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Masonry Infill Damage Impact on Seismic Response of Reinforced Concrete Building

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Abstract**:** ***Seismic response of Reinforced Concrete (RC) building depends on many parameters such as building's dynamic properties, input excitation, structural configuration, irregularities of different forms etc.. Conceptually, seismic response of RC building with masonry infill is determined considering it as a linear elastic system. However, damage in masonry infill, local or overall, under seismic excitation to RC building alters its seismic response. The present paper aims to study the impact of masonry infill damage on RC building's structural response under various seismic ground excitations. A six storey RC building infilled with Autoclaved Aerated Cement (AAC) block, nowadays common, is considered in the present study. Seismic response of bare RC building with moment resisting frame and RC building infilled with AAC block are determined and are act as a reference case for the present study. Impact of masonry infill damage is incorporated in the equation of motion by (i) modifying the stiffness matrix and (ii) modifying both, stiffness matrix and damping matrix. Modification in stiffness matrix and/or damping matrix is mapped with degradation observed during experimental investigation conducted by the authors on RC frame test specimens with and without AAC block infill under half-cyclic lateral loading. Seismic response of RC building is measured in terms of peak displacement, peak inter-storey drift, peak storey shear and storey stiffness to illustrate the impact of AAC block infill damage. It has been found that AAC block infill contributes significantly to the stiffness of RC frame vis-à-vis bare RC building. Effect of AAC block infill damage represented by modification to stiffness matrix and/or damping matrix yield higher response quantities as compared to both reference cases. Present study indicates that, seismic response of RC building can be more realistically carried out with modification to stiffness & damping matrix which is mostly missing in practical analysis and design set-up.***

Index Terms**:** ***RC building, Seismic response analysis, AAC block infill, Stiffness degradation, Rayleigh damping.***

I. INTRODUCTION

Seismic response estimation of Reinforced Concrete (RC) building is a basic but most important step to ensure the safety of the building. Most of the RC buildings comprises of Moment resisting (MR) RC frame infilled with brick masonry to fulfill functional requirements. Recently, these brick masonry infills are replaced by lightweight Autoclaved Aerated Cement (AAC) block infills to reduce dead weight on the building as well as to speed up the construction cycle. AAC block infilled RC building can be treated as shear building to derive the dynamic equilibrium equation of motion. The governing equation of motion for RC shear building, modeled as Multi Degrees of Freedom (MDOF) system, subjected to seismic excitation can be written as

$$[M]\{\ddot{x}\}+[C]\{\dot{x}\}+[K]\{x\}=-[M]\{I\}\{\ddot{x}_g\} \qquad (1)$$

where, $[M]$ is the mass matrix; $[K]$ is the stiffness matrix; $[C]$ is the Rayleigh damping matrix; $\{x\}\{\dot{x}\}$ and $\{\ddot{x}\}$ represents the displacement, velocity and acceleration vectors at each storey for a given time instance, respectively, $\{I\}$ is the influence vector and $\ddot{x}_g$ is the seismic ground acceleration. Seismic response of RC building, the MDOF system, can be determined fundamentally through (i) Modal analysis, wherein (1) is converted in to the modal coordinates through system's mode shape vector resulting to decoupled equations of motion and (ii) Numerical integration methods like Newmark's method, Runge-Kutta methods etc. The formulation of system matrices is important for the seismic response analysis of MDOF system, especially for the latter approach as mentioned above. The procedure to formulate the mass matrix and stiffness matrix for the MDOF system is relatively straightforward and is well established. However, among various approaches to formulate damping matrix of the MDOF system, the approach proposed by Rayleigh is widely used, as it leads to classical damping matrix.

Rayleigh damping matrix for the nth order MDOF system is considered to be mass & stiffness proportional and can be derived through (2).

$$[C]=\alpha[M]+\beta[K] \qquad (2)$$

where scalars α and β are calculated from the specified modal damping ratios ζ_n and modal undamped natural frequencies ω_n in any two distinct modes of vibration considered following the (3).

$$\zeta_n=\frac{\alpha}{2\omega_n}+\frac{\beta\omega_n}{2} \qquad (3)$$

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II. LITERATURE REVIEW

Study on the existing volume of literature related to damping evaluation and modeling techniques reveals that unlike other important dynamic properties of the system, the damping modeling and evaluation is a complex task. Probably the main reason for it is the coexistence of many active energy dissipation mechanisms in the system undergoing vibration. Various linear and non-linear damping models have been proposed and studied by researchers in the past few decades [1]-[4]. However, the linear viscous damping model is universally adopted due to mathematical ease and it works well for small value of damping ratio, typically lesser than 10% of critically damping coefficient [2]. In the case of MDOF system, the damping is quantified through the damping matrix. Various research investigations are devoted towards identification of linear and non-linear damping present in the MDOF system [5]-[7]. Hans et al. have discussed about damping identification through the wavelet procedure for a building model excited by harmonic and transient loading [8]. Similar work on identification of damping in the MDOF system is also discussed by C Lamarque [9].

