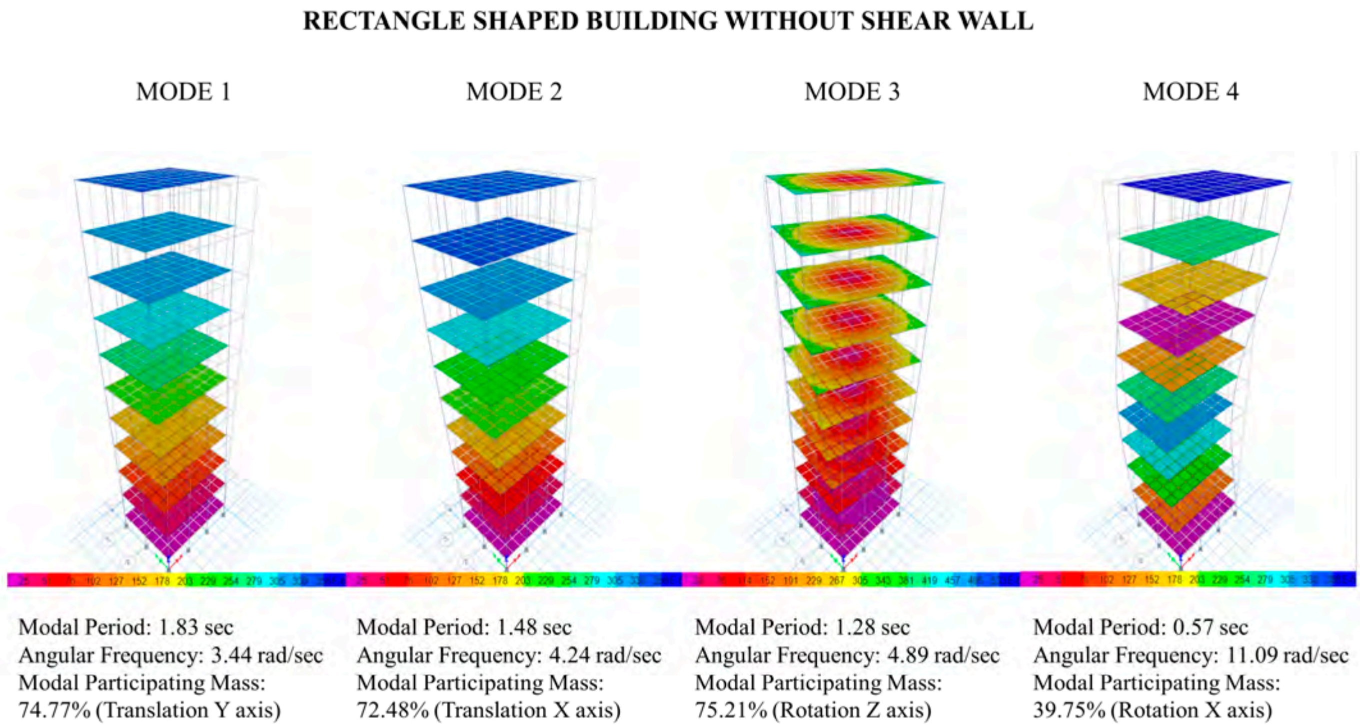


Figure 6. Modal periods and Modal Participation Masses of the rectangle-shaped building without shear walls.

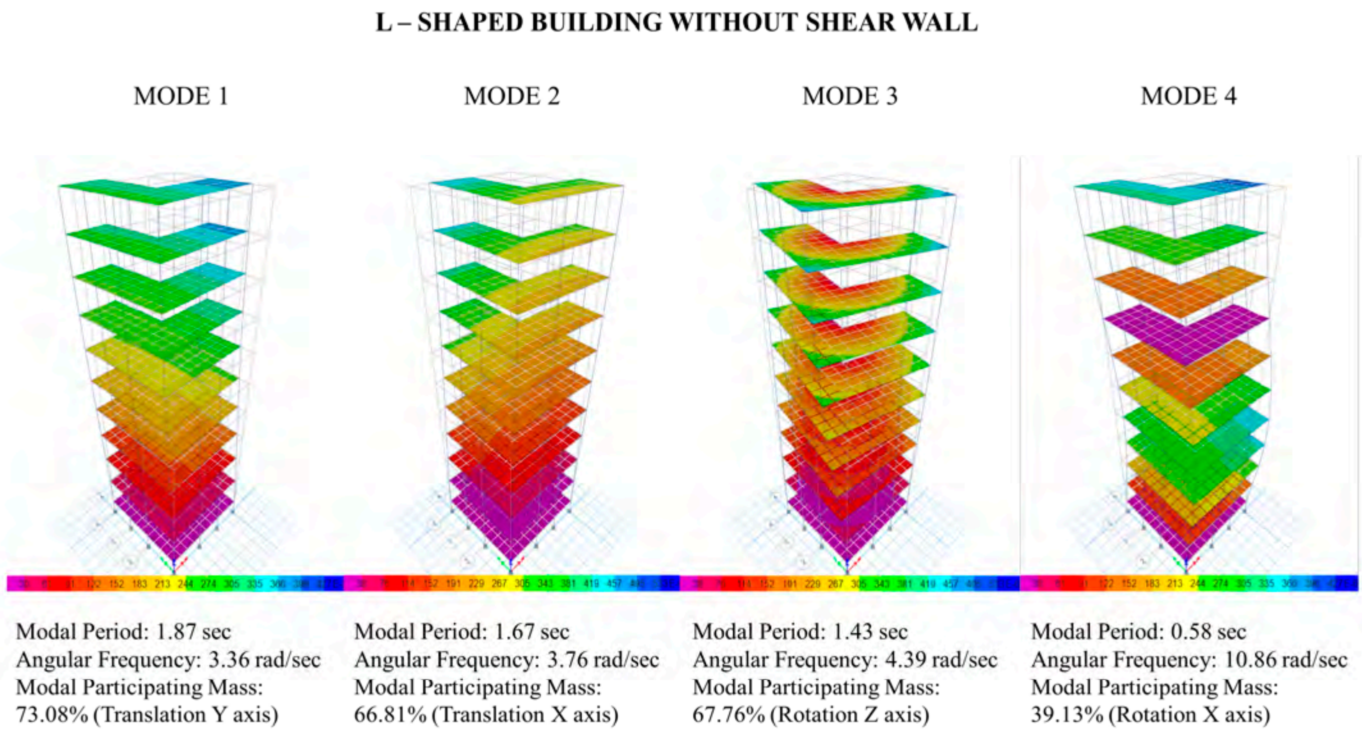


Figure 7. Modal periods and Modal Participation Masses of the L-shaped building without shear walls.

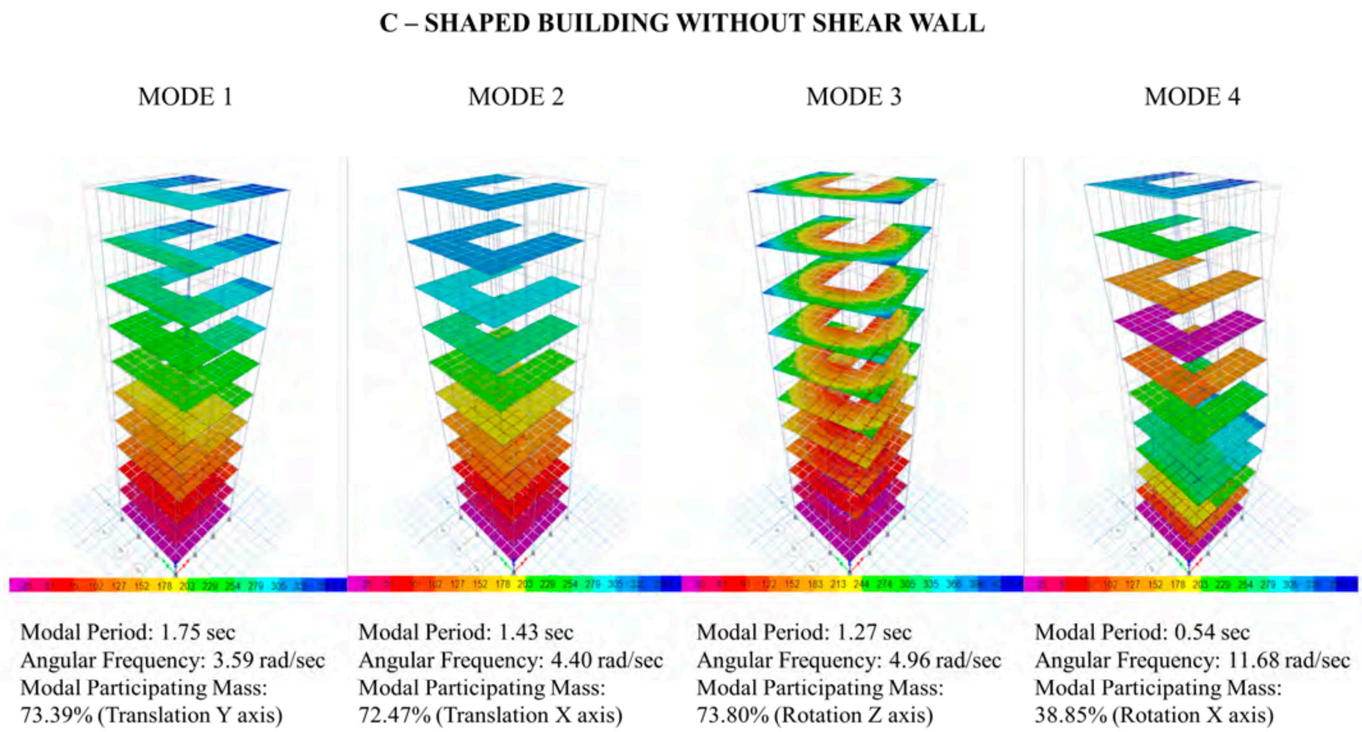


Figure 8. Modal periods and Modal Participation Masses of the C-shaped building without shear walls.

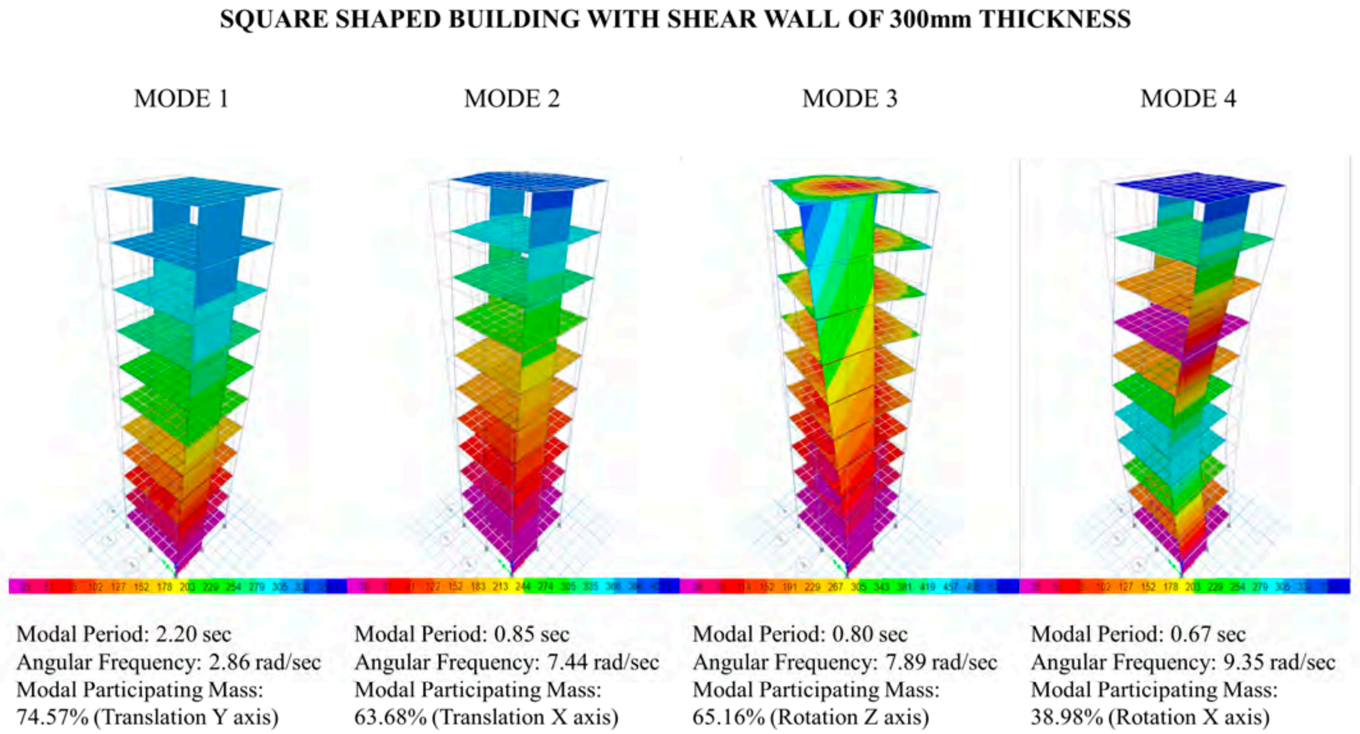


Figure 9. Modal periods and Modal Participation Masses of the square-shaped building with shear walls.

