ASSESSMENT OF RESPONSE REDUCTION FACTOR FOR CONFINED MASONRY BUILDINGS

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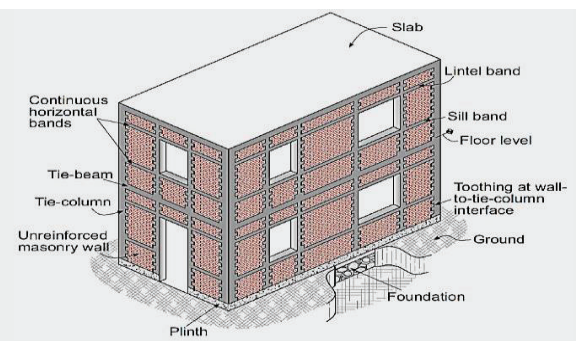
***Abstract*—Confined Masonry (CM) is one of the widely practiced construction systems in Europe, Asia and Latin America for low rise residential buildings. It is a building technology which uses the same basic materials used in unreinforced masonry and reinforced cement concrete (RCC) construction with masonry infill, but with a different construction system.**

This research is carried out to study and assess the Response Reduction Factor for confined masonry structures. Main purpose of this research is to assess the relationship of Response reduction factor of confined masonry with wall densities and it somewhat tries to formulate analytical relationship between response reduction factor and wall densities. Additionally, research aims in attracting attention of other researchers that are getting involved in confined masonry projects.

Keywords—Confined Masonry, Response Reduction Factor, overstrength factor, ductility factor, Linear Static analysis, Non-linear Static analysis

I. INTRODUCTION



Elements of a Confined Masonry Building ***[2]***

Key Components of a Confined Masonry Building[1]

Confined masonry construction consists of masonry walls and horizontal and vertical reinforced concrete (RC) *confining elements* built on all four sides of a masonry wall panel. Vertical elements, called *tie-columns*, resemble columns in RC frame construction except that they tend to be of far smaller cross-sectional dimensions. Most importantly, these RC members are built after the masonry wall has been completed. Horizontal elements, called *tie-beams*, resemble beams in RC frame construction but they are not intended to function as conventional beams since confined masonry walls are load-bearing. Alternative terms horizontal ties and vertical ties, are sometimes used instead of tie-beams and tie-columns [1].

The key features of structural components of a confined masonry building are

• *Masonry walls* transmit the gravity load from the slab(s) above down to the foundation (along with the RC tie-columns). The walls act as bracing panels, which resist horizontal earthquake forces acting in-plane. The walls must be confined by RC tie-beams and tie-columns and should not be penetrated by significant openings to ensure satisfactory earthquake performance.

• *Confining elements* (RC tie-columns and RC tie-beams) are effective in improving stability and integrity of masonry walls for in-plane and out-of-plane earthquake effects. These elements prevent brittle seismic response of masonry walls and protect them from complete disintegration even in major earthquakes. Confining elements, particularly tie-columns, contribute to the overall building stability for gravity loads.

• *Floor and roof slabs* transmit both gravity and lateral loads to the walls. In an earthquake, floor and roof slabs behave like horizontal beams and are called diaphragms. The roof slabs are typically made of reinforced concrete.

• *Plinth band* transmits the load from the walls down to the foundation. It also protects the ground floor walls from excessive settlement in soft soil conditions and the moisture penetration into the building.

• *Foundation* transmits the loads from the structure to the ground.

Response reduction factor [7*]*.

It is a factor by which actual base shear force, that would be generated if the structure were to remain elastic during its response to the Design basis earthquake shaking, reduced to obtain design lateral force. The value for response reduction factor greatly affects in the seismic design of structures, however literatures till yet has not been able to justify the value of R on exact scientific basis. The value of R is greatly affected by ductility, redundancy, overstrength, number of bays, number of storey, type of irregularity, soil condition

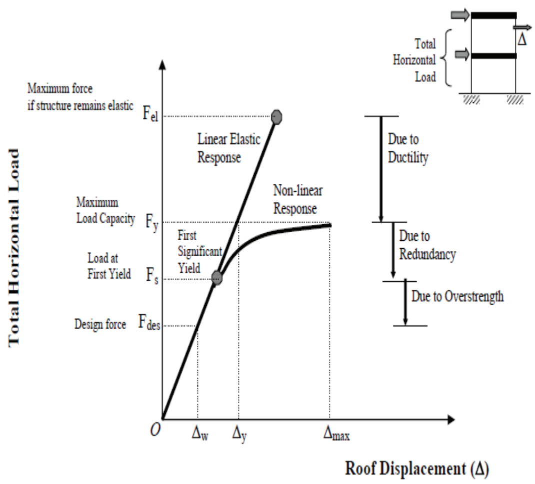
R value for the confined masonry as per National Building Code of Canada (NBCC 2005) [10]