As discussed earlier, the equation of motion for MDOF system in modal coordinates become uncoupled with principal diagonal terms and hence, it is classified as the classically damped system. However, when two consecutive stories in the MDOF system have distinct stiffness and damping characteristics, the resulting modal damping matrix may have non-zero off-diagonal terms. Luco has proposed an alternative method of formulating damping matrix for MDOF system which guarantees classical normal modes without solving algebraic equations and has related that to Rayleigh, Caughey and modal damping matrices [10]. Classical modal damping matrix is not required if classical modes and frequencies of the MDOF system are available and the damping is prescribed at the level of modes [11]. Erduran [12] has proposed trial functions, to be chosen arbitrarily based on applicability to the system to be analyzed, to derive the damping matrix. Cropper and Gupta [13] have discussed the importance of non-zero off-diagonal terms and its effect on the response of the MDOF system. Free and forced vibration experiments on simple shear building models and its comparison to show inconsistencies associated with methods of creating the damping matrix are also discussed.

As the Rayleigh and Caughey damping models result in classical normal modes, these approaches are widely adopted in practice. Also, bearing on the advantage of limited computational effort in Rayleigh damping model as compared to Caughey damping model with more terms, the former approach is mostly utilized in many analysis software packages. The issues occurred with the Rayleigh damping matrix for the inelastic systems and system with base-isolation are addressed by Finley [14] and Ryan et al. [15]. Effect of Rayleigh damping matrix on the seismic response of MDOF systems are addressed and comparison of important seismic response quantities among mass proportional, stiffness proportional and Rayleigh damping matrix are carried out by Erduran [12].

Seismic response analysis for RC building can also be carried out following the codal stipulations of IS: 1893 (Part-1):2016 [16] code of practice that recommends the use of static equivalent lateral load method, response spectrum analysis and the time history analysis. Time history analysis method, amongst the various methods, gives the flexibility to alter various seismic parameters during the analysis process and leads to better estimation of seismic response quantities.

III. PROBLEM FORMULATION

RC building infilled with AAC block is a common construction practice, nowadays. Seismic code of many countries, including India, conservatively allows one to determine seismic response of infilled RC building like a bare Moment Resisting (MR) frame, i.e. MR frame without any infills. Hence, seismic response analysis of RC building infilled with AAC block is carried out under seismic ground excitations neglecting contribution from infill. In fact, such buildings are subjected to inelastic deformation under seismic ground excitation that results into damage of varied degrees to AAC block infills in real time**.** This indicates that AAC block infills are resisting seismic forces to some extent and when undergoes damage they may increase damping in the system. In order to assess the seismic response of RC building more realistically, contribution from AAC block infill should be considered in the analysis. Apart, AAC block infill damage resulting due to seismic demand should also be incorporated in seismic analysis of RC buildings.

In the present study, two reference cases are considered as follows (i) Bare MR Frame (BMRF):- This case considers a bare MR frame of RC building without any infill walls with initial tangent stiffness that do not degrade during seismic response analysis considered under various seismic ground excitations, (ii) MR Frame with AAC Block Infill (MRFAAC):- This case considers MR frame with AAC block infill of RC building with initial tangent stiffness that includes stiffness contribution by both MR frame and AAC block infill which does not degrade under various seismic ground excitations. Experimental investigations carried out by the Authors on RC frame infilled with AAC block subjected to half-cyclic lateral load are used to quantify the damage in the RC building with AAC block infill during seismic analysis in real time. Impact of AAC block infill damage on seismic response analysis of RC building is visualized as following cases-(iii) Stiffness Matrix Modification (MRFAAC-SM):- In this case the stiffness matrix of RC building with AAC block infill is modified, once the inter-storey drift ratio exceeds the limits associated with different degree of damages established from experimental investigations and (iv) Stiffness and Damping Matrix Modification (MRFAAC-SDM):- In this case the damping matrix of RC building with AAC block infill is modified as change in stiffness matrix due to infill damage alters values of scalars ‘α’ and ‘β’ used in Rayleigh damping matrix along with stiffness matrix updation.

A. MDOF System Description

A six (G+5) storey RC building with and without AAC block infill panels idealized as a shear building model, as shown in Fig. 1, is considered in the present study. Seismic response analysis of RC building cases; BMRF, MRFAAC, with an open ground storey (with no AAC block infills), MRFAAC-SM and

