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Blast Mitigations of Low-Rise Structure by Using Control Devices

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ABSTRACT

Designer of military and high-security facilities, planner, architects and engineers throughout the world are much concerned against a blast load on structures. Blast load is a human hazard occurring in the world, due to terrorist, chemical explosives, mining area, an accident, and so on. Blast load is an unpredictable load occurring. The blast load occurs in a few seconds. The blast load does not only lead to structural but also take the life of occupations. In this study five – storey unsymmetrical structures exposed to blast load are considered. The three different control devices are considered such as cladding material, base isolation with lead rubber bearing (LRB) and MR Damper. Cladding material will absorb energy after the severe pressure release from the blast and then transfer less amount of energy to the structures. Base isolations with lead rubber bearing not only absorb energy but also increase the stiffness of the structure. Among the different devices' MR Damper plays a vital role reduce the considerable amount of responses.

1. Introduction

The technology is developed rapidly guides to the construction of structures Nevertheless, the incidents of the blast, mine explosions, and terrorist explosives are the probable failures of

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structures in urban areas [1]. The mathematical expression is developed for the structural model exposed to air blast. The explosives such as nuclear, conventional weapons, chemical explosives are considered by several researchers [2,3]. Several researchers such as explosive blast in confined and unconfined environments are carried out at The University of Adelaide. The various members such as ultra-high-performance concrete slabs, beams, and columns are exposed to blast load can be protected by using foam material [4].

To dissipate the energy of structure exposed to blast load aluminum foam is used. The beam is sandwiched by aluminum foam is analyzed and studies by several researchers [5–9]. It is a time consuming process, expensive, and tedious effort to retrofit the structure against the blast load. - In order to overcome this limitation the low density, light-weight material, excellent energy absorption capacity can be considered using metallic foam [10–12].An SDOF system exposed to blast load can be controlled by Load Cladding Structure (LCS). LCS model plays a vital role reduce the response of the structure against blast load [10,11]. Advanced technique of performance-based design procedure for a novel friction based cladding connection is used for connecting the structure with cladding and rubber. The design parameters including stiffness, damping, and design of rubber are taken from the study by Liang et al. to resist high blast load [12].

Base isolation technique is another method of reducing the response of the structure exposed to the dynamic, impulse load. Base isolation technique plays a crucial task to -mitigate the damage effects of the earthquake by isolating the system at the ground level. It also helps the structure to withstand under the action of vertical load coming from the weight of the superstructure and also provide the lateral rigidity against the accidental and natural loads such as earthquake and blast load [13].Traditional isolation bearings method for designing the isolation of structures many codes are available [14,15].An optimum value of bearing yield strength for different structural parameters are derived and the analytical response of base-isolated multi-storey building near the fault zones are considered for exposing to the earthquake load [16].The relationship between axial load and bearing response at far and near fault zone of earthquake load is controlled by Lead rubber bearing isolation system [17].The-five-storey structure exposed to blast load and earthquake load response can be controlled by using base isolation with supplementary devices like tuned mass damper [18].

Many researchers have carried out the non-linear analysis of a structure which was exposed to the dynamic load. They found that the structural responses can be controlled using semi-active damper like MR damper. MR damper is a highly reliable, low cost, consumes low battery element. Many algorithm have been developed for investigation of the nonlinear behavior of MR damper like Bingham plastic, modified Bingham model, Bouc Wen model, Dahl model, and so on [19–27].

Several studies have been conducted to determine the safety and reliability of the system [21–24]. However, in order to demonstrate a safe response limits of the protective structures – subjected to the area given blast load. Pressure–Impulse (PI) are commonly used. The analytical procedure of calculating pressure impulse curve is determined for elastic, plastic, strain hardening material of structure [25]. A new method of obtaining pressure impulse diagram is utilized using energy method [26]. Normalized pressure impulse curve method avoids the finite element method because it consumes time process and it is tedious method [27].

The present study is carried out for a low rise structure (five-storeys) exposed to the blast load. The responses are calculated in terms of displacement, velocity, acceleration, pressure-impulse diagram, normalized pressure impulse curve, and storey drift. The response can be controlled using three different methods like cladding, base isolation and M R damper.

2. Five storey modeling exposed to blast load

Fig 1 shows the plan of unsymmetrical both in plan and elevations of a five-storey structures. The width and length of the structures are 60m and 100m.The parameters used in unsymmetrical structures are shown in Table 1. The load acting on five structures are shown in Fig. 2. The Table 2 shows the dynamic properties of the structural system.

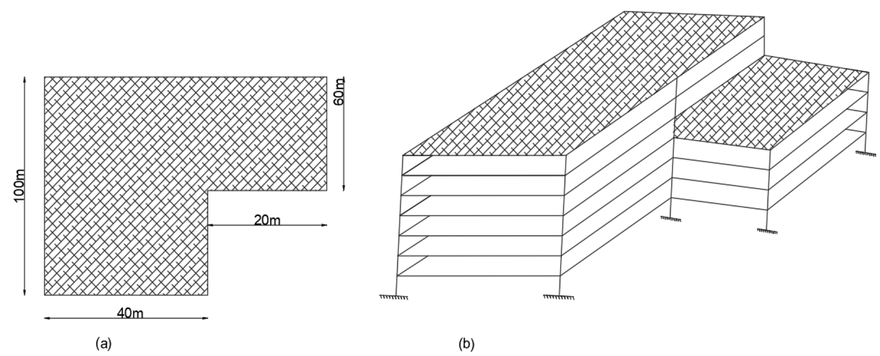


Fig. 1. Plan and elevations of unsymmetrical five story structures.