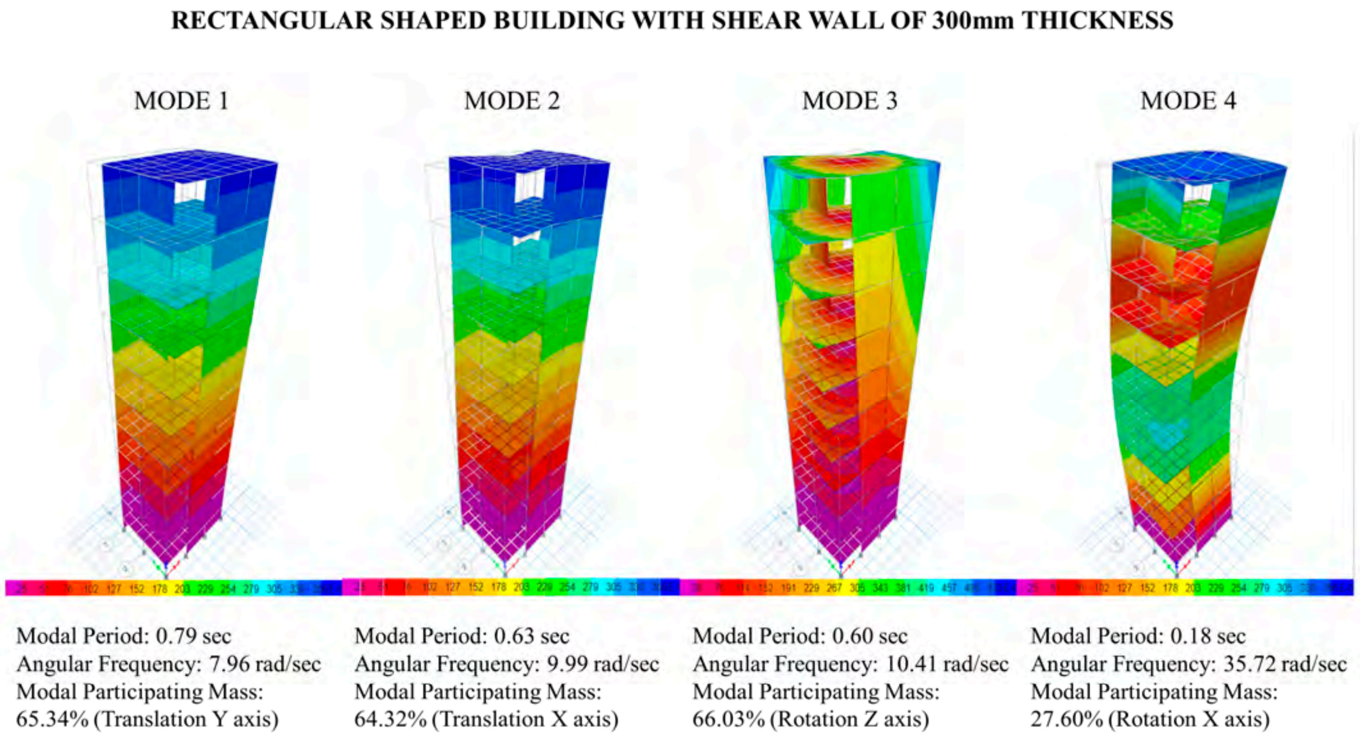


Figure 10. Modal periods and Modal Participation Masses of the rectangle-shaped building with shear walls.

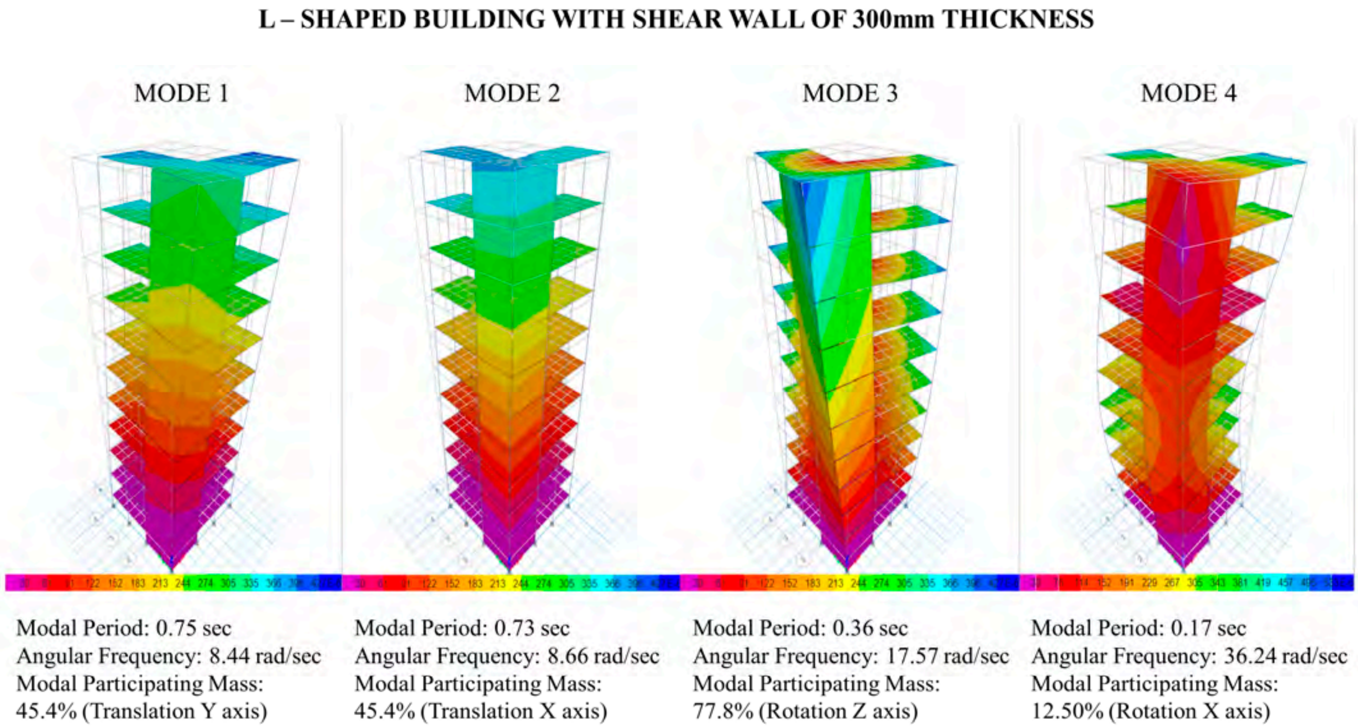


Figure 11. Modal periods and Modal Participation Masses of the L-shaped building with shear walls.

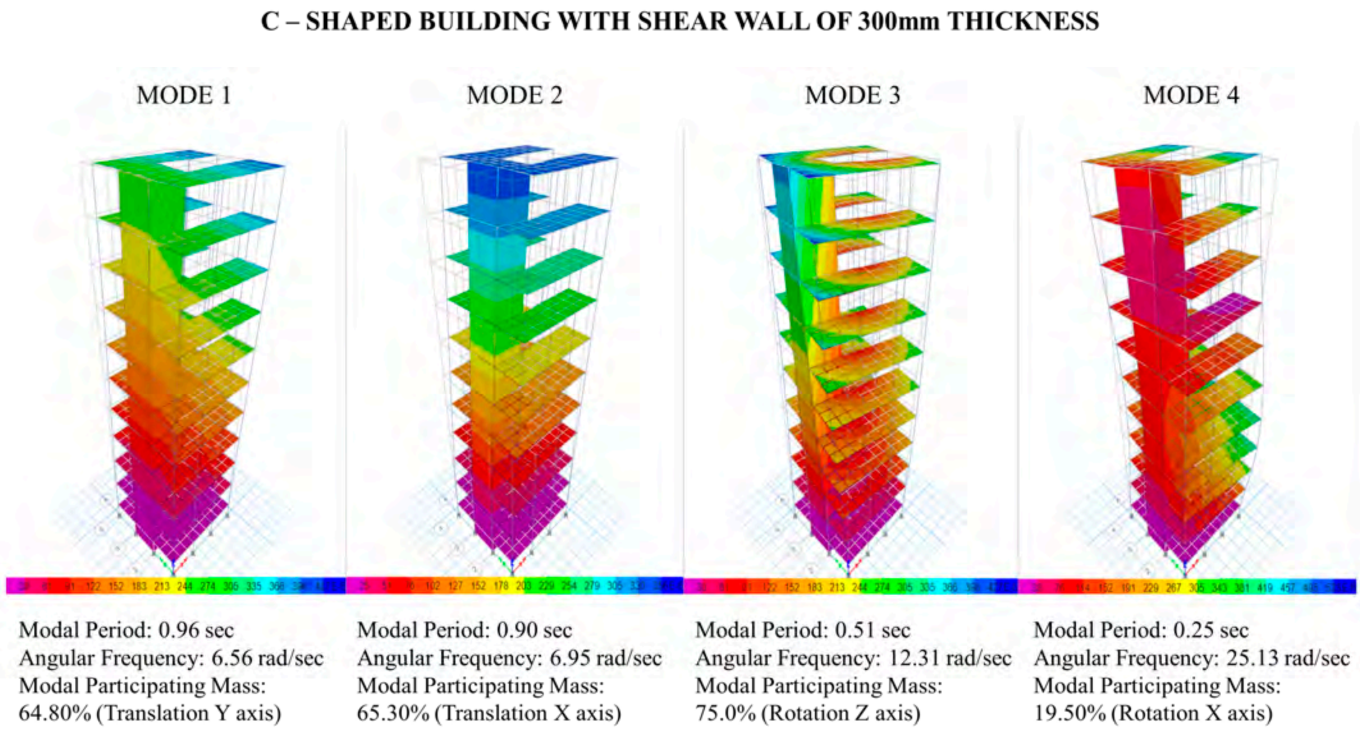


Figure 12. Modal periods and Modal Participation Masses of the C-shaped building with shear walls.

3. Results and Discussion

A comprehensive and meticulous investigation was undertaken to analyse the structural behaviours of four distinct building shapes. These buildings are designed in accordance with the IS 456:2000 standard and subjected to a 50-ton blast load at varying standoff distances, namely 100 m, 200 m, 300 m, and 400 m. The findings revealed that numerous columns and beams experienced failure due to an inadequate design against underground blast-induced vibrations which are summarized in Table 5. The percentage failures of members subjected to the blast charge at the R1 standoff distance are 87.5%, 80%, 83.8%, and 76.1% for square, rectangular, L, and C-shaped buildings, respectively. The percentage failures of members indicate the quantitative measures of failure of the selected-shaped buildings, and it was observed that the square building performed poorly as its maximum percentage of members failed under blast effects. The C-shaped buildings showed the best resistance in mitigating the underground blast-induced structural failure as compared to the other selected-shaped buildings.

Table 5. Performance of shear walls in mitigating the failure of structural members in regular and irregular buildings.

Shapes	Optimal Location	Total Members	Failure of Members							
			Without Shear Wall				With Shear Wall			
			R1	R2	R3	R4	R1	R2	R3	R4
Square-Shaped Building	S2	231	199	110	12	4	144	41	2	0
Rectangular-Shaped Building	R6	319	255	143	18	7	158	46	1	0
L-Shaped Building	L1	308	258	148	40	12	170	36	1	0
C-Shaped Building	C2	418	318	186	21	8	244	122	0	0

In the case of R2 blasts, the rectangular and C-shaped buildings showed 44.8% and 44.5% member failures, respectively, whereas square and L-shaped buildings showed 47.6% and 48.1% failures, respectively. In the case of R3, the square, rectangular, L, and C-shaped buildings showed 5.2%, 5.6%, 12.98%, and 5.7% failures, respectively. Thus, in the case of far-field blasts, the square building improved its performance as compared to the other blast scenarios. The rectangular and C-shaped buildings continued similar trends, with L-shaped buildings being the least effective in resisting the blast loads. The R4 case shows a similar trend as R3 with failure percentages of 1.7%, 2.1%, 3.9%, and 1.9% being observed for square, rectangular, L, and C-shaped buildings, respectively. A schematic representation of these trends is graphically represented in Figure 13 to help researchers understand and compare the performances of regular and irregular buildings subjected to blast-induced vibrations. Next, the study aimed to reduce the member failures of the existing buildings by installing shear walls at different locations of the regular and irregular buildings. The study evaluated the best locations of shear walls based on the structural output parameters, namely displacement, acceleration, bending moment, and shear force. The results are tabulated for different locations of shear walls with varying thicknesses in Tables 6–9 for square, rectangular, L, and C-shaped buildings, respectively. The top-storey peak displacement and peak acceleration values are noted for the topmost storey extreme right corner, whereas the shear force and bending moment values are considered for the columns located at the ground level (extreme right position). The study reported that, for the square-shaped building, the optimum values of structural output parameters were observed in case 3 (S2) with a shear wall area of 252 m^2. The other shear wall areas provided in different cases for square-shaped buildings are 504 m^2, 756 m^2, and 378 m^2. It is thus proved from the present study that the locations of shear walls play a critical role in mitigating the blast effects and the results are independent of the areas of shear walls provided. The blast analysis results demonstrated that when the square, rectangular, L, and C-shaped buildings are subjected to a blast at a standoff distance of 100 m, the peak story displacements are 0.75 m, 0.61 m, 0.65 m, and 0.58 m, respectively. This indicated that the blast load caused significant destruction to the buildings under consideration, with square and L-shaped buildings severely damaged as compared to rectangular and C-shaped buildings. It is observed from Table 6 that the maximum reductions in the storey displacement under blast cases of R1, R2, R3, and R4 are 56%, 55.6%, 60%, and 55.6%, respectively, with the shear wall thickness of 500 mm. The acceleration values were reduced by 17% and 8.2% under close blast loading, i.e., R1 and R2. The far-occurring blasts (R3 and R4) resulted in increased acceleration responses. The shear forces and bending moments were reduced by 84–76%, 85–77%, 86–78%, and 87–79% under R1, R2, R3, and R4 loadings, respectively. The optimum placement of shear walls in rectangular buildings is observed at R6 (case 7) with a shear wall area of 598.5 m^2 in comparison to shear wall areas ranging from 441 m^2 to 819 m^2. The maximum percentage reductions in displacement, acceleration, shear force, and bending moment were 59%, 18%, 89%, and 95%, respectively, with a shear wall thickness of 500 mm subjected to blasts at the R1 distance.