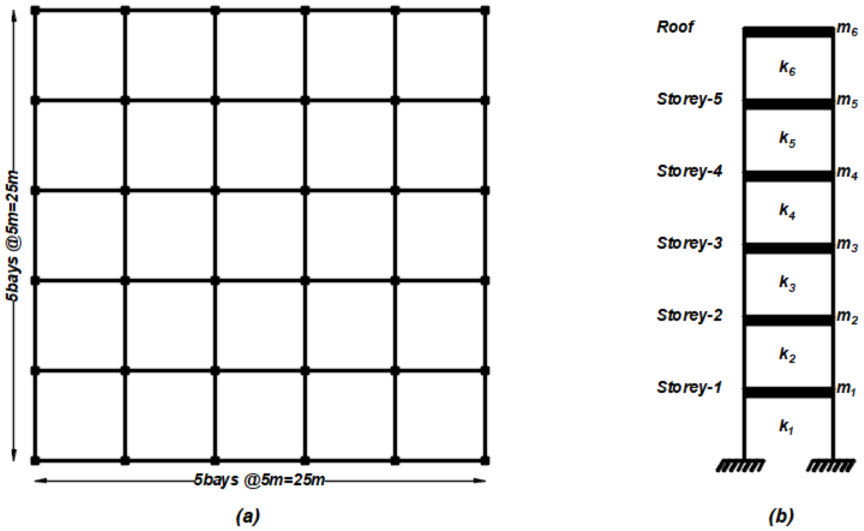


Fig-1: Reinforced concrete shear building (a) Plan (b) MDOF discrete mass model

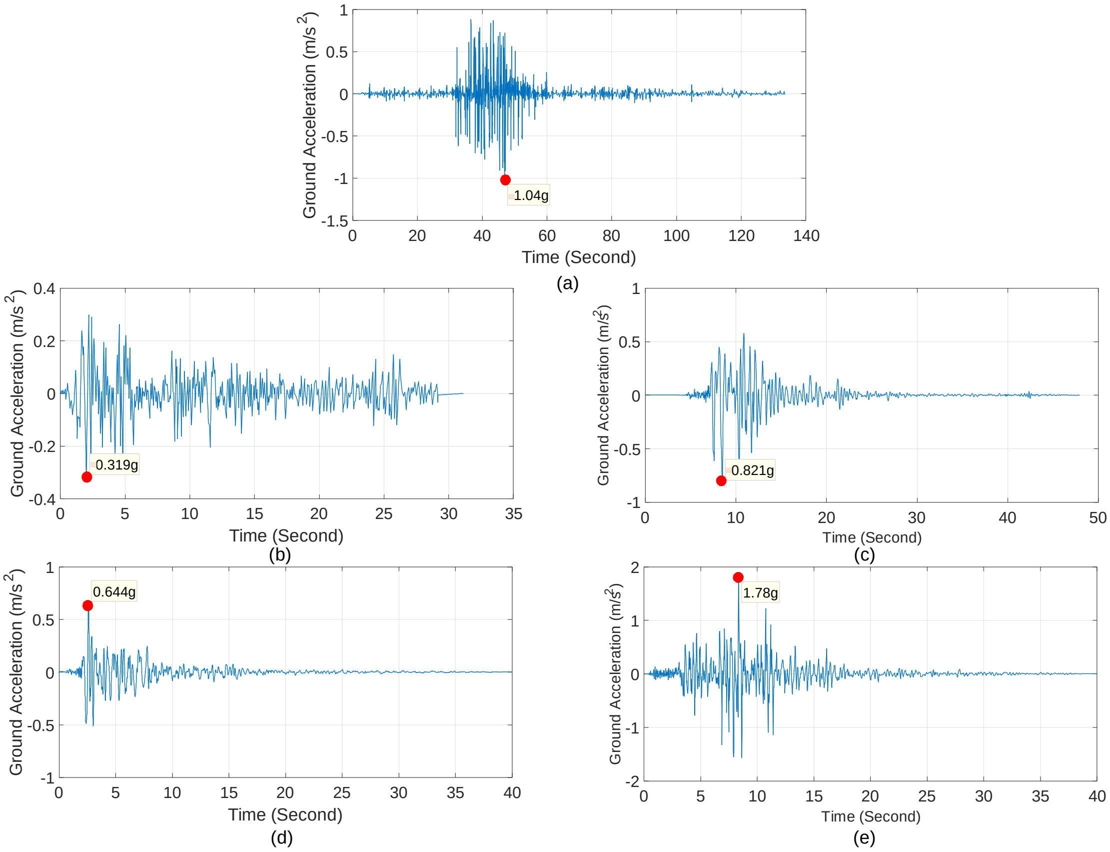


Fig-2 Seismic ground excitation time histories (a) Bhuj (b) El Centro (c) Kobe (d) Loma Prieta and (e) North Ridge

MRFAAC-SDM is carried out. All the RC buildings as discussed above are subjected to seismic ground excitations as shown in Fig. 2. The system mass matrix is derived by assembling individual storey mass calculated from the geometrical properties. Assuming the rigid floor diaphragm action, the storey stiffness of the RC building of MR frame with M25 grade of concrete is estimated from the geometric & material properties. Stiffness of AAC block infill panel surrounded by RC building of MR frame is estimated following IS: 1893 (Part-I): 2016 guidelines wherein infill is modeled as single diagonal compression only strut member [16]. The width of equivalent diagonal strut member is determined through the set of equations given as;

$$w_{ds} = 0.17\alpha_h^{-0.4} L_{ds} \qquad (4)$$

$$\alpha_h = h\left[\sqrt[4]{\frac{E_m t \sin 2\theta}{4E_f I_c h}}\right] \qquad (5)$$

where, L_{ds} is the length of equivalent diagonals strut; t is the thickness of the infill panel; θ is the angle of inclination of the diagonal strut with horizontal; I_c is moment of inertia of lateral load resisting elements and the E_m , E_f is the modulus of elasticity of masonry and frame estimated using (6)-(8).

$$E_m = 550\, f_m \tag{6}$$

$$f_m = 0.433\, f_b^{0.64}\, f_{mo}^{0.36} \tag{7}$$

$$E_f = 5000\sqrt{f_{ck}} \tag{8}$$

where f_m is the masonry prism strength; f_{ck} is the characteristic compressive strength of concrete; f_b is compressive strength of brick $(f_b = 5.94MPa)$ and f_{mo} is compressive strength of mortar $(f_{mo} = 6.17MPa)$.