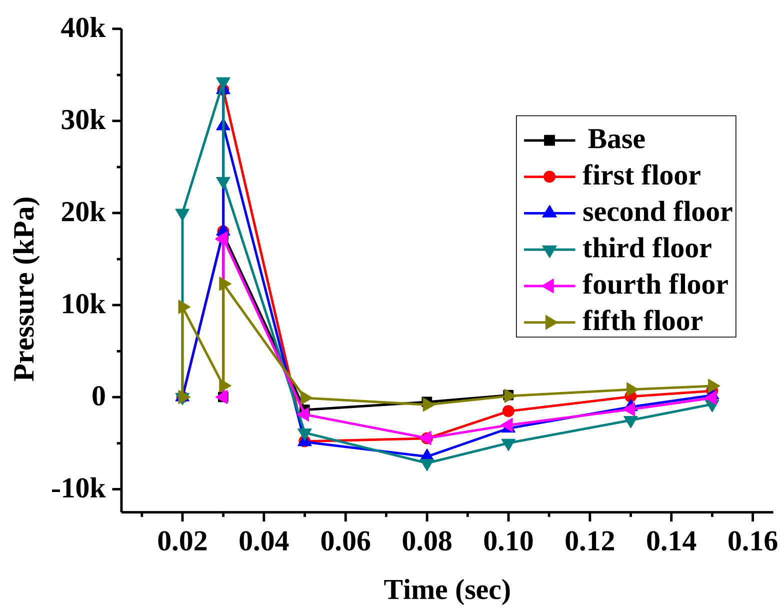


Fig. 2. Load acting on five storey structures.

Table 1
Input parameters of a structure.

Slno	Parameter of the Structure	Symbol	Magnitude
1	Weight of the blast	W	1000 TNT
2	Height of each floor	H	3m
3	Range	R	30 m
4	Scaled distance	Z	3 m/kg$^{1/3}$
5	Area of each floor	A	60 m^2

The following equations are used to determine the peak load of the structure subjected to blast load

$$R_h=\sqrt{(R_G{}^2+h^2)} \tag{1}$$

Where R_h - Standoff distance, R_G- Scaled standoff distance, h-height of each floor

$$Z_h = {}^{R_h}\!/_{W^{1/3}} \tag{2}$$

$$P_{so} = \frac{1.772}{Z_h{}^3} - \frac{114}{Z_h{}^2} + \frac{108}{Z_h} \tag{3}$$

$$t_o = W^{1/3} 10^{[-2.75+0.27\log(Z_h)]} \tag{4}$$

$$U = a_o . \sqrt{\frac{6P_{so}+7P_o}{7P_o}} \tag{5}$$

$$t_A = \frac{R_h}{U} \tag{6}$$

$$P_r = C_r\, P_{so} \tag{7}$$

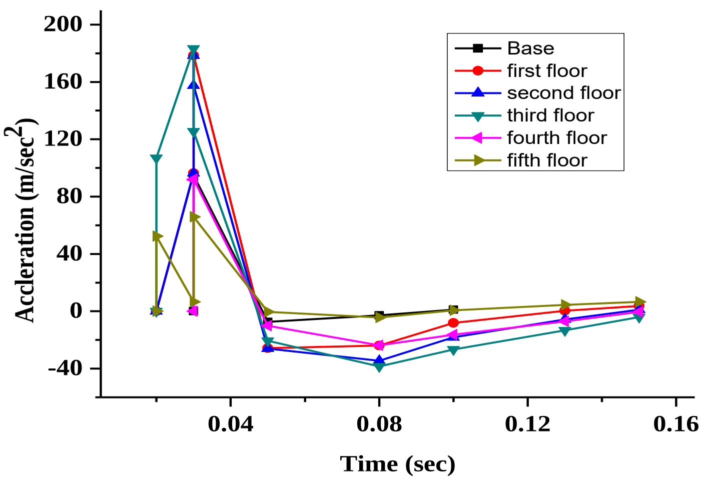
$$C_r = 3\left(\sqrt[4]{\frac{P_S}{101}}\right) \tag{8}$$

Where Z_h – Scaled standoff distance

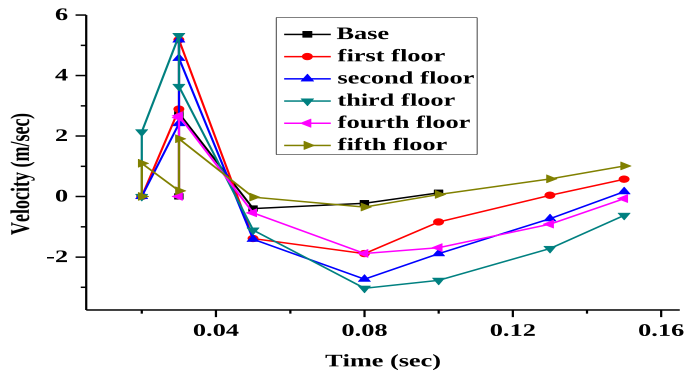
$$P(t) = P_o + P_r\left(1-\frac{t}{t_o}\right)\exp(-\gamma\frac{t}{t_o}) \tag{9}$$