$R = R_d * R_0$

Where,

R_d is ductility related force modification factor

Ro is overstrength related force modification factor



Definition of Response Reduction Factor[22]

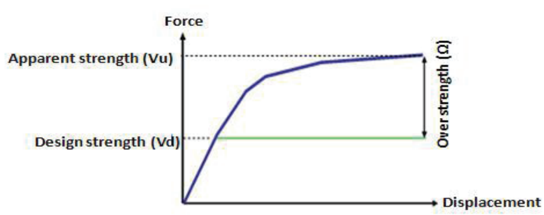
Over strength related force modification factor (Ro)

Overstrength is the additional strength beyond design strength. Maximum lateral strength of the building will exceed its design strength. The main sources of overstrength is the difference between actual and design material strength where design material strength is underestimated by using factor of safety. Other source of overstrength is the overestimation of the loading condition where actual load is multiplied by load factor to obtain design load. Sometimes theoretical analysis may not fully corelate with that of the practical case where other components of the structure share the load. [11]

As per NBCC 2005 overstrength factor can be determined as [10]

Overstrength factor (Ro) = apparent strength / design strength

$$Ro = Vu / Vd$$



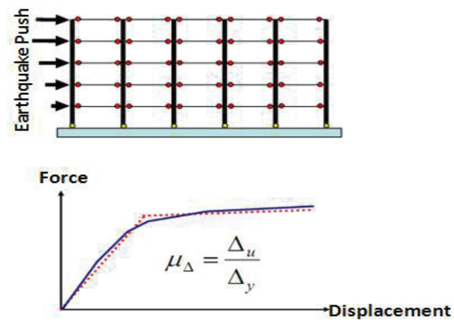
Force Displacement relationship for overstrength [11]

Ductility related modification factor

Ductility is associated with plastic deformation, hence it is associated with permanent structure damage. The requirement of a strength level is insufficient as the only parameter for seismic design. Therefore, it is necessary to combine it with an adequate criterion to estimate the maximum story drifts (or displacements) that a structure will have to accommodate during the action of a severe earthquake. With that purpose, the structural ductility factor (μ) is defined as the ratio between the maximum expected inelastic displacement and the elastic displacement induced by the seismic design forces. [11]

μ = Maximum displacement / elastic displacement.

$\mu = \Delta u / \Delta y$



Representation of displacement ductility [11]

Ductility related force modification factor (Rd) [6] can be calculated as

$$R_d = \sqrt{(2\mu-1)}$$

Where, μ = structural ductility factor

Maria O. Moroni [4] ; had conducted 3D time history analysis on the the confined masonry for several three and four storey buildings. He concluded that the reduction factor depends on wall density and ductility demand. Reduction factor decreases with increase in wall density. Also they have reported values of overstrength factor ranging from minimum value of 2.94 to maximum value of 7.91.

Wisnumurti, S. M. Dewi, and A. Soehardjono[5] have also conducted an experiment by introducing cyclic loading to the scaled model on confined masonry using local bricks found around Indonesia and reported that the value of overstrength factor for the confined masonry without reinforcement is observed ranging from minimum value of 3.6 to maximum of 4.6 whereas for that of confined masonry with reinforcement is observed ranging from minimum value of 3.47 to maximum of 7.37. Similarly ductility reduction factor for confined masonry without reinforcement was observed ranging from minimum value of 1.63 to 2.09 and for confined masonry with reinforcement was observed ranging from minimum value of 1.76 to 2.51.

Response Reduction Factor as per different codes

Response Reduction Factor for confined masonry as per IS 1893-2016 [7] = 3
As per NBCC 2005 [10] = 2.25
As per chilean seismic design Building code NCh433 [4] = 3
As per American Society of Civil Engineers (ASCE 7-10) [8] = 3

II. BUILDING DESCRIPTION AND GEOMETRY

Two different Plans were considered for the analysis namely Model A and Model B. These Models were considered for 3, 4 and 5 storey with varying wall densities. For each Plan and storey, 7 different models were created considering variation in wall densities resulting in 42 different models for Plan A and Plan B with 3, 4, 5 storey.
Since the building is regular with limited height and to scope of work is limited (storey height 3 m).
The Confined Masonry model for the building comprises of Brick Masonry walls confined by RCC tie columns and tie beams at each wall intersections and corners. Tie beams and tie columns are considered of sizes 230mm*230mm. All the internal and external walls are considered as 230mm thick.

Description of Building Model A_{i1} for 3, 4 and 5 storey.