The stiffness matrix for the AAC block infilled RC building is assembled by considering stiffness of RC frame elements and diagonal strut member. Damping matrix is determined considering it as mass and stiffness proportional, i.e. Rayleigh damping matrix, wherein the damping ratio is taken as 5% of critical damping for the first two modes of vibration. Table-(1) gives typical values for mass and stiffness estimated for two cases BMRF and MRFAAC, respectively.

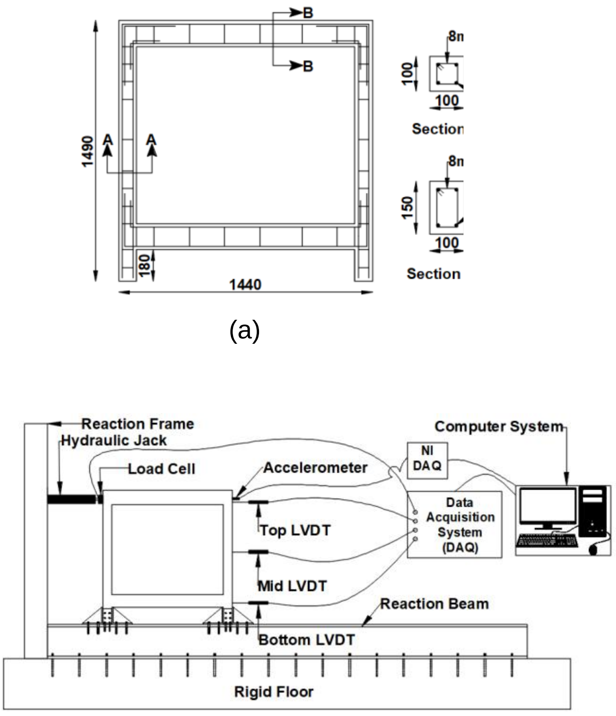
Table-1 Typical values of storey mass and storey stiffness of RC building

Case	Storey	Storey Mass (kg)	Storey Stiffness (N/m)
Bare Moment Resisting Frame (BMRF)	Ground storey	694714.58	4.38E+08
	Typical storey	881077.88	3.60E+08
	Roof	596764.73	3.60E+08
Moment Resisting Frame with AAC Block Infill (MRFAAC)	Ground storey	694714.58	8.79E+08
	Typical storey	881077.88	1.06E+09
	Roof	596764.73	1.06E+09

It is evident from the Table-(1) that the storey mass for both the RC buildings (BMRF & MRFAAC) are same, whereas storey stiffness values are different due to the addition of AAC block infill stiffness for the latter case. As mentioned in Section-III, it is a common practice to ignore the stiffness contribution of AAC block infill in RC building, BMRF case depicts a very practical case as a reference.

B. Experimental Program

The experimental program conducted in the Structures Laboratory of Nirma University is, briefly, discussed in this section. It comprises of one storey one bay RC Frame specimens with and without AAC block masonry infill panels investigated under in-plane lateral loading. Details of the experimental set-up and instrumentation used in the investigations are shown in Fig. 3. The lateral monotonic in-plane half-cyclic load is applied to the test specimen through the hydraulic jack and the resulting displacements of the test specimen are measured at three locations using LVDTs as shown in Fig. 3.



(a)

(b)

Fig-3 Experimental program consists of (a) RC frame test specimen and (b) experimental set-up and instrumentation

All test specimens were tested with the force controlled half-cyclic lateral load applied in incremental cycles until the test specimen failed completely. Table-(2) represents Drift Ratio (in %) and Stiffness Degradation (in %) derived for test specimens: Bare RC frame and RC frame with AAC block infill from lateral load-lateral displacement characteristics obtained experimentally.

Table 2: Drift Ratio and Stiffness Degradation of test specimens under lateral loading

Sr. No.	Test Specimen	Cycle No.	Drift Ratio (%)	Stiffness Degradation (%)
1	Bare RC Frame	1	2.21	11.26
		2	5.64	39.48
		3	13.27	56.89
2	RC Frame with AAC Block Infill	1	0.10	7.14
		2	0.37	19.94
		3	0.98	29.16
		4	2.53	44.61