$$\gamma = Z_h{}^2\text{-}3.7Z_h\text{+}4.2 \tag{10}$$

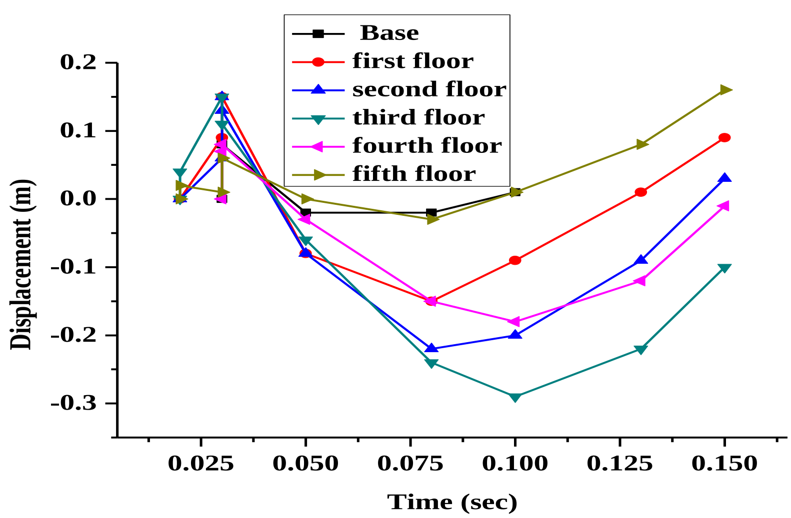
Where P(t)=pressure in time; γ=parameter controlling the rate wave amplitude, Pr=peak reflected over pressure, P_{so}=peak incident over pressure, t_A= time of arrival, t_o=positive time duration, U= wave velocity, P_o= ambient air pressure, a_o= speed of sound in air335 m/sec.



(a) Accelerations of a five storey structural system



(b) Velocity of a five-storey structural system



(c) Displacements of a five storey structural systems

Fig. 3. Response of five storey structural system.

Table 2
Dynamic properties of a structure.

Floor level	Mass at each storey (kg)	Stiffness at each storey (kN/m)	Co-efficient of damping (kg/s)
Base	m_0=61,200	k_0=2129.8	c_0=69,938
First	m_1=53,073	k_1=101,196	c_1=348,140
Second	m_2=53,073	k_2=87,279	c_2=301,380
Third	m_3=53,073	k_3=85,863	c_3=296,180
Fourth	m_4=53,073	k_4=74,862	c_4=259,810
Fifth	m_5=53,073	k_5=57,177	c_5=197,450

Fig 3 shows the maximum response occurs at the third floor where accelerations of 160 m/sec^2, velocity 5.8 m/sec and displacement 0.1 m at 0.03sec respectively. The minimum response occurs at third floor that is accelerations of 70 m/sec^2, velocity 2 m/sec and displacement 0.05 m at 0.038 sec respectively.

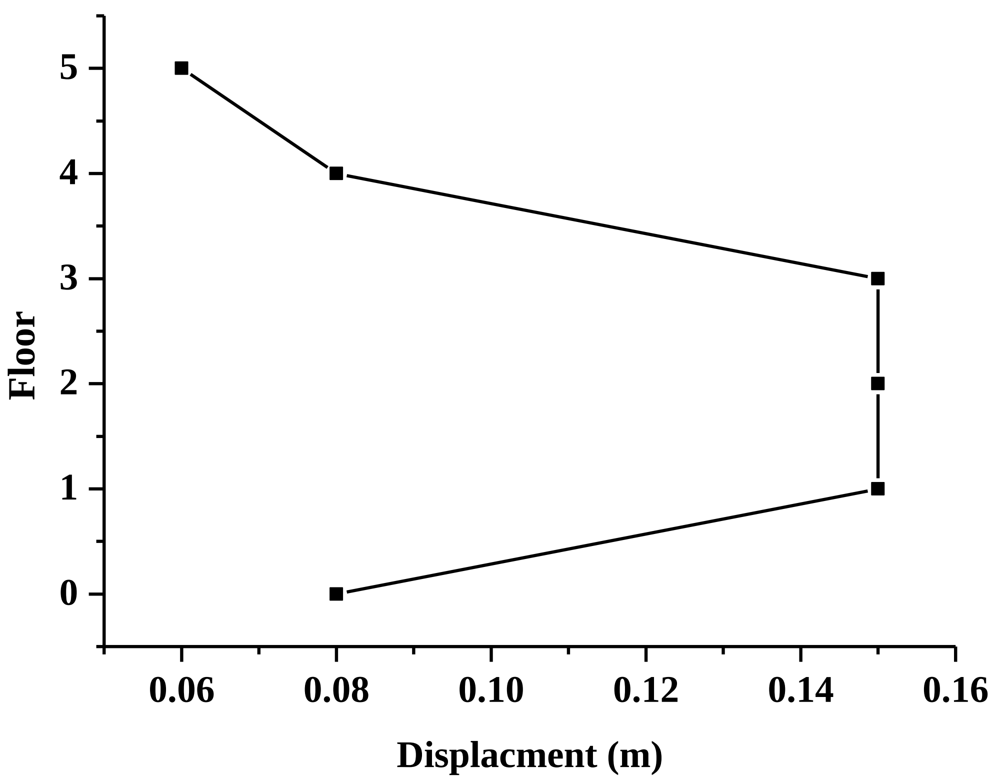
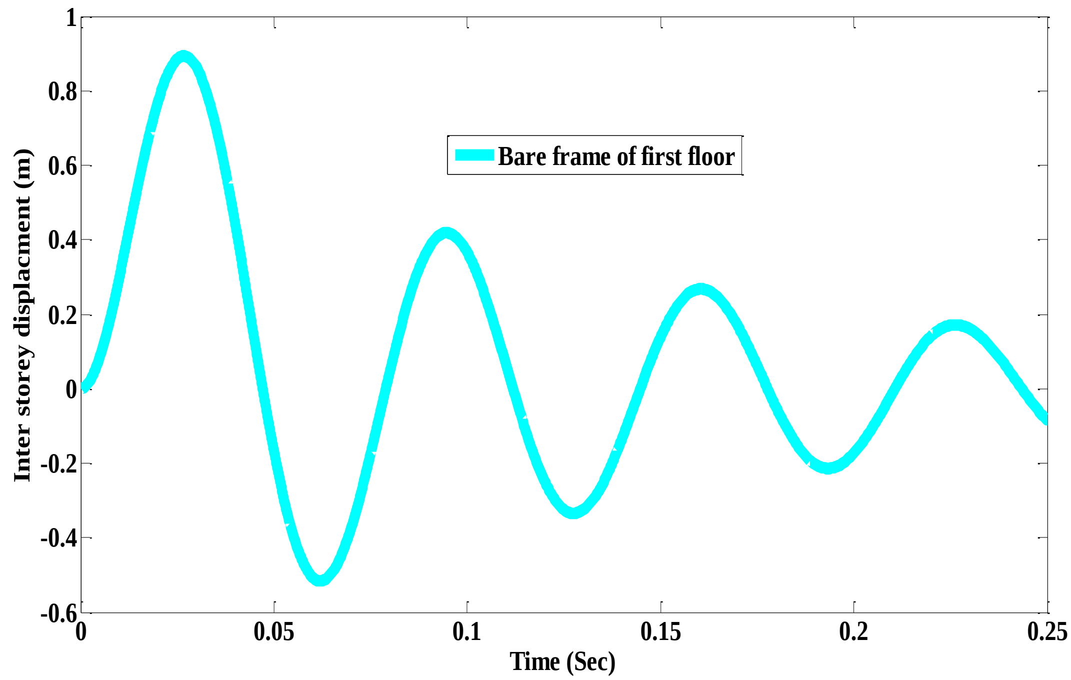
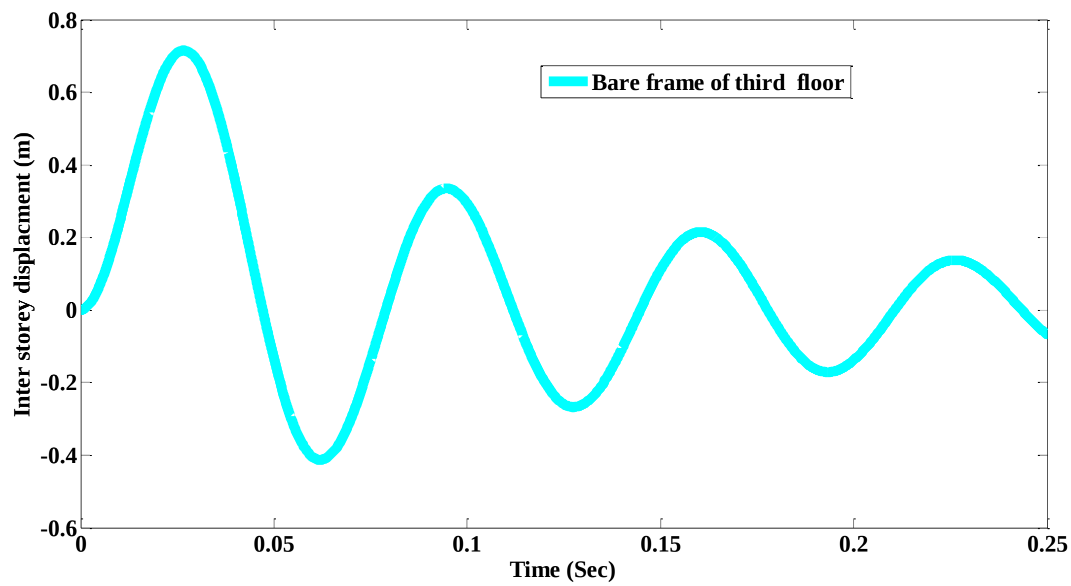