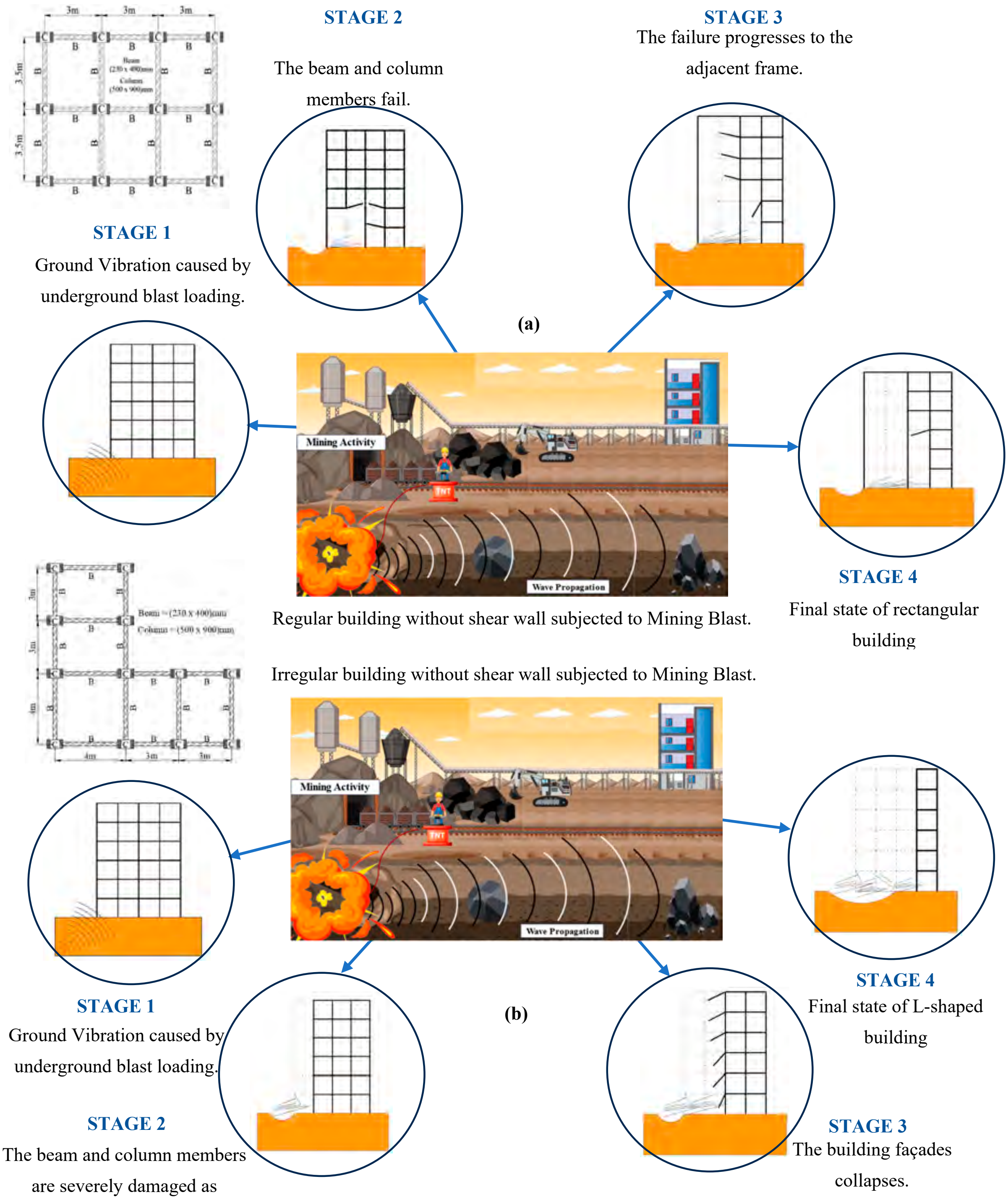


Figure 13. Structural behaviours of (**a**) regular and (**b**) irregular buildings subjected to blast-induced vibrations (R2 = 200 m) without shear walls.

Table 6. Structural responses of the square-shaped building equipped with shear walls.

Cases	Area (m^2)	Displacement (m)				Acceleration (m/s^2)				Shear Force (kN)				Bending Moment (kN-m)			
t = 300 mm		R1	R2	R3	R4	R1	R2	R3	R4	R1	R2	R3	R4	R1	R2	R3	R4
WOSW	-	0.75	0.27	0.15	0.09	87.13	15.8	5.82	2.87	1223.2	419.6	218.3	135.6	5030.1	1765.7	940.3	596.4
S_0	504	0.32	0.06	0.06	0.04	96.25	8.0	8.01	4.43	552.4	68.9	68.9	41.6	1368	224.7	224.7	141.5
S_1	504	0.37	0.13	0.07	0.05	81.9	20.3	8.95	4.91	631.9	187.9	88.9	51.9	1957.3	628.4	312.8	188.0
S_2	**252**	**0.34**	**0.12**	**0.07**	**0.04**	**72.5**	**14.3**	**6.26**	**3.55**	**227.5**	**71.8**	**35.4**	**21.1**	**1291.7**	**428.4**	**217.9**	**132.5**
S_3	504	0.26	0.09	0.05	0.03	113.4	20.6	8.34	4.6	161.5	51.3	25.2	14.9	873.6	289.2	146.1	88.0
S_4	756	0.33	0.11	0.06	0.04	106.2	20.1	8.83	4.84	650.0	201.7	98.0	58.2	1791.8	586.8	295.1	178.5
S_5	378	0.29	0.11	0.06	0.04	72.4	15.1	6.79	3.8	179.0	55.6	27.1	16.1	1073.6	352.0	177.4	107.0
S_6	504	0.34	0.12	0.07	0.04	106.8	19.4	7.3	4.09	236.0	74.4	36.5	21.7	1301.3	433.1	220.3	133.9
S_7	504	0.86	0.31	0.17	0.11	102.7	18.6	6.86	3.38	1353.8	460.9	238.8	147.9	5724.3	2012.7	1074.3	682.5
S_8	252	0.81	0.29	0.16	0.10	107.3	19.5	7.17	3.53	1357.6	461.8	239.4	148.4	5463.2	1916.3	1020.6	647.4
S_9	504	0.65	0.23	0.13	0.08	103.4	18.8	6.91	3.4	1563.4	516.9	264.7	163.7	5573.6	1931.3	1023.3	648.1
t = 400 mm, Case = (S_2)		**0.33**	**0.12**	**0.07**	**0.04**	**72.24**	**14.5**	**6.43**	**3.64**	**210.5**	**66.3**	**32.6**	**19.4**	**1251.7**	**414.0**	**210.1**	**127.5**
t = 500 mm, Case = (S_2)		**0.33**	**0.12**	**0.06**	**0.04**	**72.05**	**14.5**	**6.56**	**3.7**	**199.4**	**62.6**	**30.8**	**18.3**	**1222.7**	**403.5**	**204.4**	**123.9**
t = 200 mm, Case = (S_2)		**0.35**	**0.12**	**0.07**	**0.04**	**73.03**	**14.2**	**6.00**	**3.41**	**264.2**	**83.8**	**41.4**	**24.7**	**1369.9**	**455.9**	**232.6**	**141.9**

Table 7. Structural responses of the rectangular-shaped building equipped with shear walls.

Cases	Area (m^2)	Displacement (m)				Acceleration (m/sec^2)				Shear Force (kN)				Bending Moment (kN-m)			
t = 300 mm		R1	R2	R3	R4	R1	R2	R3	R4	R1	R2	R3	R4	R1	R2	R3	R4
WOSW	-	0.61	0.22	0.12	0.07	115.4	20.9	7.71	3.8	1166.7	395.6	204.8	127.3	4379.5	1520.4	805.0	509.6
R_0	441	0.66	0.24	0.13	0.08	92.9	16.9	6.21	3.1	1269.7	440.8	231.4	144.7	4727.2	1668.0	890.9	566.4
R_1	409.5	0.38	0.13	0.07	0.04	100.4	18.2	7.21	4.0	260.8	85.9	44.8	28.0	1348.6	475.5	254.2	160.6
R_2	315	0.39	0.14	0.07	0.05	91.1	16.5	6.08	3.4	407.6	113.4	59.4	37.3	1553.9	549.4	293.8	186.6
R_3	535.5	0.60	0.21	0.1	0.07	91.8	16.7	6.13	3.0	1403.6	476.4	246.2	152.4	5132.5	1789.8	947.9	598.9
R_4	441	0.66	0.24	0.13	0.08	102.8	18.7	6.87	3.4	1203.0	417.7	219.5	137.5	4657.4	1644.8	879.6	559.9
R_5	378	0.33	0.11	0.06	0.04	72.1	14.7	6.16	3.5	455.3	139.5	67.4	39.8	1662.6	539.7	270.9	163.6
R_6	**598.5**	**0.26**	**0.09**	**0.05**	**0.03**	**88.7**	**22.4**	**9.77**	**5.3**	**144.5**	**32.9**	**13.3**	**6.9**	**226.6**	**51.5**	**20.8**	**10.8**
R_7	630	0.39	0.14	0.07	0.04	106.7	15.8	7.23	4.0	735.6	237.6	118.4	71.5	2213.1	746.3	383.2	235.6
R_8	315	0.47	0.16	0.09	0.05	107.0	19.4	7.15	3.9	441.9	151.3	78.9	50.0	2106.6	744.9	396.8	250.3
R_9	819	0.30	0.10	0.06	0.03	88.3	21.8	9.51	5.2	640.9	192.2	91.6	53.6	1733.3	553.0	273.4	163.1
t = 400 mm, Case = (R_6)		**0.25**	**0.09**	**0.05**	**0.03**	**91.3**	**23.4**	**10.1**	**5.4**	**132.2**	**29.8**	**12.0**	**6.2**	**210.6**	**47.3**	**19.0**	**9.8**
t = 500 mm, Case = (R_6)		**0.25**	**0.09**	**0.05**	**0.03**	**94.7**	**24.0**	**10.3**	**5.6**	**122.6**	**27.4**	**11.0**	**5.6**	**197.6**	**44.0**	**17.6**	**9.1**
t = 200 mm, Case = (R_6)		**0.26**	**0.09**	**0.05**	**0.03**	**113.8**	**20.6**	**8.1**	**4.5**	**128.8**	**30.1**	**12.2**	**6.4**	**194.2**	**47.2**	**21.1**	**11.8**

Table 8. Structural responses of the L-shaped building equipped with shear walls.

Cases	Area (m^2)	Displacement (m)				Acceleration (m/s^2)				Shear Force (kN)				Bending Moment (kN-m)			
t = 300 mm		R1	R2	R3	R4	R1	R2	R3	R4	R1	R2	R3	R4	R1	R2	R3	R4
WOSW	-	0.65	0.23	0.13	0.08	94.8	17.2	6.3	3.12	1215.7	420.2	220.0	137.1	5710.6	1996.4	1057.9	668.6
L_0	504	0.33	0.11	0.06	0.04	90.3	16.4	6.0	3.46	421.2	106.7	50.5	30.9	1329.5	457.0	237.7	147.1
L_1	**504**	**0.28**	**0.10**	**0.05**	**0.03**	**78.9**	**14.3**	**6.0**	**3.38**	**251.7**	**74.8**	**36.1**	**21.4**	**1121.9**	**362.8**	**182.6**	**110.4**
L_2	756	0.28	0.10	0.05	0.03	114.5	20.8	8.4	4.65	286.5	92.5	45.7	27.3	1230.3	410.0	207.2	125.1
L_3	252	0.6	0.22	0.12	0.07	91.2	16.5	6.1	3.00	947.5	305.2	162.4	103.2	3505.7	1229.4	658.3	419.4
L_4	504	0.4	0.14	0.07	0.05	107.7	19.5	7.2	3.54	509.7	162.3	80.3	48.3	2005.5	670.4	343.7	211.3
L_5	630	0.19	0.06	0.03	0.02	86.1	15.6	6.0	3.32	209.6	58.6	28.7	16.9	673.8	222.3	111.5	66.3
L_6	441	0.45	0.16	0.08	0.05	88.9	16.1	7.2	4.06	518.9	169.0	87.4	53.8	2221.5	754.0	393.9	245.1
L_7	378	0.37	0.13	0.07	0.04	107.3	19.5	7.2	3.78	380.0	114.0	55.0	32.6	1608.4	524.8	266.2	162.4
L_8	441	0.39	0.14	0.07	0.05	109.4	19.8	7.3	3.6	722.7	199.7	93.4	56.5	1972.6	646.8	331.3	204.8
L_9	630	0.34	0.12	0.06	0.04	106.1	19.2	7.4	4.15	623.1	189.1	93.3	55.9	1891.2	613.5	310.7	188.9
t = 400 mm, Case = (L_1)		**0.27**	**0.10**	**0.05**	**0.03**	**77.7**	**14.1**	**6.3**	**3.52**	**237.4**	**70.2**	**33.7**	**19.9**	**1082.8**	**348.3**	**174.5**	**105.0**
t = 500 mm, Case = (L_1)		**0.27**	**0.09**	**0.05**	**0.03**	**76.4**	**14.4**	**6.6**	**3.64**	**227.4**	**67.1**	**32.1**	**18.9**	**1053.7**	**337.8**	**168.6**	**101.1**
t = 200 mm, Case = (L_1)		**0.29**	**0.10**	**0.05**	**0.03**	**80.3**	**14.6**	**5.6**	**3.14**	**282.7**	**85.2**	**41.4**	**24.7**	**1198.2**	**391.0**	**198.2**	**120.6**

Table 9. Structural responses of the C-shaped building equipped with shear walls.

Cases	Area (m^2)	Displacement (m)				Acceleration (m/s^2)				Shear Force (kN)				Bending Moment (kN-m)			
t = 300 mm		R1	R2	R3	R4	R1	R2	R3	R4	R1	R2	R3	R4	R1	R2	R3	R4
WOSW	-	0.58	0.21	0.11	0.07	115.4	20.9	7.7	3.8	1401.6	476.1	247.2	154.1	4545.5	1574.4	832.5	526.6
C_0	283.5	0.62	0.22	0.12	0.08	86.6	15.7	5.8	2.85	1457.0	506.3	266.2	166.9	4746.9	1666.9	887.9	563.7
C_1	283.5	0.38	0.13	0.07	0.04	85.7	15.6	6.3	3.31	804.1	256.9	127.1	76.3	2305.3	764.5	389.8	238.6
C_2	**378**	**0.38**	**0.13**	**0.07**	**0.04**	**81.5**	**14.8**	**6.3**	**3.27**	**571.0**	**186.7**	**94.0**	**57.1**	**1970.1**	**660.4**	**339.0**	**208.2**
C_3	378	0.43	0.15	0.08	0.05	117.0	21.2	7.8	3.85	620.8	213.6	110.8	68.4	2207.5	771.0	405.0	252.5
C_4	378	0.39	0.13	0.07	0.04	74.0	13.4	5.6	3.03	613.5	198.5	99.2	60.0	2144.2	715.4	366.1	224.6
C_5	756	0.40	0.14	0.07	0.05	112.3	20.4	7.5	3.69	590.3	184.6	96.5	59.9	2096.5	696.7	363.0	226.0
C_6	756	0.33	0.11	0.06	0.04	118.0	21.4	7.9	4.38	577.9	190.1	95.2	57.4	1713.3	579.4	296.7	181.3
C_7	661.5	0.32	0.11	0.06	0.04	71.1	15.1	6.4	3.44	612.4	189.1	91.8	54.4	1822.4	589.3	295.2	178.0
C_8	378	0.63	0.22	0.12	0.08	86.8	15.7	5.8	2.85	1398.0	485.9	255.3	160.0	4701.5	1651.6	880.0	558.6
C_9	756	0.33	0.11	0.06	0.04	101.5	18.4	6.8	3.39	404.5	124.6	64.5	39.7	1556.0	511.2	264.1	163.1
t = 400 mm, Case = (C_2)		**0.37**	**0.13**	**0.07**	**0.04**	**79.0**	**14.9**	**6.4**	**3.3**	**525.5**	**170.9**	**85.8**	**51.9**	**1856.2**	**620.1**	**317.5**	**194.4**
t = 500 mm, Case = (C_2)		**0.36**	**0.12**	**0.06**	**0.04**	**77.5**	**15.1**	**6.4**	**3.31**	**491.0**	**158.9**	**79.6**	**48.0**	**1766.9**	**588.3**	**300.4**	**183.5**
t = 200 mm, Case = (C_2)		**0.40**	**0.14**	**0.07**	**0.05**	**88.7**	**16.1**	**6.0**	**3.1**	**645.6**	**212.6**	**107.7**	**65.6**	**2151.1**	**724.7**	**373.6**	**230.3**

In the case of R2, these values are reduced by 59%, 0%, 93%, and 97%, respectively. For blasts at R3 and R4, these output parameters are reduced by 58%, 0%, 95%, 98%, 57%, 0%, 96%, and 98%. The 0% increase in the acceleration responses denotes that the acceleration responses have increased due to the placement of shear walls. The comparisons of shear wall performances in square and rectangular-shaped buildings show that the installation of shear walls in rectangular buildings resulted in better control, as compared to square-shaped buildings. However, it must be noted that the shear wall areas also increased by 58%, in the case of rectangular buildings, to achieve the desired results as compared to square-shaped buildings. The irregular-shaped buildings of L and C, equipped with 500 mm thick shear walls, led to maximum reductions in responses at L1 (case 2) with a shear wall area of 504 m^2 and C2 (case 3) with a shear wall area of 378 m^2, respectively.