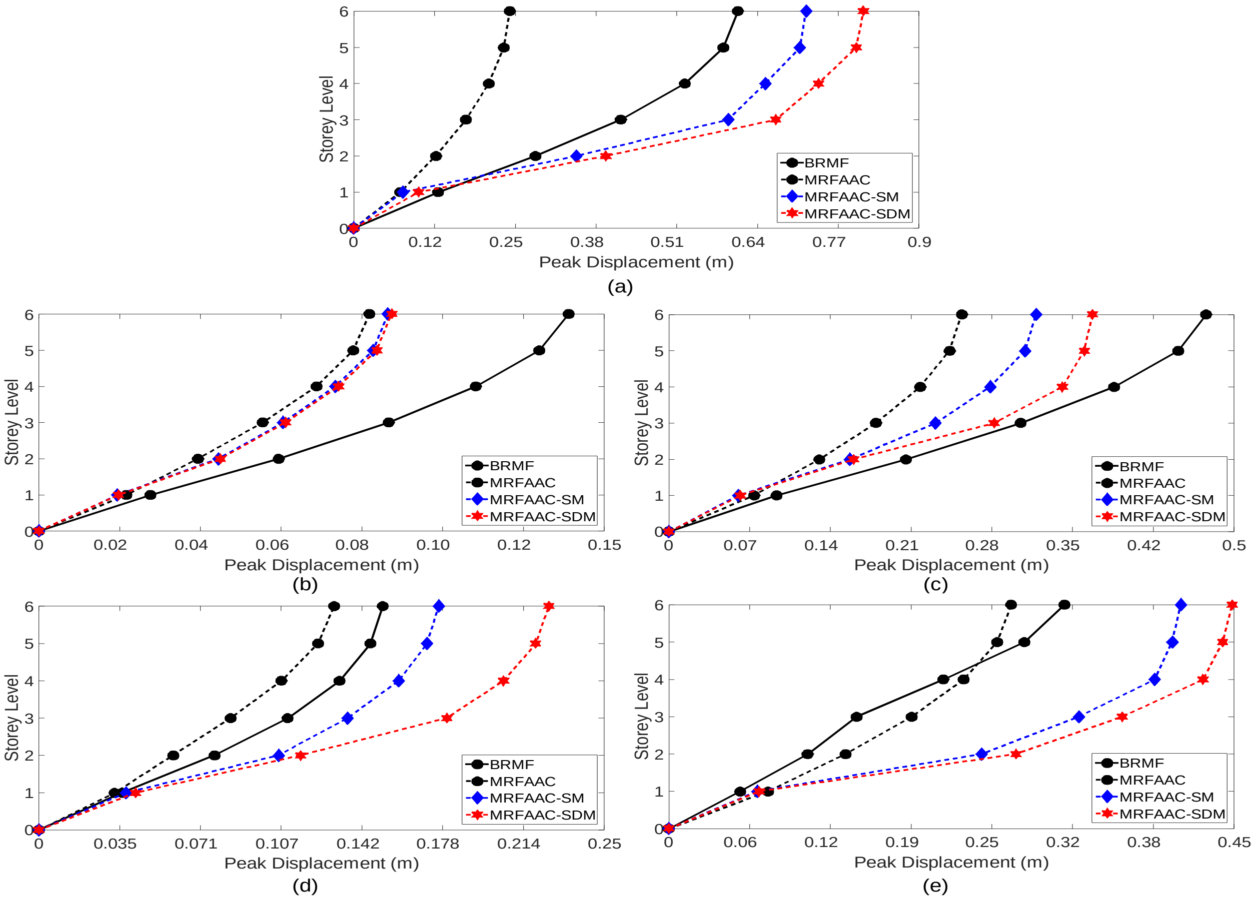


Fig-4 Peak displacement of MDOF system subjected to (a) Bhuj (PGA-1.04g) (b) El Centro (PGA-0.319g) (c) Kobe (PGA-0.821g) (d) Loma Prieta (PGA-0.644g) and (e) North Ridge (PGA-1.779g) ground excitation

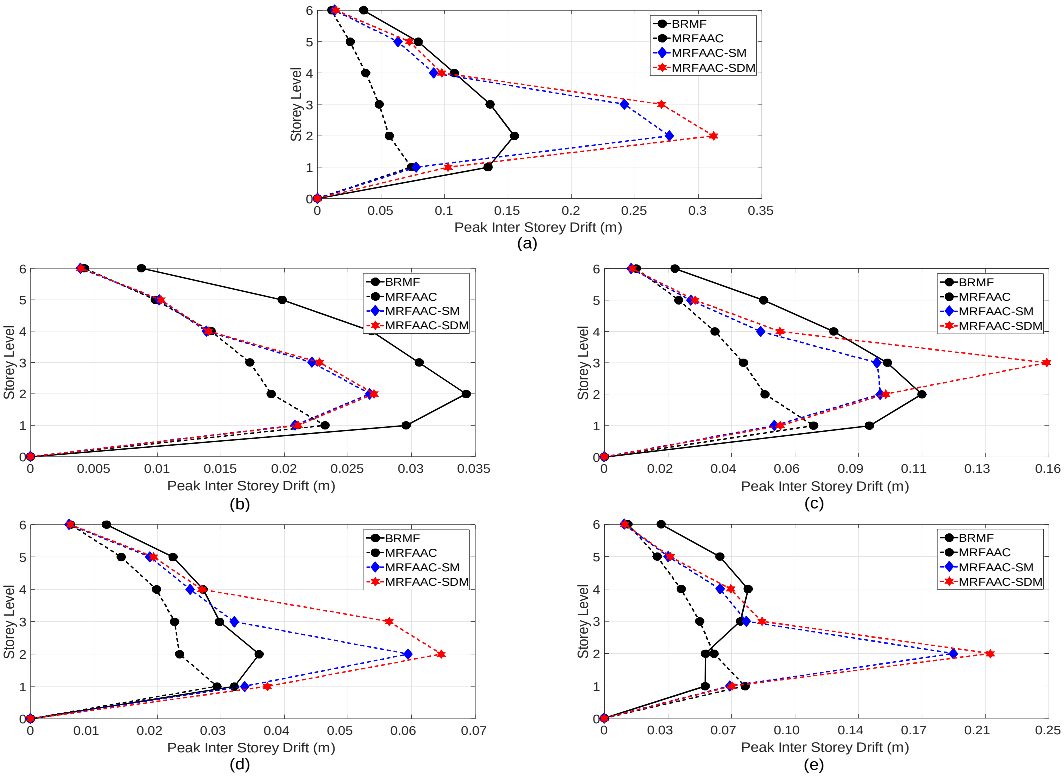


Fig-5 Peak Inter Storey Drift of MDOF system subjected to (a) Bhuj (PGA-1.04g) (b) El Centro (PGA-0.319g) (c) Kobe (PGA-0.821g) (d) Loma Prieta (PGA-0.644g) and (e) North Ridge (PGA-1.779g) ground excitation