Fig. 4. Storey drift of five storey structural system.



(a) Inter storey displacement of first floor



(b). Inter storey displacement of third floor

Fig. 5. Inter storey displacement of a structural system.

Fig 4. Shows the storey drift of the structural system, the maximum storey drift 0.012 occurs at the second floor and minimum drift 0.005 occurs at third and fourth floor.fig 5 shows the inter storey displacement of first and third floor.

3. Controlling of response of five storey structural system by various devices

There are various devices like cladding, base isolation and MR damper used to control the response of structural system.

3.1. Cladding material

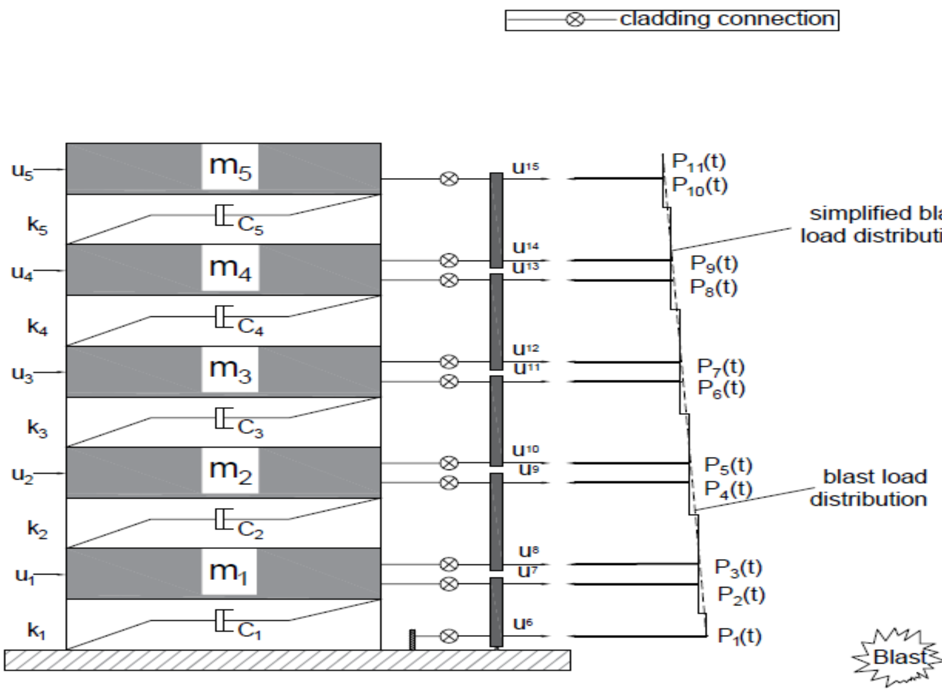


Fig. 6. Simulated structure by using cladding material [12].