The displacement, acceleration, shear force, and bending moment responses for L-shaped buildings with shear walls are reduced in the ranges of 58–63%, 0–19%, 81–86%, and 82–85%, respectively, for all selected blast loads. For C-shaped buildings with shear walls, the reductions are in the ranges of 38–45%, 13–33%, 65–69%, and 61–65%, respectively. Thus, it was observed that shear walls installed in C-shaped buildings yielded the least reductions in structural responses as compared to the other shaped buildings, and rectangular-shaped buildings installed with shear walls showed the maximum reductions in responses. Tables 6–9 summarize the effect of shear wall thickness and placement in mitigating the performances of regular (square and rectangular) and irregular (C and L) shaped buildings. The selection of shear wall parameters in the present study has been influenced by the research conducted by Mooty et al. [55], showing the effectiveness of 500 mm thick shear walls in mitigating the damages incurred to the walls. The presence of shear walls has protected and prevented the failures of nearly 25% of members in no-shear wall conditions. It is important to note that in cases of far-occurring blasts, i.e., R3 and R4, all the members present in the square, rectangular, L, and C-shaped buildings were safe due to the installation of shear walls, as compared to nearly 5–13% failures observed in buildings without shear walls. This conclusion highlights the effectiveness of shear walls in mitigating the blast-induced vibrations in regular and irregular buildings. The study also illustrated an overview of the effectiveness of shear walls in mitigating the blast responses of the selected buildings with the help of Figure 14. Table 10 presents a comparison of buildings equipped with shear walls with the passive control dampers, namely fluid viscous and X-plate dampers. The past study by Raikar and Kangda [54] observed that the optimum viscous damping coefficient of 330 yielded percentage reductions of nearly 9–27%, 8–26%, and 6–16% in the peak displacement, shear force, and bending moment, respectively, for square-shaped buildings subjected to different blast scenarios as considered in the present study. The X-plate dampers reduced the storey displacement, shear force, and bending moment by 33–67%, 17–35%, and 20–30%, respectively, when installed in square-shaped buildings. The present study reported that the installation of 500 mm thick shear walls at optimum locations resulted in 56–60%, 84–87%, and 76–79% reductions in displacement, shear force, and bending moment, respectively. Thus, proving the efficiency of shear walls in mitigating the blast effects as compared to the available passive control techniques. The installation of shear walls in rectangular buildings improved the displacement, shear force, and bending performances by nearly 54%, 87%, and 90%, respectively, when compared with passive control techniques. In cases of L and C-shaped buildings, the installation of shear walls proved to be an efficient technique and improved the displacement, shear force, and bending moment by nearly 54–32%, 79–48%, and 74–55%, respectively. Thus, shear walls proved to be an efficient technique in mitigating the blast-induced vibrations in regular and irregular-shaped buildings. The present study also evaluated the storey drift ratios of buildings under the selected blast-induced vibrations. It was observed that the absence of shear walls in square, rectangular, L, and C-shaped buildings resulted in storey drift ratios of nearly 0.0054, 0.0039, 0.0056, and 0.0041 at the topmost level under blast case R2 (as shown in Figure 15). Thus, the square and L-shaped buildings were the most affected buildings due to the selected blast loading. These values exceeded the limiting value of 0.004 specified in the Indian Standard for Plain and Reinforced Concrete: IS 456 2000 [56], and the selected structures must be redesigned or protected with the installation of shear walls. The installation of shear walls with a thickness of 300 mm results in storey drift ratios of 0.004, 0.0029, 0.0036, and 0.0036 for the square, rectangular, L, and C-shaped buildings. It must be noted that the installation of shear walls resulted in the protection of these selected structures. Under blast cases 3 (R3) and 4 (R4), the storey drift ratios were within the prescribed limits for regular and irregular buildings with and without shear walls. In blast case 1 (R1), the drift ratios are 0.0156, 0.0115, 0.016, and 0.0112 for square, rectangular, L, and C-shaped buildings, and the limits exceeded the prescribed limits.

It must be noted that the installation of shear walls with 300 mm thickness is an ineffective technique in reducing these values within the prescribed limits, and the values obtained are 0.012, 0.009, 0.010, and 0.014 for square, rectangular, L, and C-shaped buildings, respectively. The study also observed that for the 500 mm thick shear wall, the storey drift ratios are found to be 0.0044, 0.003, 0.0033, and 0.0044, respectively for square, rectangular, L, and C-shaped buildings. Thus, the thickness of the shear wall played an important role in mitigating the blast effects with an additional cost incurred due to the increase in size. The study has selected 300 mm thick shear walls in its results and discussion section to optimize the best possible results with a limited size of shear walls. Moreover, the blast effects considered in case 1, i.e., R1, resulted in the most catastrophic destructions to the structure, considering the blast charge of 50 tons and a 100 m standoff distance. Blast wave R1 is primarily considered in the present study due to the accidental blast loading, as reported by Mondal et al. [57]. Thus, by implementing appropriate retrofitting measures, such as shear walls, the story drift can be effectively controlled, ensuring the buildings' structural stability, and minimizing the potential for damage and failure during blast events. Next, the study evaluated the shear stresses induced in the shear walls. Shear stress is one of the critical parameters in the design of shear walls as the shear pressures severely alter the building's stability and structural integrity. When the lateral blast pressures occur on a structure, shear stresses form within the shear walls as internal forces attempt to resist the exterior loads. An inadequate shear wall design resulted in shear failure, in which the material fails parallel to the direction of the applied shear pressures. The buildings undergo excessive lateral displacements due to inadequate shear stress consideration in the design, resulting in damage or failure of the structural system. Thus, the shear stresses in the walls must be kept below acceptable limits to avoid wall failure or damage to other structural components. Building codes and regulations frequently specify minimum standards for shear wall design to ensure the structural stability of the building during extreme loading conditions caused by earthquakes and high winds.

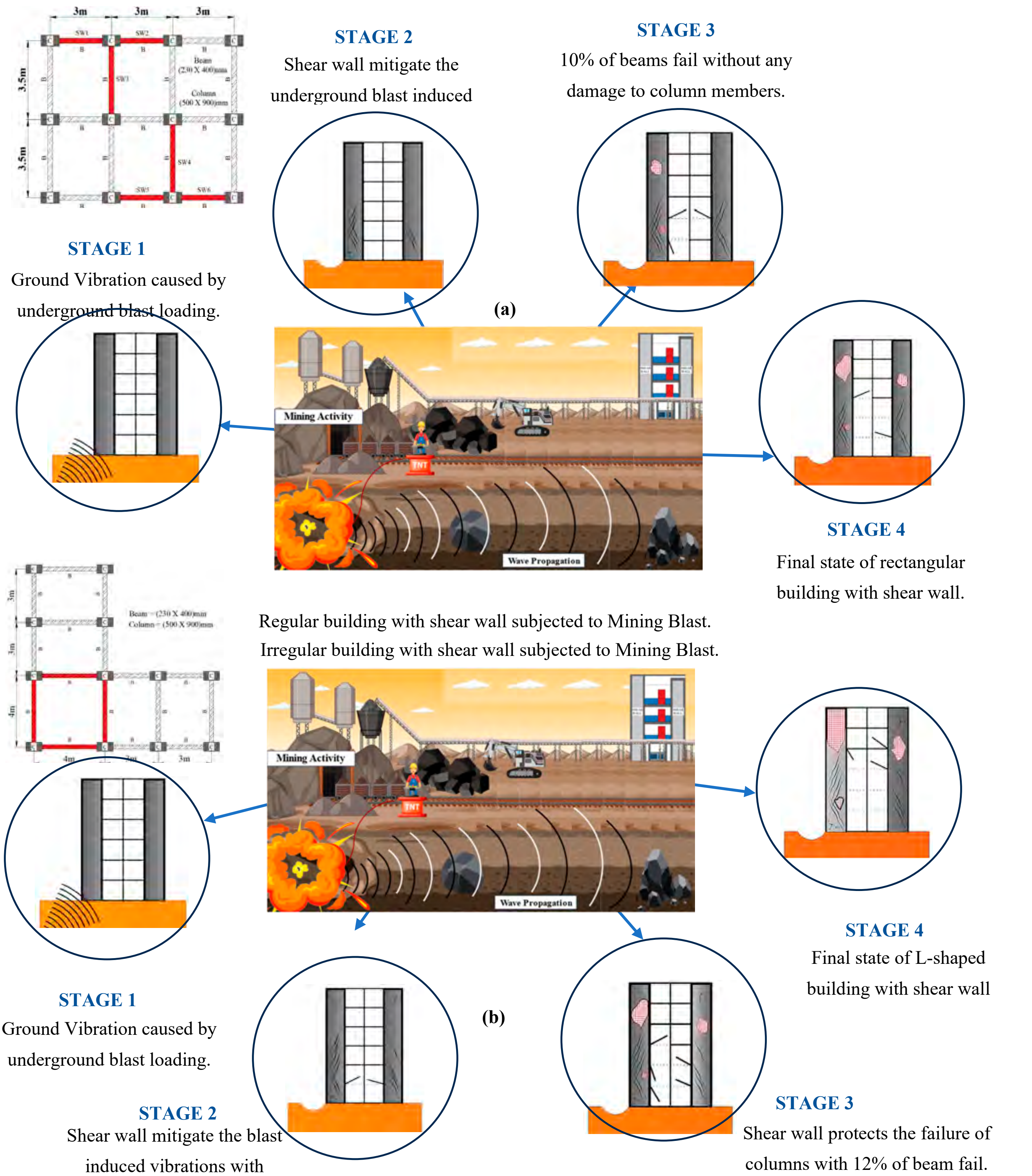


Figure 14. Structural behaviours of (**a**) regular and (**b**) irregular buildings subjected to blast-induced vibrations (R2 = 200 m) with shear walls.

Table 10. Comparing buildings equipped with fluid viscous dampers, X-plate damper, and shear walls under blast load.

Geometry	Control Techniques	Property	Displacement (m)				Shear Force (kN)				Bending Moment (kN-m)			
			R1	R2	R3	R4	R1	R2	R3	R4	R1	R2	R3	R4
Square-Shaped Building	Existing Square-Shaped Building		0.75	0.27	0.15	0.09	1223.2	419.6	218.3	135.6	5030.1	1765.7	940.3	596.4
	Fluid Viscous Damper [44]	C = 330, α = 0.36	0.68	0.22	0.11	0.07	1131	348.1	170.8	100.9	4711.0	1476	794.1	512.3
	X-Plate Damper [44]	a = 20, b = 160 mm	0.50	0.16	0.07	0.03	1013	304.4	147.7	88.1	4020.0	1296	698.9	417.8
	Shear Wall (Present Study)	t = 300 mm	0.34	0.12	0.07	0.04	227.5	71.8	35.4	21.1	1291.7	428.4	217.9	132.5
		t = 400 mm	0.33	0.12	0.07	0.04	210.5	66.3	32.6	19.4	1251.7	414.0	210.1	127.5
		t = 500 mm	0.33	0.12	0.06	0.04	199.4	62.6	30.8	18.3	1222.7	403.5	204.4	123.9
Rectangle-Shaped Building	Existing Rectangle-Shaped Building		0.61	0.22	0.12	0.07	1166.7	395.6	204.8	127.3	4379.5	1520.4	805.0	509.6
	Fluid Viscous Damper [44]	C = 330, α = 0.36	0.55	0.18	0.09	0.05	1017.0	327.2	163.2	97.6	4251.0	1378.0	710.4	449.8
	X-Plate Damper [44]	a = 20, b = 160 mm	0.44	0.14	0.06	0.03	892.8	275.8	132.8	83.6	3656.0	1173.0	594.7	367.7
	Shear Wall (Present Study)	t = 300 mm	0.26	0.09	0.05	0.03	144.5	32.9	13.3	6.9	226.6	51.5	20.8	10.8
		t = 400 mm	0.25	0.09	0.05	0.03	132.2	29.8	12.0	6.2	210.6	47.3	19.0	9.8
		t = 500 mm	0.25	0.09	0.05	0.03	122.6	27.4	11.0	5.6	197.6	44.0	17.6	9.1
L-Shaped Building	Existing L-Shaped Building		0.65	0.23	0.13	0.08	1215.7	420.2	220.0	137.1	5710.6	1996.4	1057.9	668.6
	Fluid Viscous Damper [44]	C = 330, α = 0.36	0.59	0.20	0.10	0.06	1097.0	340.1	167.0	99.6	4173	1369	741.6	473.9
	X-Plate Damper [44]	a = 20, b = 160 mm	0.45	0.14	0.06	0.03	962.2	287.4	137.1	83.6	3674	1182	620.1	371.4
	Shear Wall (Present Study)	t = 300 mm	0.28	0.10	0.05	0.03	251.7	74.8	36.1	21.4	1121.9	362.8	182.6	110.4
		t = 400 mm	0.27	0.10	0.05	0.03	237.4	70.2	33.7	19.9	1082.8	348.3	174.5	105.0
		t = 500 mm	0.27	0.09	0.05	0.03	227.4	67.1	32.1	18.9	1053.7	337.8	168.6	101.1
C-Shaped Building	Existing C-Shaped Building		0.58	0.21	0.11	0.07	1401.6	476.1	247.2	154.1	4545.5	1574.4	832.5	526.6
	Fluid Viscous Damper [44]	C = 330, α = 0.36	0.53	0.17	0.08	0.05	951.4	305.5	150.9	90.4	3940.0	1311.0	670.5	418.4
	X-Plate Damper [44]	a = 20, b = 160 mm	0.40	0.12	0.05	0.02	811.9	241.1	123.0	76.6	3392.0	1065.0	550.5	336.1
	Shear Wall (Present Study)	t = 300 mm	0.38	0.13	0.07	0.04	571.0	186.7	94.0	57.1	1970.1	660.4	339.0	208.2
		t = 400 mm	0.37	0.13	0.07	0.04	525.5	170.9	85.8	51.9	1856.2	620.1	317.5	194.4
		t = 500 mm	0.36	0.12	0.06	0.04	491.0	158.9	79.6	48.0	1766.9	588.3	300.4	183.5