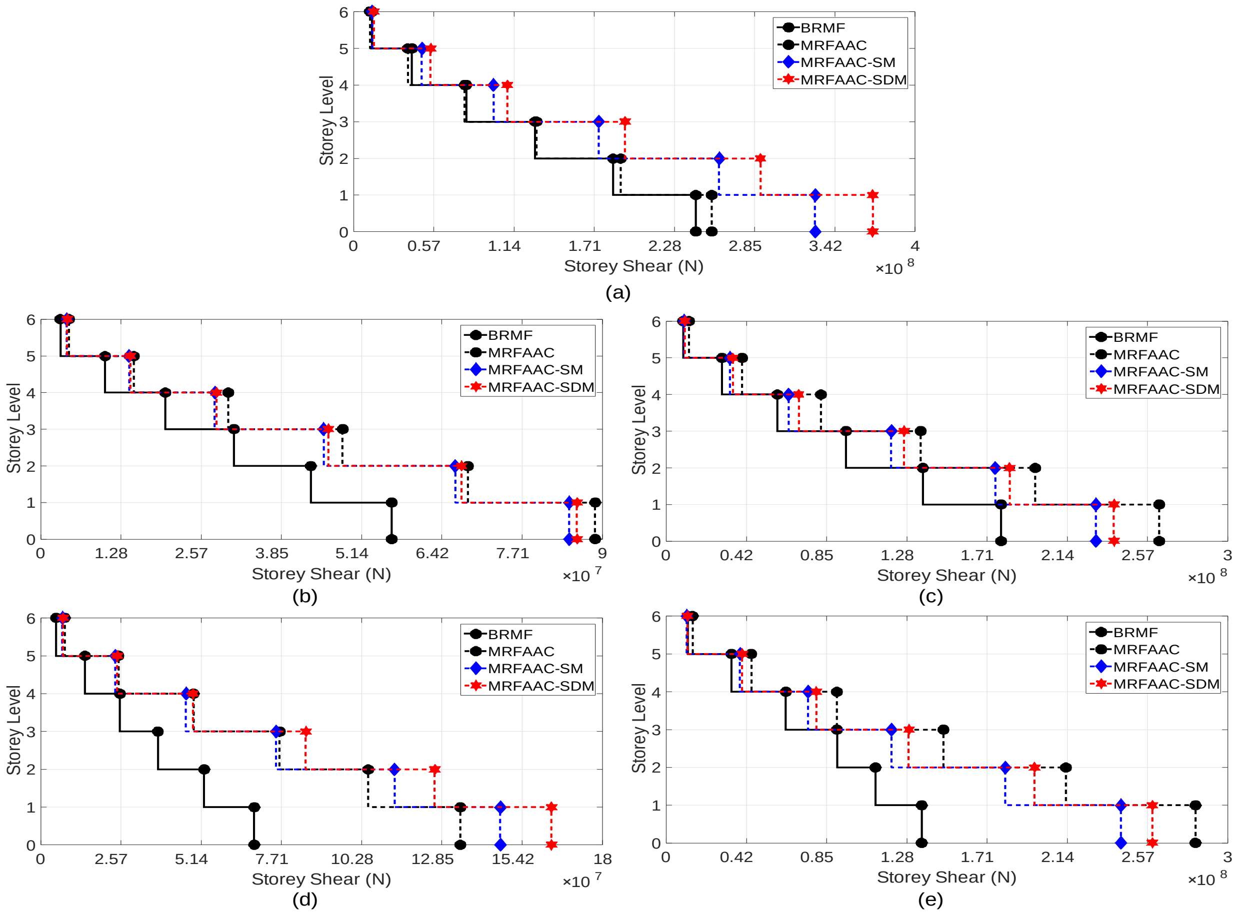


Fig-6 Peak storey shear of MDOF system subjected to (a) Bhuj (PGA-1.04g) (b) El Centro (PGA-0.319g) (c) Kobe (PGA-0.821g) (d) Loma Prieta (PGA-0.644g) and (e) North Ridge (PGA-1.779g) ground excitation