The following equations represents the equations of motion of a 5 storey structure subjected to blast load

$$m_c\ddot{u}_c + c_c\dot{u}_c + k_c u_c + F_c = F_m\left(1 - \frac{t}{t_{blast}}\right) \qquad \text{for } 0<t<t_{blast} \tag{11}$$

$$m_c\ddot{u}_c + c_c\dot{u}_c + k_c u_c + F_c = 0 \qquad \text{for } t>t_{blast} \tag{12}$$

Where u_c, $\dot{u}_c$ and $\ddot{u}_c$ are the displacement, velocity and acceleration of the cladding material. F_c are the friction force, F_m is the peak blast force.

3.2. Base isolation

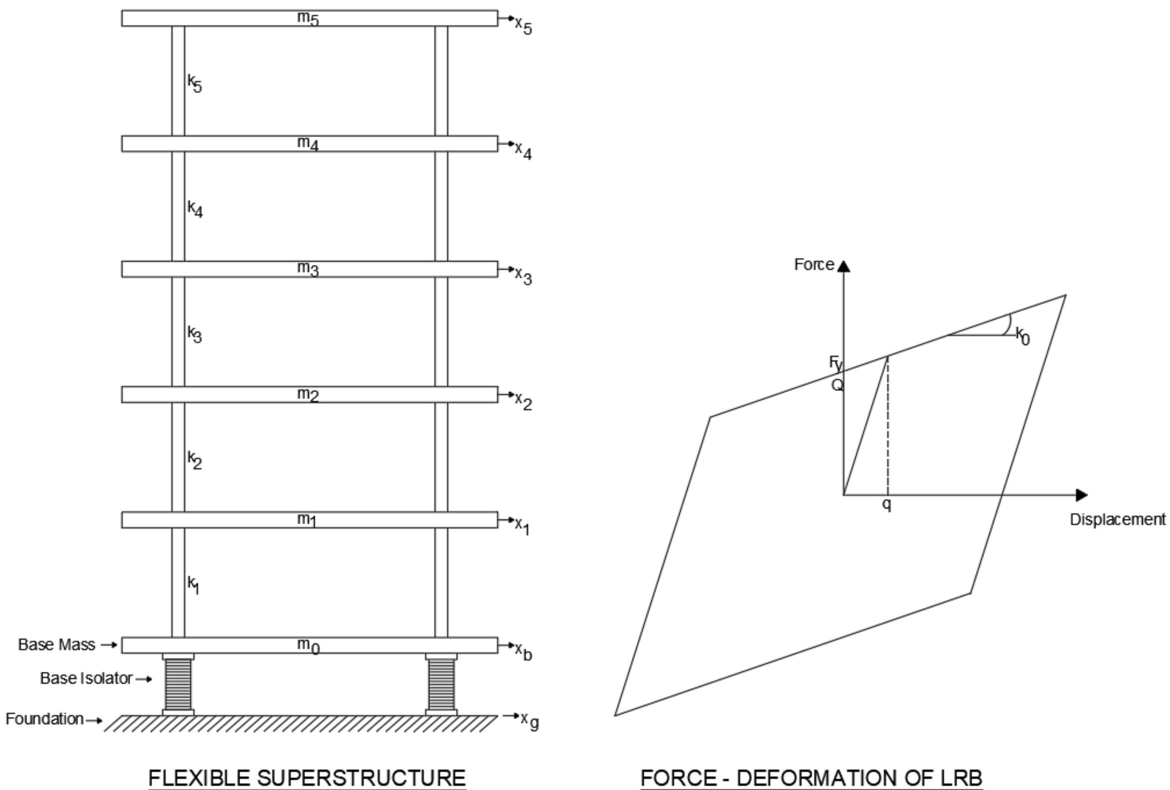


Fig. 7. Reduction of response by using Base isolation [16].

The matrix form of 5 storey structures governing equation is

$$[M]\{\ddot{x}\} + [C]\{\dot{x}\} + [K]\{x\} = -[M]\{I\}(\ddot{x_b}) \tag{13}$$

Where the mass, stiffness and damping matrices are [M],[K] and [C] of the fixed base structure in the order 5 x 5;

The displacement vector of the super structure is $\{x\} = \{x_1, x_2, x_3, x_4, x_5\}$. The lateral displacement of the j^{th} floor relative to the base mass is x_j (j=1,2,3,4,5); The influence coefficient vector is $\{I\}=\{1,2,3,4\ \&5\}^T$; $\ddot{x_b}$ is the base relative to ground pressure.

$$m_b\ddot{x}_b + c_b\dot{x_b} + F_b - c_1\dot{x_b} - k_1x_1 = -m_b\ddot{x_g} \tag{14}$$

Where m_b =mass of the base raft; F_b =Restoring force mobilized in the LRB (shown in Figure 4 (b); c_b =Viscous damping of the rubber; k_1, c_1- Stiffness and viscous damping of the first storey superstructure;

$$T_b = 2\pi\sqrt{\frac{M}{k_b}} \tag{15}$$

$$F_b = K_{eff}x_b + C_{eff}\dot{x_b} \tag{16}$$

$C_{eff}= 2\beta_{eff} M\omega_{eff}$ (17)

$K_{eff} = K_b+\frac{Q}{D}$ (18)

$\beta_{eff} = \frac{4Q(D-q)}{2\pi D^2 K_{eff}}$ (19)

Where, the total mass of the isolated building is $M=(m_b +\sum_j^N m_j)$ and mass of the j^{th}floor

is m_j. $k_b$is the post yield stiffness, Q is related to yield strength of the lead core ,K_{eff} is the linear effective stiffness, β_{eff} is the effective viscous damping ratio.