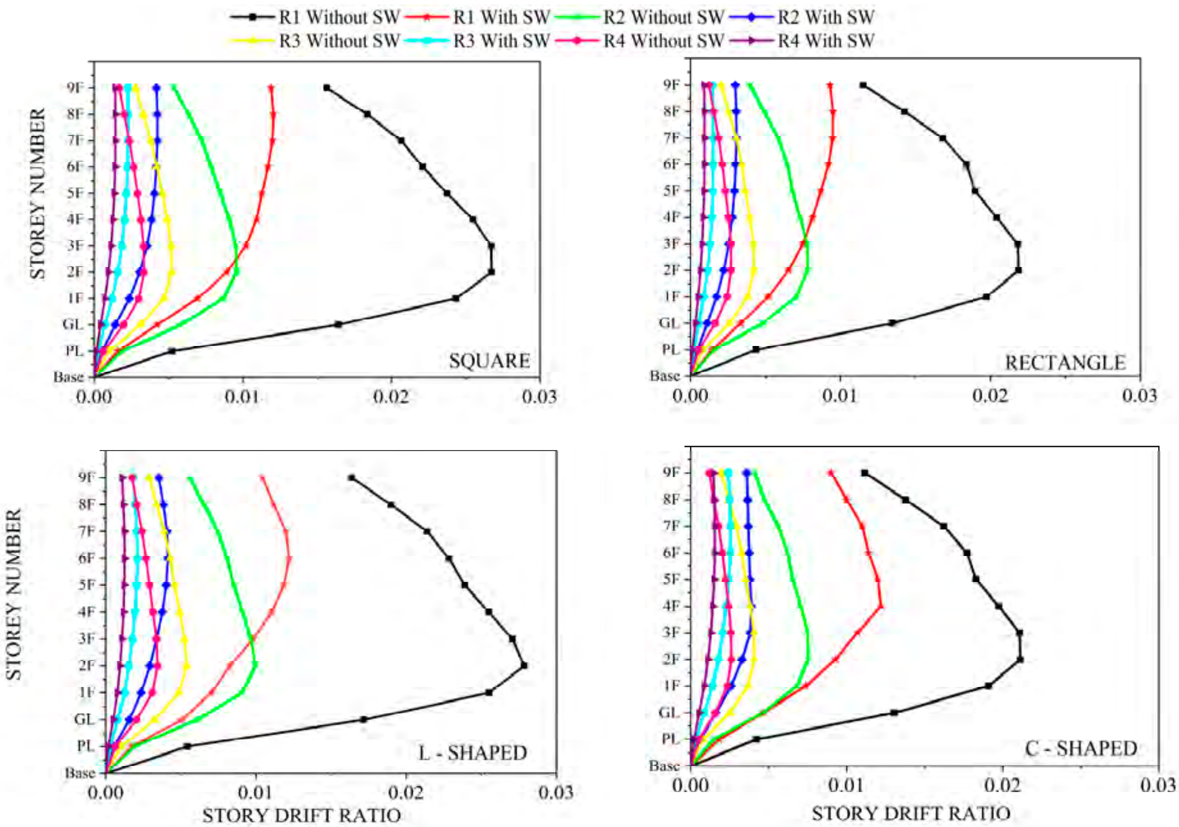
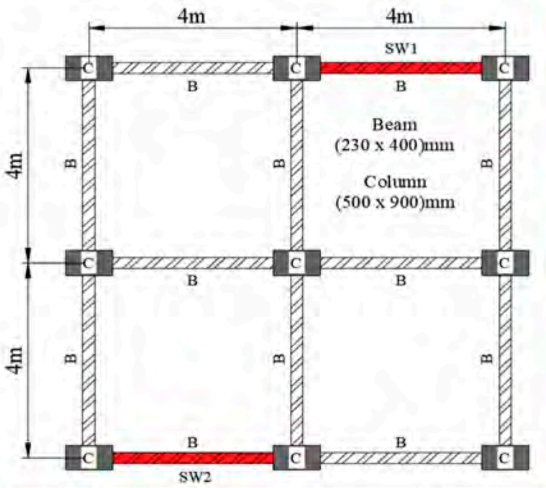


Figure 15. Storey drift ratio responses of regular and irregular-shaped buildings installed with shear walls with a thickness of 300 mm.

It was observed from Figure 16 that the shear stress values developed in the walls decreased with the increase in the thickness of the shear wall installed in the square-shaped buildings subjected to R3 blast cases. The values shown in Figure 16 are well within the acceptable limit of 0.17 f_{ck} = 0.17 × 30 = 5.1 MPa specified in Clause 32.4.2.1 of IS-456:2000. The study detailed a summary of shear stress distributions in the selected shear walls at the optimal locations. It noted, from Figure 17, that the shear stress values decreased by 43% when the shear wall thickness increased from 200 mm to 500 mm in the case of rectangular-shaped buildings under R3 blast cases. The shear stress values were reduced by 36% when the shear wall thickness increased from 200 mm to 500 mm under R3 blast cases when placed at optimal locations in L-shaped buildings (as shown in Figure 18). It is observed, from Figure 19, that the optimal placement of shear walls in C-shaped buildings resulted in a stress reduction of nearly 42% when the thickness increases from 200 mm to 500 mm. It is also observed from the dynamic analysis of shear walls that the stress values are within acceptable limits under R4 blast cases. However, the buildings subjected to blast load case R1 encountered notable magnitudes of shear stress, specifically at 11.96 MPa, 13.45 MPa, 23.50 MPa, and 17.05 MPa for square, rectangular, L, and C-shaped structures installed with 500 mm thick shear walls, respectively. This proves that the thickness of the shear wall is inadequate to bear these magnitudes of shear stresses and must be strengthened by increasing the thickness of the walls. The researchers plan to investigate techniques of retrofitting and strengthening the capacity of shear walls subjected to extreme blast loading as the future scope of work. However, the present study is restricted to evaluating the performance of the selected shear walls in mitigating different blast scenarios. Next, the energy dissipation ability of the selected shear walls is discussed under various blast conditions.

Energy dissipation in buildings is an important parameter in studying the building responses subjected to blast loads. It was observed, in the present study, that the energy dissipations of both regular and irregular buildings without a shear wall are generally lower as compared to buildings with shear walls when subjected to near and far blasts. In a near blast scenario, where the explosion occurs close to the building, the blast wave imparts a high-intensity pressure directly on the building's surfaces. Without a shear wall, the building's structural elements, such as columns and beams, bear the brunt of the blast load. These elements have insufficient capacity to dissipate energy effectively, resulting in higher stresses and potential failure. In a far blast scenario, where the explosion occurs at a distance from the building, the blast wave travels a longer distance before reaching the structure. Consequently, the energy dissipation requirements are different compared to a near-blast scenario. It was also observed from Figures 20 and 21 that an increase in the thickness of the shear walls from 200 mm to 500 mm results in an increase in energy dissipation for square, rectangular, L, and C-shaped buildings by approximately 18%, 30%, 28%, and 15%, respectively, subjected to near blast effects (R1 case). Thus, the presence of shear walls in a rectangular building improves its energy dissipation ability with the maximum amount, whereas installation of shear walls in a C-shaped building yields minimal improvement in its performance. In the case of far-occurring blasts, i.e., R3 cases, the energy dissipations of square, rectangular, L, and C-shaped buildings improved by 18%, 28%, 22%, and 12%, respectively. The presence of shear walls leads to an increase of nearly 41% in energy dissipation by installing 500 mm shear walls in rectangular buildings when compared with the rectangular buildings without shear walls subjected to R1 blast cases. The results observed for square, L, and C-shaped buildings show increases of nearly 25.4%, 40%, and 20%, respectively, when 500 mm shear walls are placed when subjected to R1 blast cases. This increase in shear wall thickness serves as an effective strategy to enhance the energy dissipation capacity of a building. It contributes to improved structural stiffness, enhanced damping characteristics, and more efficient load redistribution within the building. The energy dissipation results are aligned with the structural output results discussed earlier in the results and discussion section.



MPa	200mm	300mm	400mm	500mm
Max	−3.20	−2.35	−1.98	−1.69
	−2.34	−1.66	−1.50	−1.38
	−1.38	−0.93	−0.91	−0.90
	−0.69	−0.52	−0.50	−0.49
Min	0.40	0.30	0.09	0.01

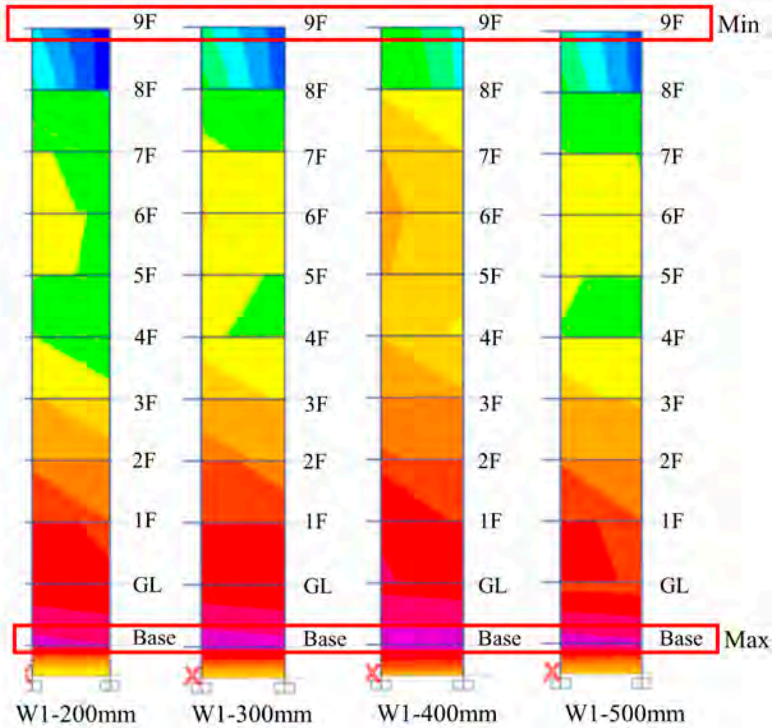
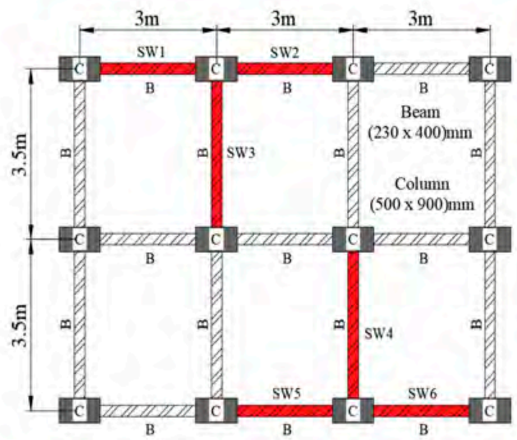


Figure 16. Shear stress variations at optimal locations in square buildings subjected to R3 blast cases.



MPa	200mm	300mm	400mm	500mm
Max	−3.19	−2.46	−2.10	−1.82
	−2.62	−2.09	−1.76	−1.47
	−1.80	−1.37	−1.14	−0.95
	−1.10	−0.88	−0.73	−0.48
Min	0.35	0.29	0.18	0.01

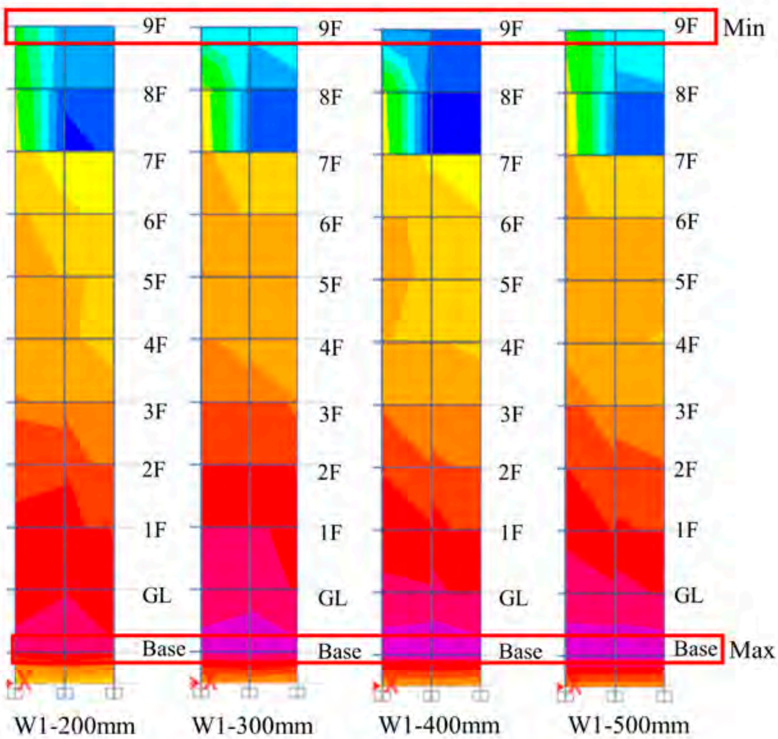
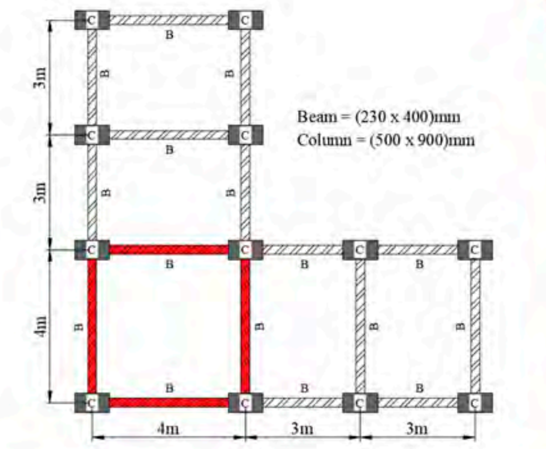


Figure 17. Shear stress variations at optimal locations in rectangular buildings subjected to R3 blast cases.