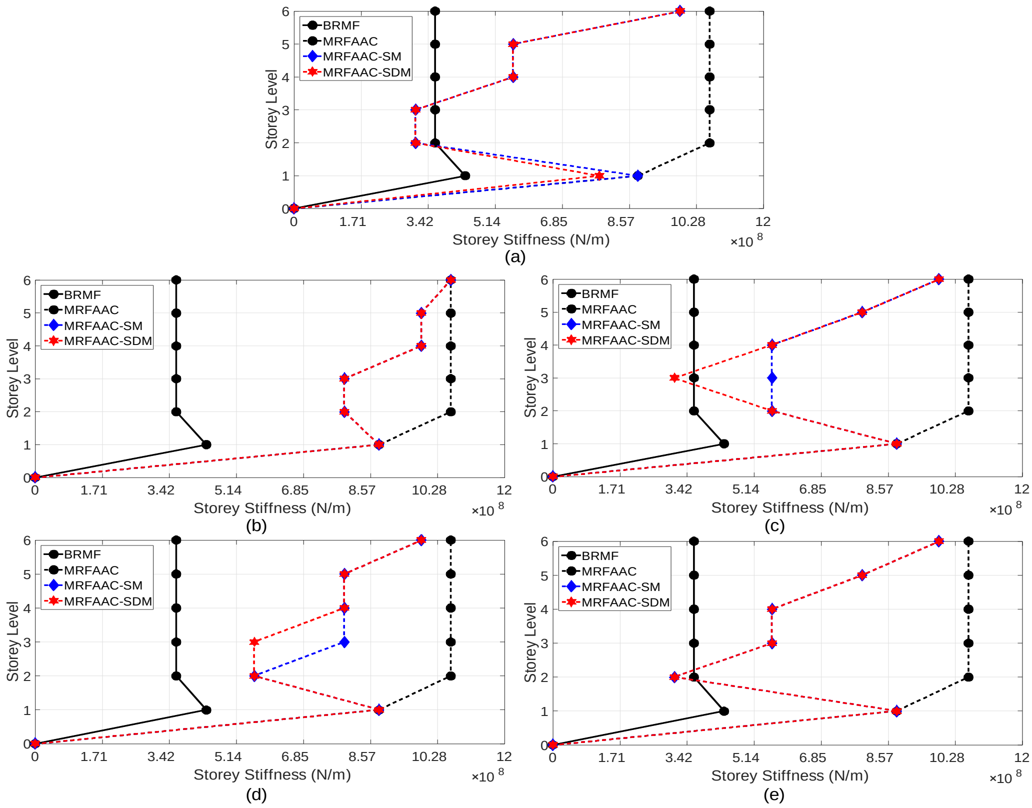


Fig-7 Storey stiffness of MDOF system subjected to (a) Bhuj (PGA-1.04g) (b) El Centro (PGA-0.319g) (c) Kobe (PGA-0.821g) (d) Loma Prieta (PGA-0.644g) and (e) North Ridge (PGA-1.779g) ground excitation

IV. RESULTS AND DISCUSSION

A six storey RC shear building is subjected to seismic ground excitations of Bhuj (2001), El Centro (1940), Kobe (1995), Loma Prieta (1989) and North Ridge (1994). Four cases, as described in Section III, are considered and seismic response of RC building is evaluated solving (1) using numerical integration Newmark's method through computer programming on MATLAB platform. While BMRF and MRFAAC cases of RC building observed straight forward methodology, cases of MRFAAC-SM and MRFAAC-SDM have been analyzed enforcing permissible limits of Drift Ratio and corresponding stiffness degradation as given in Table-(2). It means, the system stiffness matrix and/or damping matrix are updated, in real time, to account stiffness degradation associated with each Drift Ratio limits (Table-(2)) during numerical solution of MRFAAC-SM and MRFAAC-SDM cases. Effect of AAC block infill damage on RC building under seismic ground excitations is measured in terms of Peak Displacement, Peak Inter Storey Drift and Peak Storey Shear parameters. Apart, the status of stiffness degradation with the onset of AAC block infill damage in RC building is also studied through storey stiffness.

Fig. 4(a) to Fig. 4(e) shows peak displacement of RC building under different seismic ground excitations. It is evident from Fig. 4(a) to Fig. 4(e) that, peak displacement at first storey is almost identical for almost all cases of RC building under each seismic excitations considered. This is due to the fact that, ground storey is identical, an open storey, for RC building with and without AAC block infill. It is observed that Case-MRFAAC-SDM yields higher peak displacement at each storey of the RC building infilled with AAC block due to reduction in the stiffness of the infills. Impact of AAC block infill damage on seismic response of RC building is found to be severe, since modification to both, stiffness and damping matrix, yields highest displacement at each storey vis-à-vis MRFAAC and MRFAAC-SM cases. Severe seismic response for MRFAAC-SDM case is attributed to change in dynamic properties due to reduction in stiffness as AAC block infill damages which also influence Rayleigh damping matrix. It is also observed that with the onset of AAC block infill damage, RC building tends to behave like BMRF case as seen in Fig. 4(c), however, it may respond more critically as compared to BMRF case as evident from Fig. 4(a), Fig. 4(d) and Fig. 4(e) under various seismic excitations. Thus, the seismic response of RC building with AAC block infill without stiffness degradation underestimates displacement response of building and associated damage to AAC block infills.

Peak inter-storey drift of bare and AAC block infill building at each storey level under various seismic ground excitations are evaluated and plotted as shown in Fig. 5(a) to Fig. 5(e). It is evident that case BMRF shows higher peak inter-storey drift at the second floor due to excitation of lower fundamental modes. Case-MRFAAC yields higher peak inter-storey drift at first floor of RC building due to fixity at the base. Due to increase in stiffness of RC building with AAC block infills, maximum peak inter-storey drift for MRFAAC case reduces substantially as compared to BMRF case for each seismic excitations considered. Fig. 5(a) to Fig. 5(e) shows that peak inter-storey drift at each floor of RC building with AAC block infill shows increment for both cases of MRFAAC-SM and MRFAAC-SDM due to drift ratio limit, as given in Table-(2), exceeds under each seismic excitations that leads to stiffness degradation in the RC building. Maximum peak inter-storey drift is achieved at second floor level of RC building under each seismic excitations for MRFAAC-SDM case, followed by MRFAAC-SM case, due to large displacement of the RC building because of reduction in storey stiffness which is reflected in Fig. 7(a) to Fig. 7(e). It is observed from Fig. 5(a) to Fig. 5(e) that peak inter-storey drift reduces moderately for storey level 4, 5 and 6, as residual storey stiffness, after AAC block infill damage, is still higher as compared to BMRF case which is evident from Fig. 7(a) to Fig. 7(e).