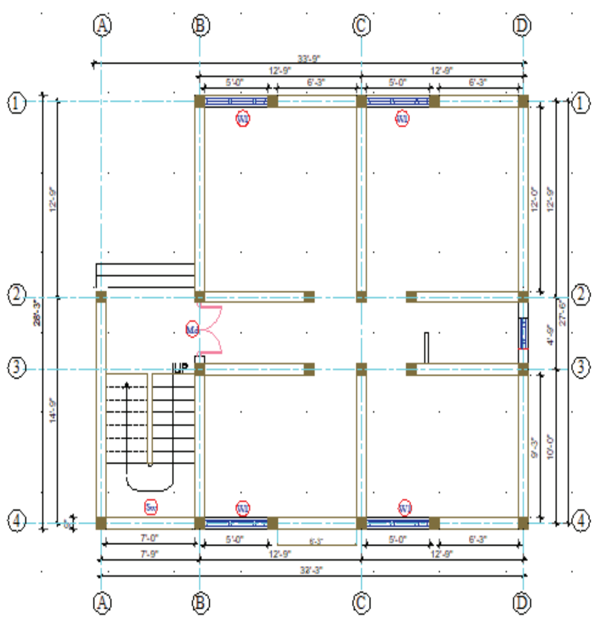


Figure A-1: Building Model A_{i1} for 3, 4 and 5 storey.

Description of Building Model A_{i2} for 3, 4 and 5 storey.

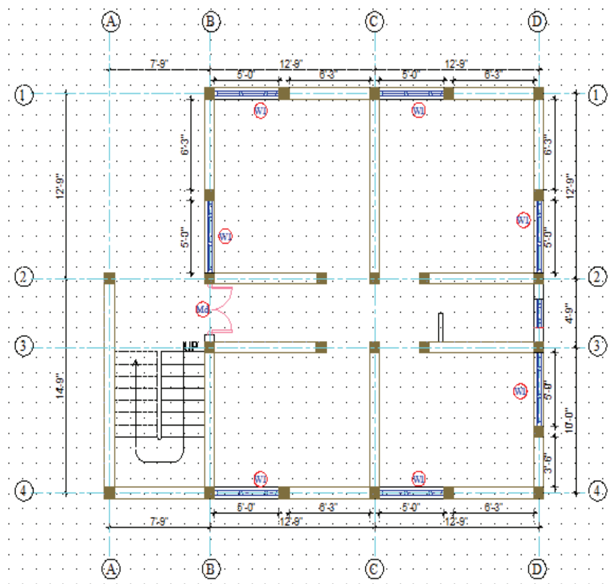


Figure A-2: Building Model A_{i2} for 3, 4 and 5 storey.

Description of Building Model A_{i3} for 3, 4 and 5 storey.

All Description of walls dimension and openings in X direction is same as Building Model A_{i2}. Windows in Y direction is increased from 5ft and made to 6ft in the building model A_{i2} to get Model A_{i3} except for the portion of wall along the grid D4-D3 in which opening is decreased from 5 ft and made to 4ft in order to maintain wall density requirement of external walls.

Description of Building Model A_{i4} for 3, 4 and 5 storey.

All Description of walls dimension and openings in X direction is same as Building Model A_{i2}. All Description of walls and dimensions in Y direction is same as Building Model A_{i2} except there is 5ft window along grid A – A located near region A2 of grid A-A along Y- direction and 2-2 along X- direction.

Description of Building Model A_{i5} for 3, 4 and 5 storey.

All Description of walls dimension and openings in X direction is same as Building Model A_{i2}. All Description of walls and dimensions in Y direction is same as Building Model A_{i2} except window size of 5ft is increased to 6ft in Y direction and for the portion of wall along the grid D4-D3 in which opening is decreased from 5 ft and made to 4ft in order to maintain wall density requirement of external walls. Along the grid A – A located window of length 6ft is added near region A2 of grid A-A along Y- direction and 2-2 along X- direction.

Description of Building Model A_{i6} for 3, 4 and 5 storey.

For X direction every wall is kept same as that of A_{i2} except in the grid along 4-4 where openings are replaced by wall. For Y direction all walls dimensions and opening are kept same as that of A_{i4} as shown in figure below.

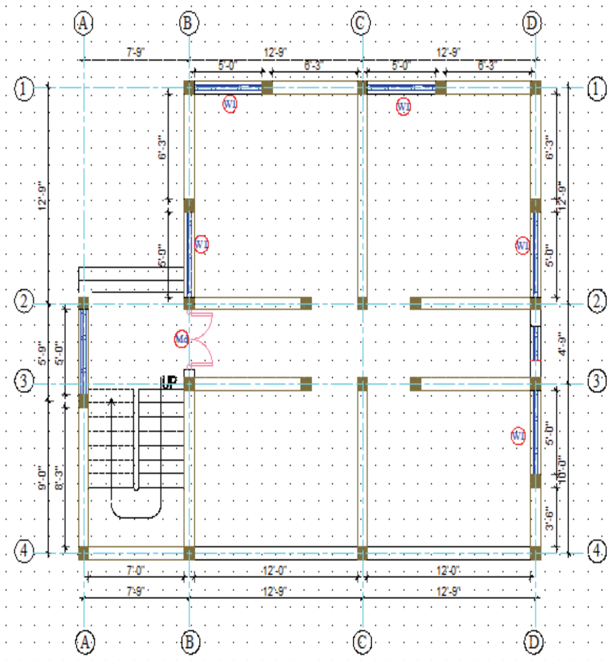


Figure A-3: Building Model A_{i6} for 3, 4 and 5 storey.