3.3. MR damper

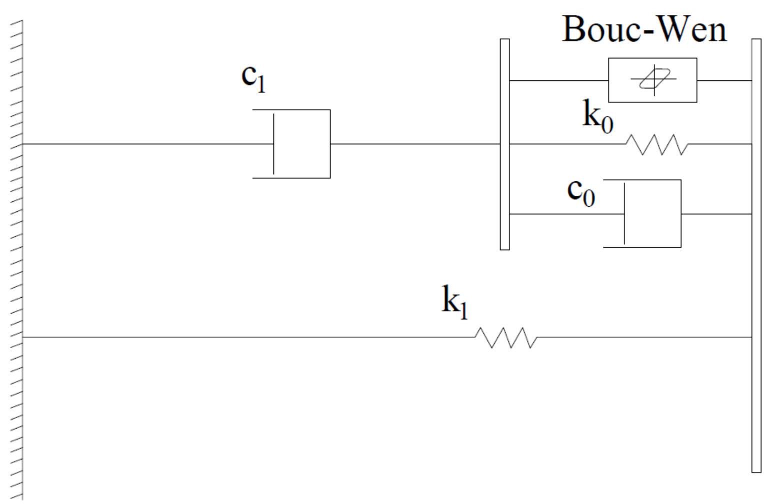


Fig. 8. Bouc-Wen model.

The governing equations of force predicting model are shown in Fig.15 are

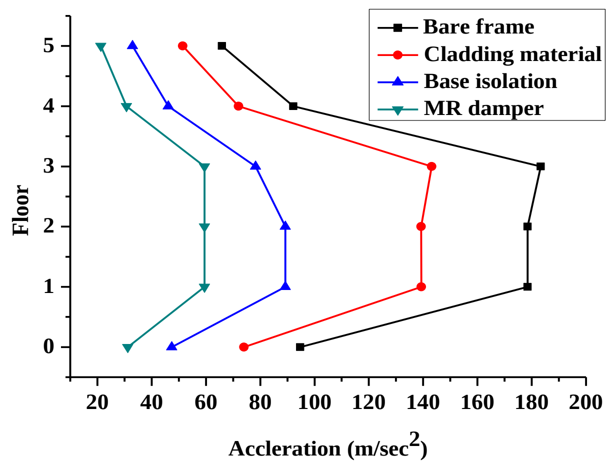
$f = c_1\dot{y} + k_1 (x_d - x_o)$ (20)

$\dot{Z}=-\gamma|\dot{x_d} - \dot{y}|Z|Z^{n-1}| - \beta(\dot{x}_d - \dot{y})|Z^n| + A(\dot{x_d} - \dot{y})$ (21)

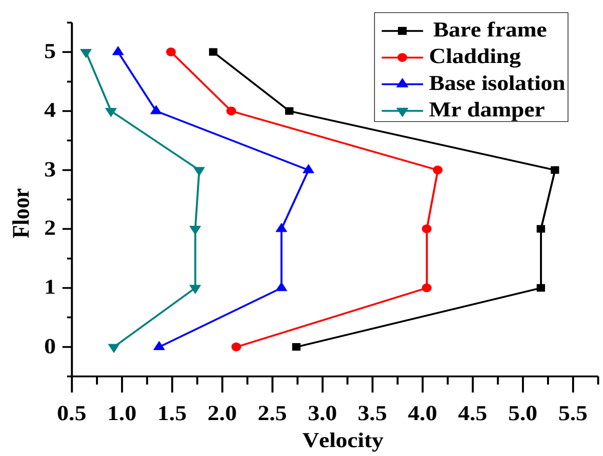
Solving the above equation, $\dot{y}$ gives

$$\dot{y} = \frac{1}{(c_o+c_{vl})}\{\alpha Z + c_o\dot{x_d} + k_o(x_d - y)\} \quad (22)$$

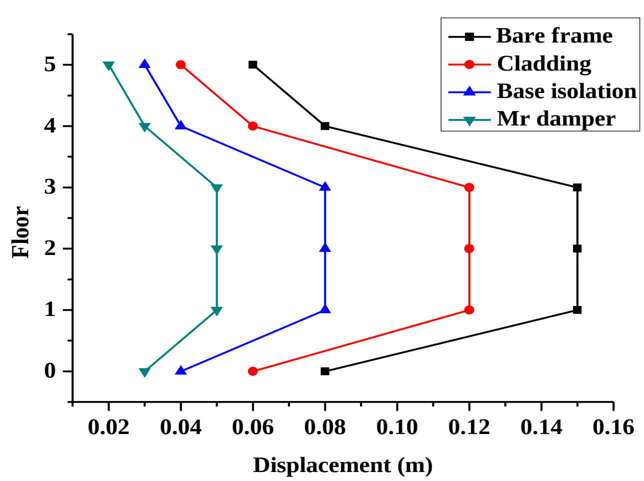
Where Z is the evolutionary variable that accounts for the history dependence of the response, x_d is the damper displacement, $\dot{x_d}$ is the velocity across the damper, k_{al} is the accumulator stiffness, c_{vl} is the viscous damping at the lower velocity of the model to produce the roll-off, c_o is the viscous damping at larger velocity, k_o is the stiffness of the larger velocity and x^i is the initial displacement of the spring and α, β, γ , n and A are the shape or characteristic parameters of the model.



a. Reduction of accelerations of bare frame by various control devices.



b. Reduction of velocity of bare frame by various control devices.



c. Reduction of displacement of bare frame by various control devices.

Fig. 9. Reduction of response of bare frame by various control devices.

Fig. 9(a) shows the maximum acceleration is reduced from 178.49 m/sec^2 to 31.25 m/sec^{2}at first floor, the maximum velocity is reduced from 5.176 m/sec to 1.73 m/sec at second floor and maximum displacement is reduced from 0.15 m 0.05m at second floor by using MR damper respectively.