Peak storey shear at each storey level of bare and AAC block infill RC buildings are calculated and plotted in Fig. 6(a) to Fig. 6(e). It is evident that storey shear increases towards bottom stories as compared to the top stories due to higher inter-storey drift resulting under various seismic excitations. Storey shear at each storey of RC building is higher or similar to storey shear of case MRFAAC for both cases; MRFAAC-SM & MRFAAC-SDM. Resulting storey shear for both cases of MRFAAC-SM & MRFAAC-SDM are quite higher as compared to BMRF case. Here also, the case MRFAAC-SDM yields highest peak storey shear among cases of BMRF, MRFAAC & MRFAAC-SM for most of the seismic excitations. Impact of AAC block infill damage can be understood by storey stiffness at each storey level of the RC buildings. Fig. 7(a) to Fig. 7(e) shows the variation of storey stiffness of RC building with and without AAC block infill under various seismic excitations. Difference between storey stiffness of BMRF case and MRFAAC case is evident and straightforward to realize that AAC block infill contributes heavily in the storey stiffness vis-à-vis BMRF case. Variation at second storey level for RC building for each case considered is clearly visible. Reduction in storey stiffness at second storey level for BMRF case is due to reduction in column size. Increase in storey stiffness at second-floor level for MRFAAC cases is due to the fact that ground storey is without AAC block infill but second storey onwards there is AAC block infill that contributes to storey stiffness. Reduction in storey stiffness for cases MRFAAC-SM and MRFAAC-SDM indicates that drift limit as mentioned in Table-(2) is exceeded and hence stiffness matrix gets updated emphasizing the impact of AAC block infill damage. It is clearly evident from Fig. 7(a) to Fig. 7(e) that there is moderate to a substantial reduction in storey stiffness of RC building with AAC block infill due to damage in AAC block infill during seismic excitation. Thus, if RC building is analyzed for seismic response considering no degradation in AAC block infill, it overestimates the storey stiffness of the building than actual behavior.

V. CONCLUSIONS

A six storey Reinforced Concrete (RC) shear building bare and infilled with AAC block infill are considered in the present study. RC building with AAC block infill is modeled with diagonal compression strut member dimensionalized using provisions of IS:1893(Part-1): 2016 [16]. Both RC buildings; bare (BMRF) and AAC block infilled (MRFAAC) are subjected to various seismic excitations of Bhuj (2001), El Centro (1940), Kobe (1995), Loma Prieta (1989) and North Ridge (1994) assuming them as linear elastic MDOF systems. Impact of AAC block infill damage due to seismic demand is incorporated in the seismic response analysis by adhering to drift ratio limits as derived through experimental investigation on Bare RC frame and AAC block infilled RC frame specimens under half-cyclic monotonic lateral loading at structures laboratory by authors. Seismic response analysis of RC building is carried out in the form of cases; (i) effect of AAC block infill damage reduces stiffness of the storey and thus stiffness matrix is modified as soon as the drift ratio is exceeded (MRFAAC-SM); (ii) damage in the AAC block infill reduces stiffness of the storey and hence dynamic properties of building which also impacts the Rayleigh damping matrix that is derived as mass & stiffness proportional (MRFAAC-SDM). Response quantities extracted are; Peak displacement; Peak inter-storey drift; Peak storey shear and storey stiffness to study the impact of AAC block infill damage on seismic response of RC building.

It has been observed that both MRFAAC-SM and MRFAAC-SDM cases yield maximum peak displacement, inter-storey drift and storey shear under various seismic excitations, except Kobe seismic excitation. This indicates that seismic response analysis of RC building considering either as bare frame or frame with AAC infill without stiffness degradation does not capture actual seismic behavior. Both cases; MRFAAC-SM & MRFAAC-SDM yields higher maximum peak displacement, inter-storey drift and storey shear demanding more careful approach while designing. MRFAAC-SDM case yields highest response quantities for RC building subjected to various seismic excitations. This establishes an importance of consideration of change in both stiffness and damping matrices for RC building which is merely observed during practical analysis and design of such buildings. It is also evident that RC building with damaged AAC block infill behaves better vis-à-vis bare RC building due to higher residual storey stiffness even after infill damage.

The present study clearly establishes that the AAC block infill contributes significantly to the stiffness of RC building which yields better seismic performance despite damage to infills vis-à-vis bare RC frame building. However, it is also realized that damage in AAC block infill reduces stiffness significantly due to seismic excitation and hence more realistic seismic response analysis like MRFAAC-SDM case is to be resorted that attempt to quantify infill damage more realistically. More research investigations are required for realistic quantification of masonry infill damage under seismic excitations that may help to determine seismic response of RC building much closer to physical behavior.

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