MPa	200mm	300mm	400mm	500mm
Max	−5.00	−4.62	−3.98	−3.20
	−4.69	−3.81	−2.93	−2.90
	−3.00	−2.37	−1.73	−1.60
	−1.38	−1.12	−0.86	−0.42
Min	0.60	0.52	0.41	0.35

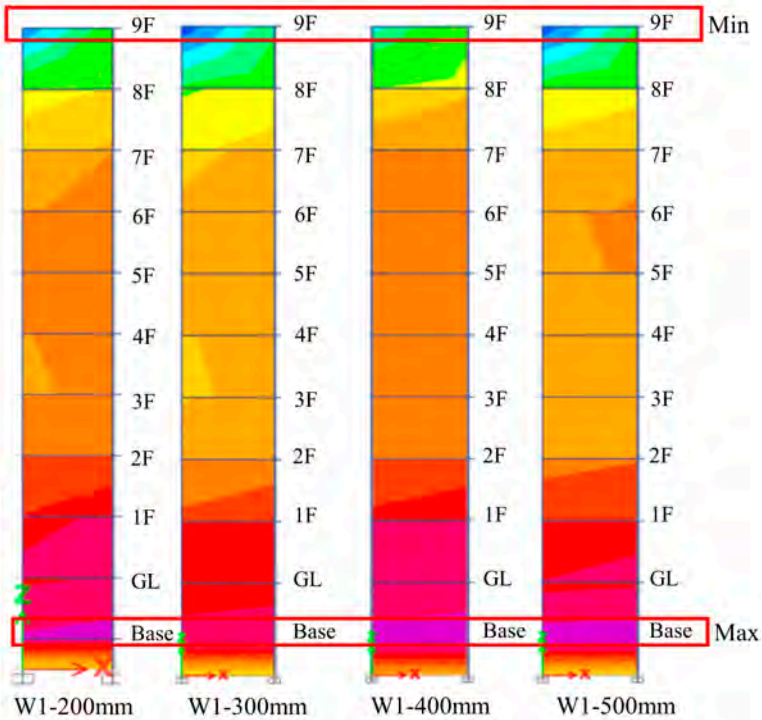
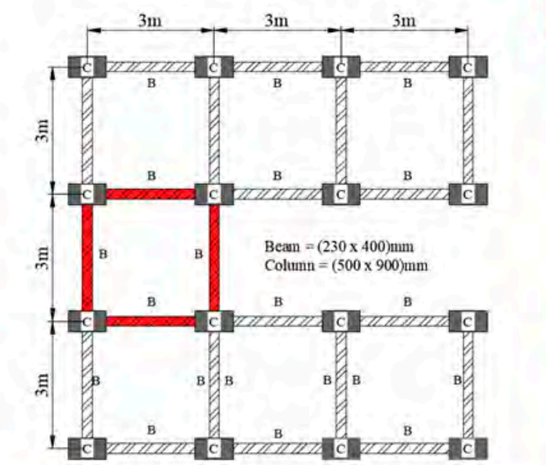


Figure 18. Shear stress variations at optimal locations in L-shaped buildings subjected to R3 blast cases.



MPa	200mm	300mm	400mm	500mm
Max	−4.32	−3.54	−2.90	−2.50
	−3.11	−2.59	−2.07	−1.79
	−1.60	−1.35	−1.10	−0.83
	−0.62	−0.50	−0.38	−0.42
Min	0.51	0.41	0.32	0.29

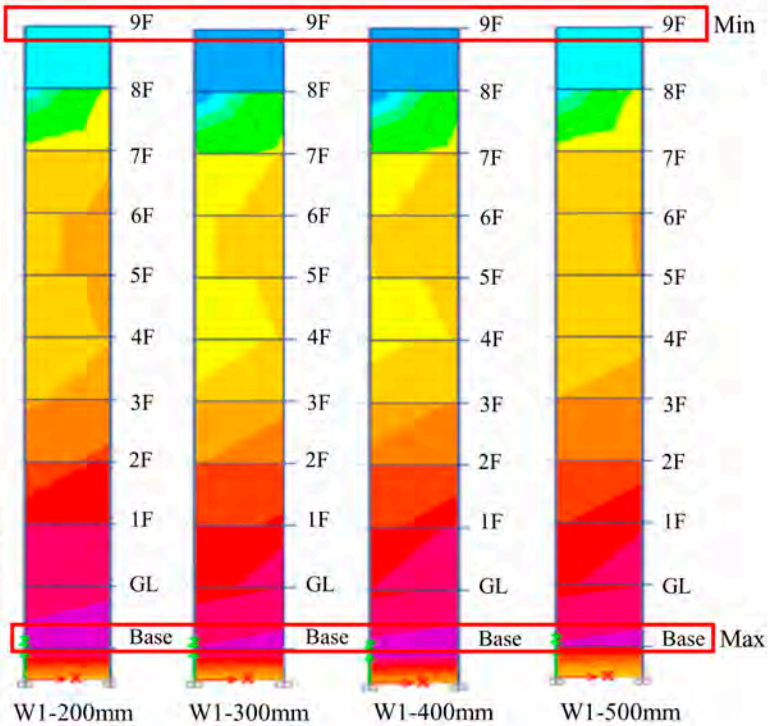


Figure 19. Shear stress variations at optimal locations in C-shaped buildings subjected to R3 blast cases.

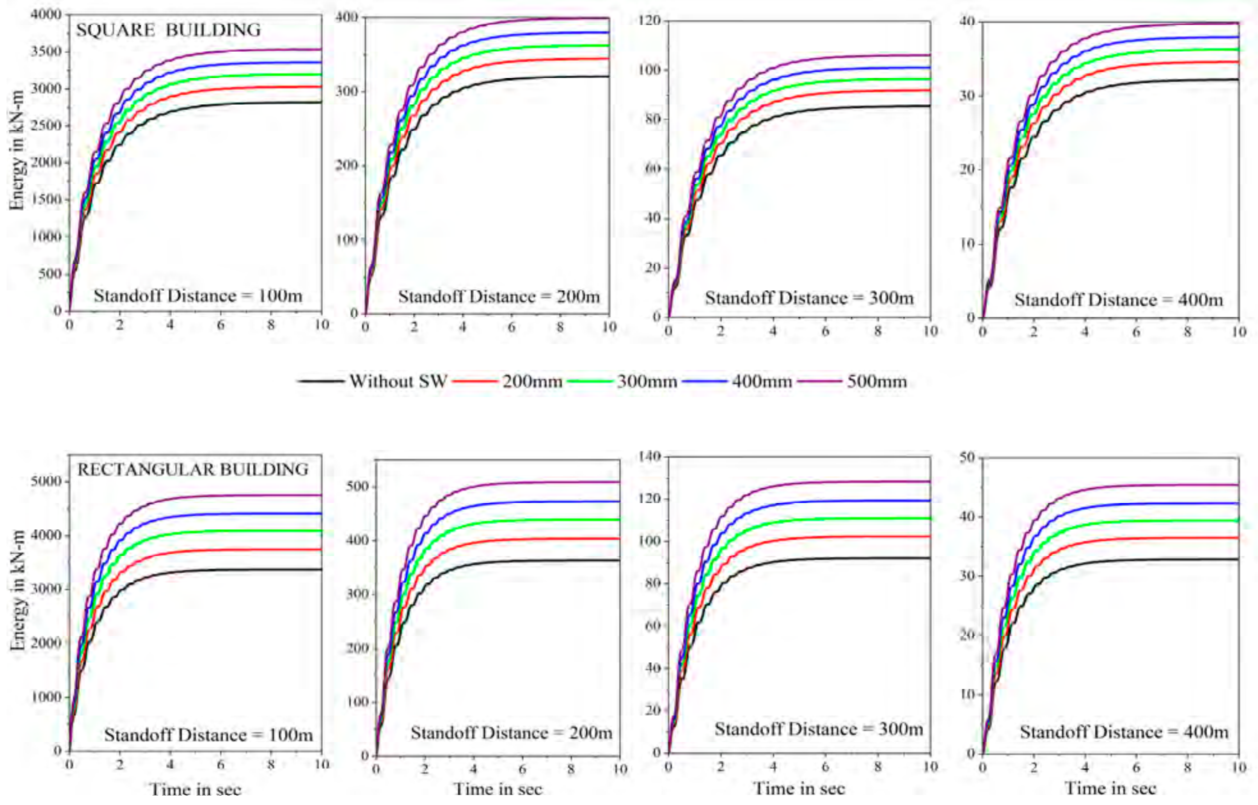


Figure 20. Energy dissipations by shear walls installed in regular buildings.

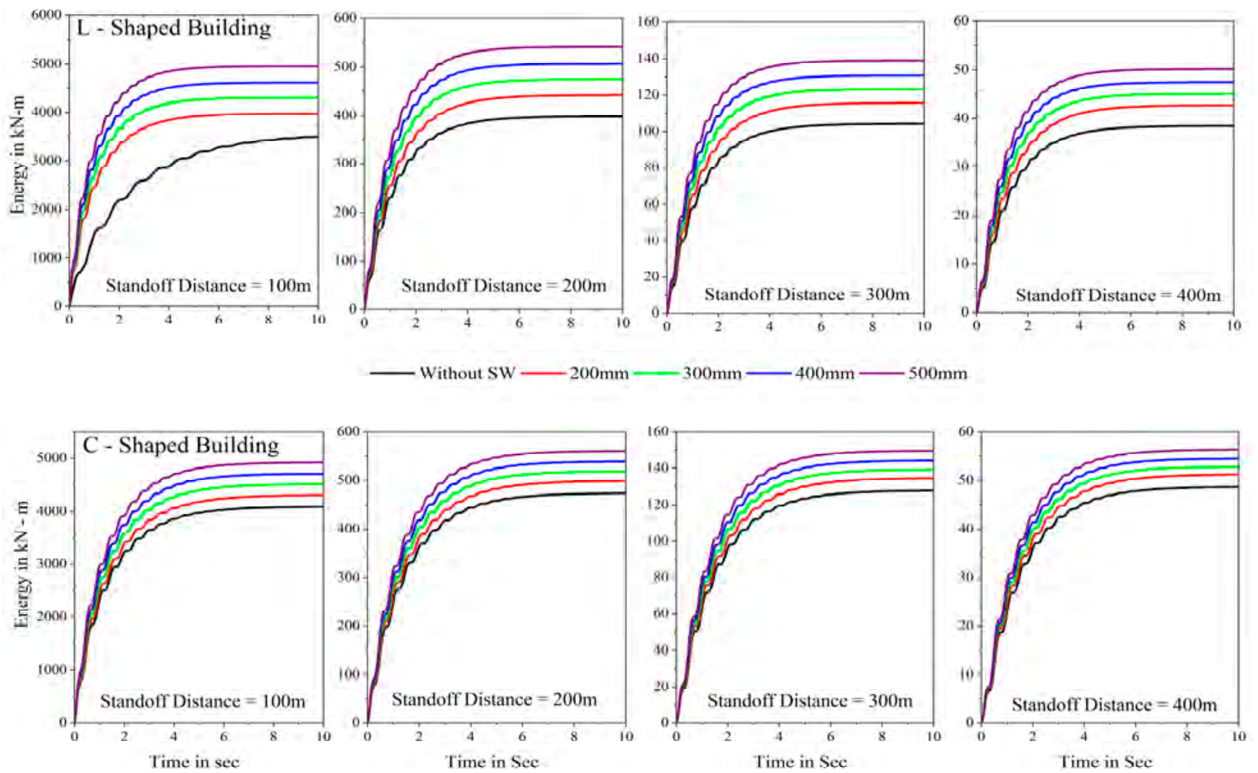


Figure 21. Energy dissipations by shear walls installed in the irregular buildings.

The study also included an Appendix A in the study highlighting the design and detailing of shear walls subjected to blast induced vibrations.

4. Conclusions

The present study proposes a blast retrofitting and strengthening technique in the form of installing shear walls in regular-shaped buildings (square and rectangular plan) and irregularly-shaped buildings (L-shaped and C-shaped plan) plagued with re-entrant corners as per the provisions of IS 1893:2016. The primary objective of this study is to assess the responses of reinforced buildings with and without geometric irregularity subjected to blast loadings. The blast load history is developed from the past available research considering a 50-ton blast charge occurring at varying standoff distances of 100 m (R1), 200 m (R2), 300 m (R3), and 400 m (R4). The study adopted a retrofitting strategy by installing shear walls at various locations to mitigate substantial failures and represents an overview of the optimum placement of shear walls to yield maximum reductions in structural responses. The thickness of the shear walls varied from 200 mm to 500 mm with a total of ten distinct placement positions investigated. The study concluded that the installation of shear walls provided valuable insights into understanding the structural behaviours of the selected buildings with and without shear walls subjected to blast-induced vibrations. The important conclusions derived from the detailed investigations conducted in the present study are summarized as follows:

1. The study summarized that nearly 87.5% (square), 80% (rectangular), 83.8% (L-shaped), and 76.1% (C-shaped) of structural members fail subjected to close-range blasts (R1) and strategies to protect these structures need to be investigated. The study also reported that in the case of far-occurring blasts (R4), there were 5.2% (square), 5.6% (rectangular), 12.98% (L-shaped), and 5.7% (C-shaped) failed structural members. It was revealed from the dynamic analysis that the square building performed poorly, with the highest percentage of member failures under blast effects, while the C-shaped buildings showed the best resistance. The installation of shear walls with a 500 mm thickness reduced the percentage failures of members by 26%, 31%, 29%, and 18% for square, rectangular, L-shaped, and C-shaped buildings.
2. The optimal placements of shear walls in square-shaped buildings were achieved in the S2 case with a shear wall area of 252 m^2. In rectangular-shaped buildings, the optimal case was R6 with an area of 598.5 m^2. In L-shaped buildings, the optimal case was L1 with an area of 504 m^2. For C-shaped buildings, the optimal case was C2 with an area of 378 m^2.
3. The installation of 500 mm thick shear walls reduced the peak storey displacement by 56%, 55.6%, 60%, and 55.6% subjected to blast cases R1, R2, R3, and R4, respectively. The shear forces and bending moments were reduced by 84–76%, 85–77%, 86–78%, and 87–79% under the R1, R2, R3, and R4 loading cases, respectively. In rectangular-shaped buildings, the maximum percentage reductions in displacement, acceleration, shear force, and bending moment were 59%,18%, 89%, and 95%, respectively, with 500 mm thick shear walls subjected to blasts at the R1 distance. For blasts at R3 and R4, these output parameters were reduced by 58%, 0%, 95%, 98%, 57%, 0%, 96% and 98%.
4. The irregular L-shaped buildings equipped with the 500 mm thick shear walls led to reductions in displacement, acceleration, shear, and bending moments in the ranges of 58–63%, 0–19%, 81–86%, and 82–85%, respectively, for all selected blast loads. For C-shaped buildings with shear walls, the reductions are in the ranges of 38–45%, 13–33%, 65–69%, and 61–65%, respectively. It is finally concluded that the shear walls installed in C-shaped buildings yield the least reduction in structural responses as compared to the other building shapes, and rectangular-shaped buildings installed with shear walls show the maximum reduction in responses.
5. The energy dissipations improved by 25.4%, 41%, 40%, and 20% for square, rectangular, L-shaped, and C-shaped buildings, respectively, when the 500 mm thick shear walls were installed and subjected to R1 blast cases. In the case of R3 blast cases, the energy dissipation efficiencies were improved by 24.1%, 39.3%, 33.5%, and 17.1% for the square, rectangular, L-shape, and C-shaped buildings, respectively.