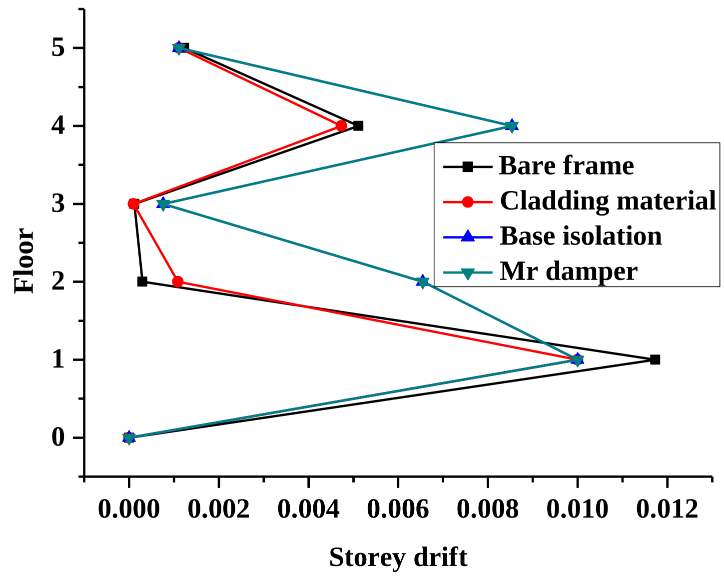


Fig. 10. Reduction of storey drifts of bare frame by various control devices.

Fig 10. Shows the reductions of storey drift by using control devices. The maximum drift occurs at first floor and minimum occurs at second and third floor.

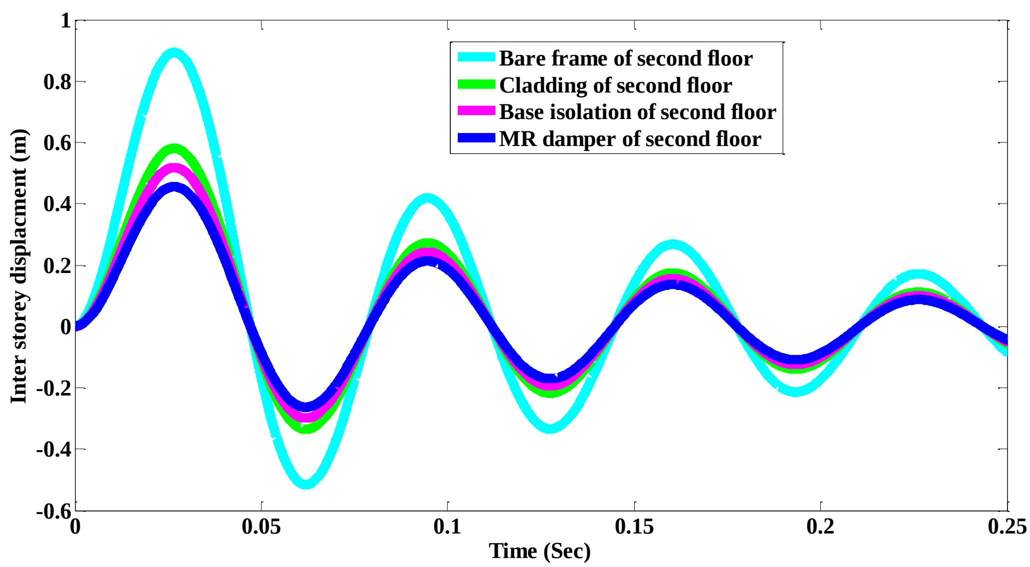


Fig. 11. Reduction of inter storey displacement of bare frame by various control devices.

Fig 11. Shows the reductions of inter storey displacement by using control devices. The maximum inter storey displacement is 0.8m is reduced to 0.4 m by using MR damper.

4. Pressure impulse curve

The area enclosed by the load time curve is known as an impulse. The combination of pressure and impulse curve is known as pi curve. The input parameter of a structure subjected to blast load is pressure versus time curve. The combinations of load and impulse that will cause failure or specific damage level is obtained from pi curve.

In the case of pressure impulse curve that falls to the right and above the graph will produce the damage in excess of the specific limit and that fall to the left of and below the curve will not produce damage.

The below equations are used to plot the pressure impulse curve

$$E_{input} = \frac{I^2}{2M} \tag{23}$$

Where I – impulse (area under blast load time curve)

The actual absorbed energy (imparted) is given

$$E_{imparted} = \int_0^{x_{max}} kxdx \tag{24}$$

Wherex_{max}– maximum displacement, x is displacement, k is stiffness.

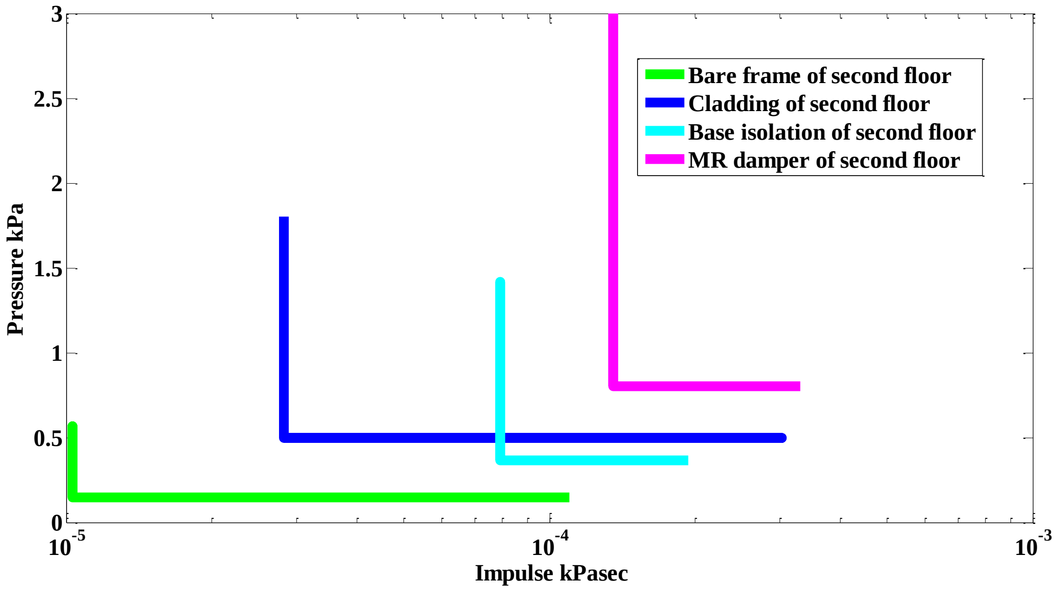
Input energy rate is defined as

$$E_{input\ rate} = \frac{E_{input}}{\beta t_d} \tag{25}$$

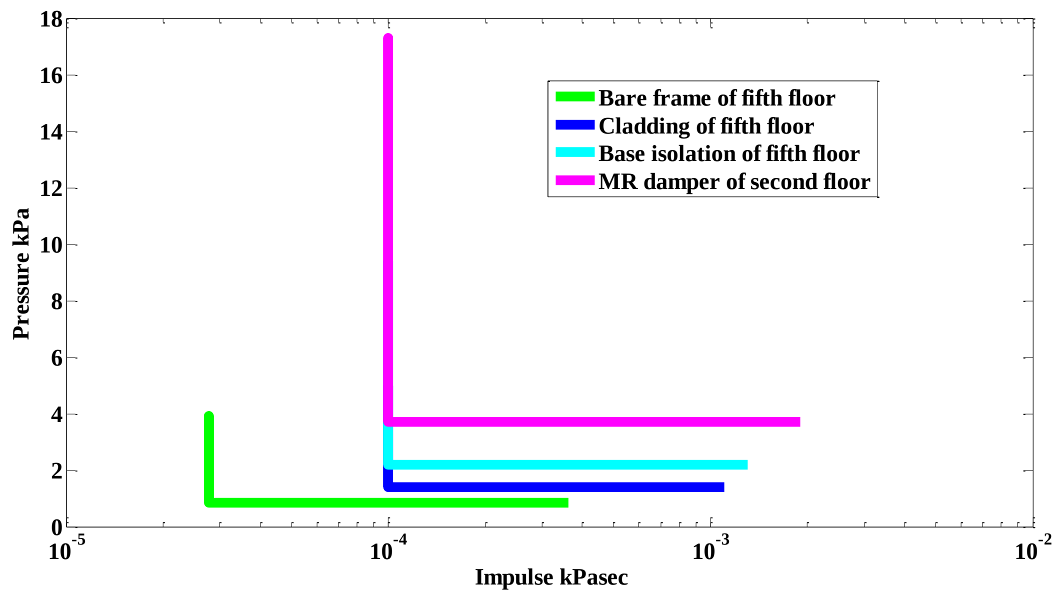
Where β is a load pulse shape factor is 0.5 for triangular load, t_d is time duration

$$\overline{E} = \frac{E_{input}}{E_{imparted}} = \text{Pressure} \tag{26}$$

$$\overline{R} = \frac{E_{input\ rate}}{E_{imparted}\,\omega} = \text{Impuls} \tag{27}$$



a. Increase of pressure impulse absorption of second by using control devices.



b. Increase of pressure impulse absorption of fifth by using control devices.

Fig. 12. Increase of pressure impulse absorption of fifth floor by using control devices.

Pressure impulse curve shows the pressure below the right curve below will be safe and not causing the failure of the structure. From Fig. 12. it is absorbed that by using cladding materials at the fifth floor the 25 % increase in pressure absorption, by using base isolation 30% and by using MR damper 40% increase in pressure absorption. Table 3, 4 and 5 shows the percentage of reductions of response by using control devices.

Table 3
Percentage of reductions of accelerations.

Floor	Cladding material	Base isolation	MR damper
Base	21.93	50.00	67.057
First	21.93	50.00	66.665
Second	21.99	50.00	66.667
Third	21.93	57.32	67.548
Fourth	21.93	50.00	66.670
Fifth	21.93	50.00	67.735

Table 4
Percentage of reductions of velocity.

Floor	Cladding material	Base isolation	MR damper
Base	21.8978	50.0	66.42
First	22.0077	50.0	66.60
Second	22.0077	50.0	66.60
Third	21.9925	46.2	66.73
Fourth	21.7228	49.8	66.67
Fifth	21.9895	49.7	66.49

Table 5
Percentage of reductions of displacement.

Floor	Cladding material	Base isolation	MR damper
Base	25.0	50.00	62.50
First	20.0	46.67	66.67
Second	20.0	46.67	66.67
Third	20.0	46.67	66.67
Fourth	25.0	50.00	62.50
Fifth	33.3	50.00	66.67

5. Conclusions

From the comparative study of the five storey structure exposed to blast load using control devices and consideration of Cladding material, Bse-isolations, and MR damper following conclusions are avhieved.

1. Using cladding material, base-isolation, and MR damper illustrated that the inter- storey displacement response are reduced by 22 %, 50%, and 65% respectively.
2. The maximum storey drift occurs at second floor and minimum drift occurs at the third and fourth floor for the bare frame of the five-storey structure.
3. Using cladding material, base-isolation, and MR damper caused to reduce storey drift by 15 %, 18%, and 25% respectively.

4. Using cladding material, base-isolation, and MR damper showed that the 25%, 35%, and 45% of increase in pressure will not cause any failure of the structure due to the impulse blast load.
5. Comparing the various devices, illustrated that the MR damper plays a vital role to mitigate the responses of a bare frame structure.

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