6. The researchers suggest conducting experimental tests in the future to prove the effectiveness of shear walls subjected to blast-induced effects and evaluate various retrofitting and strengthening strategies to improve the performance of shear walls in mitigating the damages and reducing the shear stresses in the shear walls. The application of artificial intelligence and machine learning tools in optimizing the placement of shear walls will help in enhancing the performance of regular and irregular buildings subjected to various dynamic loadings.

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Data Availability Statement: The data used to support the findings of the study are included within the article.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Design of Shear Walls

A shear wall is a structural element typically composed of reinforced concrete or brick masonry material which is intended to resist lateral forces such as wind and seismic loads. Its purpose is to transfer these loads from the upper levels of a building to the foundation, thereby ensuring stability and preventing excessive horizontal displacements. This paper discussed various factors considered during the construction of shear walls, including their location, configuration, thickness, aspect ratio, design of shear reinforcement (horizontal), and design of longitudinal reinforcement (vertical) subjected to blast-induced vibrations. In India, the design of shear walls is carried out with the guidelines provided in IS 13920:2016. The paper follows these guidelines to design the shear walls installed in square, rectangular, L-shaped and C-shaped buildings subjected to blast-induced vibrations. Some of the parameters considered for the design of shear walls are discussed below:

1. General Requirements for a shear wall. The wall thickness (t_w) of 150 mm is the minimum thickness that must be provided as specified in Clause 9.1.2 of IS13920:2016. Shear walls with a thickness greater than 200 mm are required to have horizontal and vertical reinforcement installed in two separate layers or curtains as specified in Clause 9.1.5, IS 13920:2016. According to Clause 9.1.6 of IS 13920:2016, the maximum diameter of reinforcement must not exceed $(t_w)/10$. The minimum distance between reinforcements is not to exceed the smaller of $L_w/5$, 3 tw and 450 mm (Clause 9.1.7, IS 13920:2016). According to Clause 9.1.4, IS 13920:2016, the minimum longitudinal and transverse in-plane reinforcement in the shear walls shall be 0.25 per cent and 1 per cent of the respective gross sectional area of the wall.
2. Shear strength requirements. Consider the nominal shear stress in the wall (τ_v) (Clause 9.2.1, IS:13920:2016) given by Equation (A1) as:

$$\tau_v = \frac{V_u}{t_w x d_w} \tag{A1}$$

where V_u is the factored shear forces and d_w is the effective depth of the wall and its value is equal to $0.9L_w$ as per Clause 9.2.1, IS:13920:2016. To calculate the maximum shear stress from Table 20 of IS:456-2000, if $\tau_v < \tau_{cmax}$, the wall section is adequate for shear, assuming the minimum 0.25% steel in the wall in the vertical direction as well as in the horizontal direction. From Table 19 of IS 456-2000 for calculating design shear stress (τ_c), if $\tau_v > \tau_c$, the wall needs to be designed for shear reinforcement.

3. Horizontal and vertical shear reinforcement. Provide horizontal and vertical reinforcement as per IS 13920:2016, Clause 9.2.5 and Clause 9.2.6, which shall be uniformly distributed in the wall section and shall not be less than the horizontal reinforcement.
4. Check for flexural strength. With reference to Clause 9.3.1 of IS 13920:1993, the wall is checked against flexure as per IS 13920:2016 Clause 9.3.1.
5. Check for boundary elements. If the extreme fibre compressive stress in the wall, due to factored gravity loads plus factored earthquake loads, is greater than 0.2 f_{ck}, boundary elements are required in the shear wall design as per Clause 9.4.1 of IS 13920:2016.
6. Design of boundary elements. The boundary element is essentially treated as a column. The vertical reinforcement in the boundary elements shall not be less than 0.80% nor greater than 6%, as per Clause 9.4.4, IS 13920:2016. The axial compressive load on the boundary element, due to seismic forces, is $(M_u - M_{uv})/C_w$ (Clause 9.4.2, IS 13920:2016), where M_u is the factored design moment, M_{uv} is the moment of resistance provided by the distributed vertical reinforcement across the wall section, and C_w is the centre-to-centre distance between the boundary elements along the two vertical edges of the shear wall. The boundary element shall be assumed to behave as an axially loaded short column, as per Clause 9.4.2, IS 13920:2016. As per Clause 9.4.5, IS 13920:1993, boundary elements shall be provided with special confining reinforcement throughout their height, i.e., the area of special confining reinforcement.
7. Detailing of Shear Wall Reinforcement. The above-mentioned steps are followed to design the shear walls installed in square, rectangular, L-shaped, and C-shaped buildings with various thicknesses, and finally, the detailing of shear wall reinforcement is illustrated in the present study.

The blast forces obtained from the ETABS results are used to design the shear walls with different thicknesses subjected to R3 blast conditions. It is observed from Figure A1 that a shear wall with a thickness of 300 mm installed in the square building requires vertical reinforcement of two layers of 20 mm ϕ (where ϕ represents the diameter of the bar) at 65 mm c/c (centre to centre) along with horizontal reinforcement of two layers of 10 mm ϕ at 140 mm c/c. It is observed from the study that the compressive stress in the present condition is greater than 0.2 f_{ck}, where f_{ck} is the compressive strength of concrete, and, hence, the boundary element is provided, as per IS 13920:2016. The study provides two layers of # 9 (numbers) of 16 mm diameter at 75 mm c/c. In the case of rectangular buildings, the shear wall requires vertical reinforcement at 100 mm c/c, horizontal reinforcement at 110 mm c/c, and boundary elements having # 6 of 16 mm diameter at 50 mm c/c (as shown in Figure A2). Thus, in the case of rectangular buildings, the amount of steel required to design the shear wall has reduced, as compared to square buildings subjected to R3 blast cases due to the increase in the gross area of shear walls in rectangular buildings as compared to square-shaped buildings. For L-shaped buildings, the shear wall requires vertical reinforcement at 80 mm c/c, horizontal reinforcement at 165 mm c/c, and boundary elements having # 8 of 16 mm diameter at 50 mm c/c (as shown in Figure A3). In the case of C-shaped buildings, vertical reinforcement at 100 mm c/c, horizontal reinforcement at 250 mm c/c, and boundary elements having # 5 of 16 mm diameter at 75 mm c/c (as shown in Figure A4). It must be noted that the selected buildings with shear walls require two layers of horizontal and vertical reinforcement. Thus, the total reinforcing steel areas required in all shear walls with the 300 mm thickness at optimum locations in square, rectangular, C-shaped, and L-shaped buildings to safely withstand the blast case R3 are found to be 72,037 mm^2, 111,220 mm^2, 121,941 mm^2, and 111,039 mm^2. Table 10 highlights the design results obtained at the optimum placements of shear walls for various thicknesses under R3 blast conditions following the above-mentioned steps to design the shear walls. It is observed from Table A1 that the steel required to safeguard the various selected buildings subjected to blast loading follows the same pattern as illustrated in Figures 1–4. It is also observed that the shear walls installed in rectangular buildings require the minimum reinforcement to safeguard the structure against R3 blast cases, whereas the maximum reinforcement in shear walls is required for L-shaped buildings. This conclusion is made after considering the gross areas of shear walls and their reinforcement requirement. Thus, the present study provides extensive research on the performances of shear walls in mitigating the blast effects of regular and irregular buildings along with the reinforcement detailing of these structural elements. Finally, some important conclusions drawn from this study are reported and highlighted in the next section.

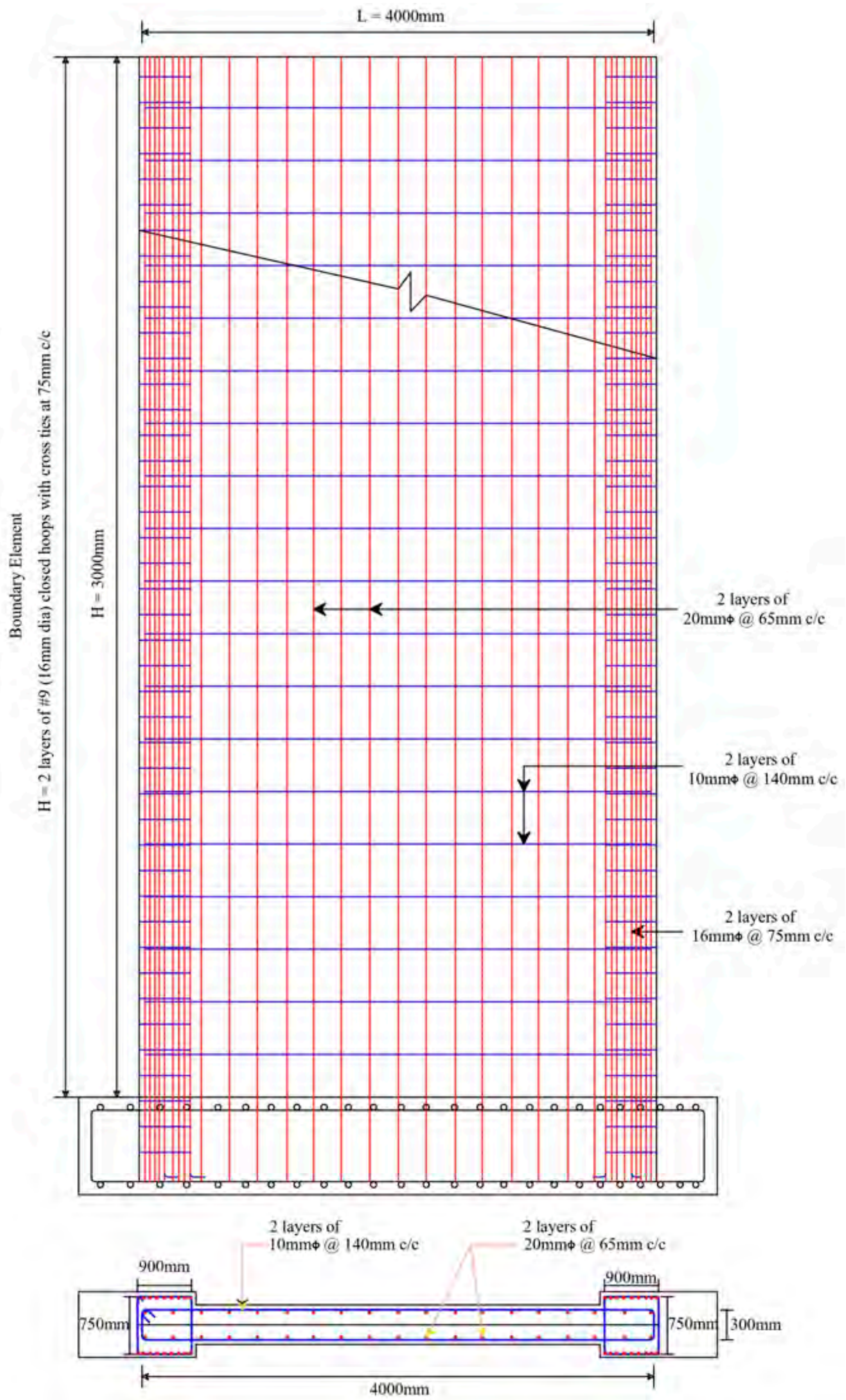

Figure A1. Reinforcement detailing of the 300 mm thick shear wall subjected to R3 blast cases (square-shaped building).

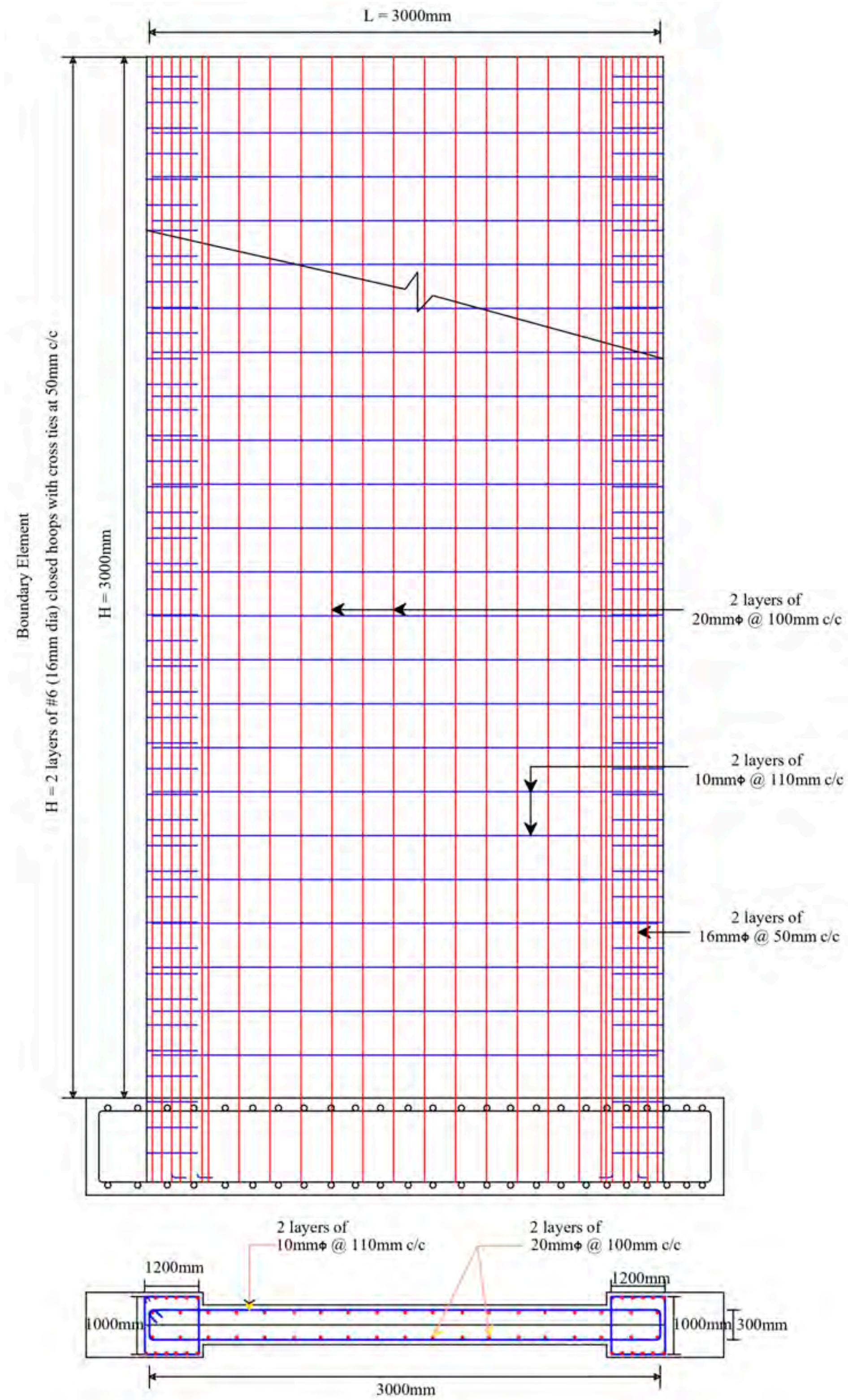

Figure A2. Reinforcement detailing of the 300 mm thick shear wall subjected to R3 blast cases (rectangular-shaped building).

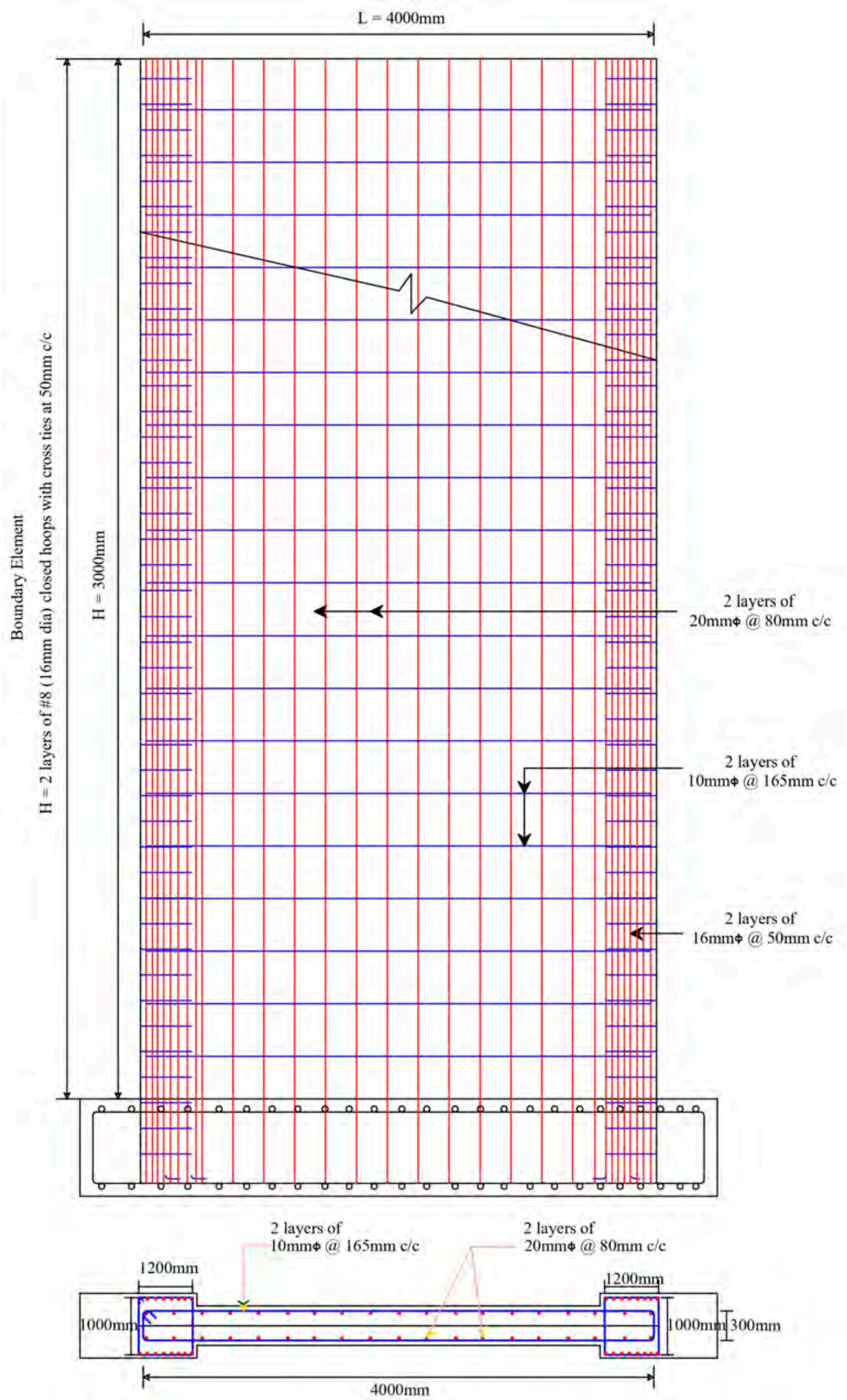

Figure A3. Reinforcement detailing of the 300 mm thick shear wall subjected to R3 blast cases (L-shaped building).

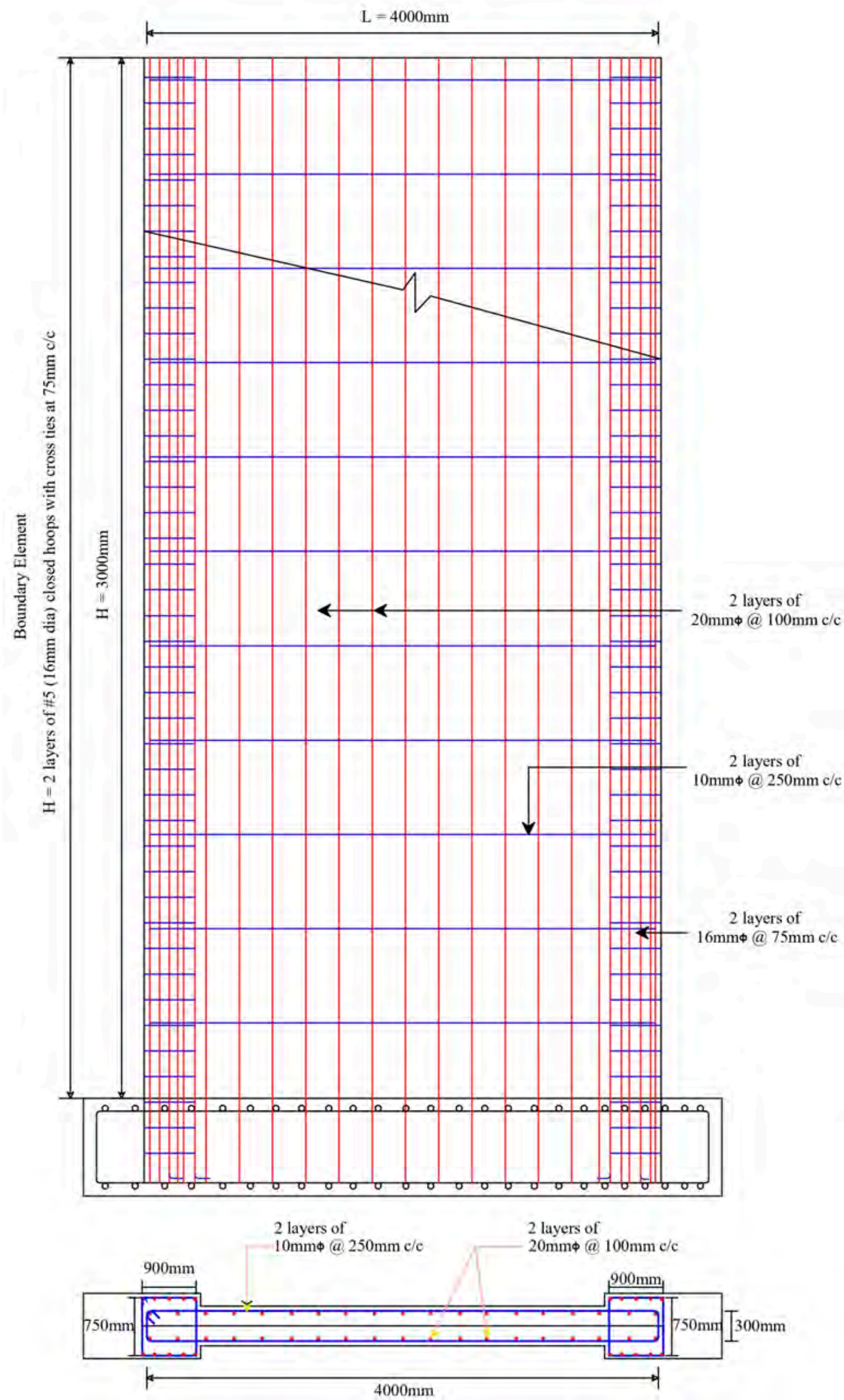

Figure A4. Reinforcement detailing of the 300 mm thick shear wall subjected to R3 blast cases (C-shaped building).

Table A1. Structural detailing of reinforced concrete shear walls with varying thicknesses installed in regular and irregular buildings subjected to R3 blast cases.

Design Parameters	Square-Shaped Building			Rectangular-Shaped Building			L-Shaped Building			C-Shaped Building		
	200 mm	400 mm	500 mm	200 mm	400 mm	500 mm	200 mm	40 0mm	500 mm	200 mm	400 mm	500mm
Length in mm	8000	8000	8000	19,000	19,000	19,000	16,000	16,000	16,000	12,000	12,000	12,000
f_{ck} in MPa	30	30	30	30	30	30	30	30	30	30	30	30
f_y in MPa	415	415	415	415	415	415	415	415	415	415	415	415
Flexural Design												
M_{u2} in kN-m	3003	4135	4494	−5480	−8820	−9989	7298	7765	−7462	33,105	60,004	71,989
M_{u3} in kN-m	−20,905	−37,704	−45,484	−40,568	−76,803	−93,739	−53,308	−98,527	−119,036	−166.2	−202.4	−209
Req. Reinforcement Area in mm^2	50,580	89,760	102,265	78,100	138,500	164,400	86,541	153,511	184,293	68,099	118,800	138,600
Number of bars	80	143	163	125	220	260	137	244	293	108	190	221
Flexural Reinforcement	20 mm ϕ @ 90 mm c/c	20 mm ϕ @ 50 mm c/c	20 mm ϕ @ 40 mm c/c	20 mm ϕ @ 150 mm c/c	20 mm ϕ @ 80 mm c/c	20 mm ϕ @ 70 mm c/c	20 mm ϕ @ 110 mm c/c	20 mm ϕ @ 60 mm c/c	20 mm ϕ @ 50 mm c/c	20 mm ϕ @ 110 mm c/c	20 mm ϕ @ 60 mm c/c	20mm ϕ @ 50mm c/c
Shear Design												
P_u in kN	−426	−580	−623	−670	−1134	−1304	−8925	−16,857	−20,450	−7118	−13,285	−16,034
M_u in kN-m	7575	13,777	16,537	14,782	28,376	34,360	5505	−15,204	13,756	−5170	6686	8053
V_u in kN	−1754	−2360	2606	−2689	−3943	−4381	−3128	−4612	−5047	−1810	−2536	−2735
Shear Reinforce Area in mm^2/m	1135	1286	1328	1218	1615	1716	871	1001	3450	500	2200	2274
Number of bars	8	9	9	8	11	11	6	7	22	4	14	15
Shear Reinforcement	10 mm ϕ @ 140 mm c/c	10 mm ϕ @ 125 mm c/c	10 mm ϕ @ 125 mm c/c	10 mm ϕ @ 140 mm c/c	10 mm ϕ @ 100 mm c/c	10 mm ϕ @ 100 mm c/c	10 mm ϕ @ 200 mm c/c	10 mm ϕ @ 160 mm c/c	10 mm ϕ @ 40 mm c/c	10 mm ϕ @ 300 mm c/c	10 mm ϕ @ 75 mm c/c	10mm ϕ @ 70mm c/c
Boundary Element (BE) Design (IS13920 clause 10.4.1) (stress > 0.2f_{ck})												
Compressive Stress (MPa)	17.55	16.3	16.47	15.24	15.58	14.39	15.2	13.47	14.08	16.56	15.25	13.56
Edge length in m	(1 × 0.8)	(1 × 0.8)	(1 × 0.75)	(1.3 × 1)	(1.2 × 1)	(1.3 × 1)	(1.2 × 0.9)	(1.2 × 1.2)	(1 × 1)	(0.9 × 0.6)	(1 × 0.8)	(1 × 0.8)
Reinforced area (mm^2)	8000	8000	7500	13,000	12,000	13,000	10,800	14,400	10,000	5400	8000	8000
Number of bars	20	20	19	32	30	32	27	36	24	13	20	20
BE Reinforcement	16 mm ϕ @ 75 mm c/c	16 mm ϕ @ 75 mm c/c	16 mm ϕ @ 75 mm c/c	16 mm ϕ @ 50 mm c/c	16 mm ϕ @ 50 mm c/c	16 mm ϕ @ 50 mm c/c	16 mm ϕ @ 60 mm c/c	16 mm ϕ @ 50 mm c/c	16 mm ϕ @ 75 mm c/c	16 mm ϕ @ 100 mm c/c	16 mm ϕ @ 75 mm c/c	16mm ϕ @ 75mm c/c

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