Description of Building Model A_{i7} for 3, 4 and 5 storey.

Every details of Building Model A_{i7} is kept same as in Building Model A_{i2} in X direction except along grid 3-3 where both walls in X direction are removed. Every details in Y direction in Building Model A_{i7} is kept same as that of Building Model A_{i2} except there is 5ft window along grid A – A located near region A2 of grid A-A along Y- direction and 2-2 along X-direction and also for the portion of wall along the grid D4-D3 in which opening is decreased from 5 ft and made to 4ft in order to maintain wall density requirement of external walls.

Description of Building Model B_{i1} for 3, 4 and 5 storey.

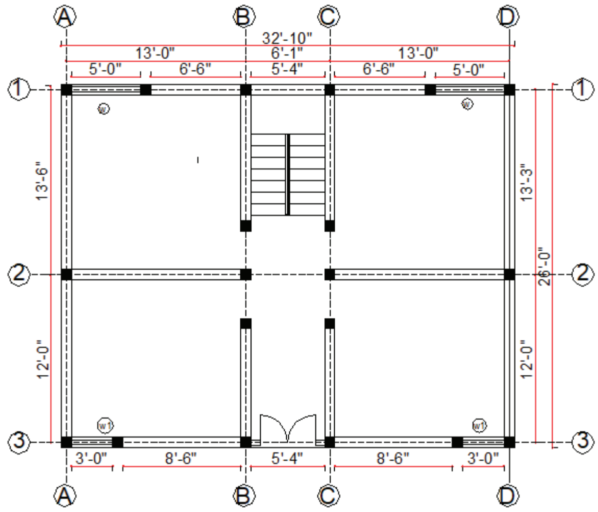


Figure B-1: Building Model B_{i1} for 3, 4 and 5 storey.

Description of Building Model B_{i2} for 3, 4 and 5 storey.

Every details of Building Model B_{i2} is kept same as in Building Model B_{i1} in X direction except windows dimension is changed from 5ft to 6ft along grid 1-1 but along grid 3-3 opening is not changed in order to maintain minimum wall density requirement for exterior wall. Every details in Y direction in Building Model B_{i2} is kept same as that of Building Model A_{i1}.

Description of Building Model B_{i3} for 3, 4 and 5 storey.

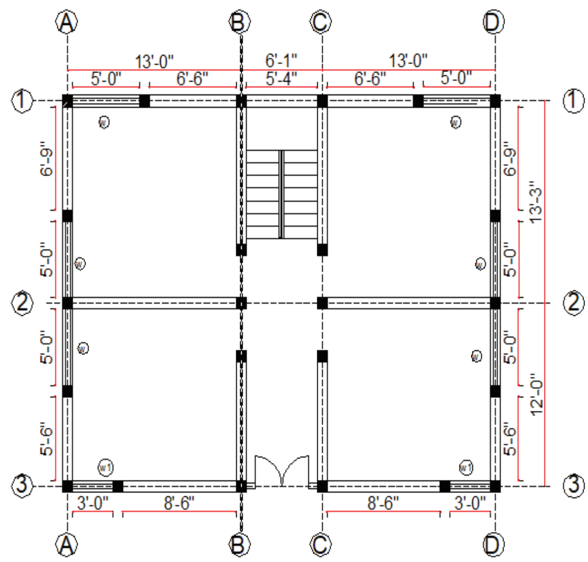


Figure B-2: Building Model B_{i3} for 3, 4 and 5 storey.

Description of Building Model B_{i4} for 3, 4 and 5 storey.

Every details of Building Model B_{i4} is kept same as in Building Model B_{i3} in X direction except windows dimension is changed from 5ft to 6ft along grid 1-1 but along grid 3-3 wall length remains same as that of model B_{i3}. Every details of Building Model B_{i4} is kept same as in Building Model B_{i3} in Y direction except windows dimension is changed from 5ft to 6ft.

Description of Building Model B_{i5} for 3, 4 and 5 storey.

Every details of Building Model B_{i5} is kept same as in Building Model B_{i3} in X direction. Every details of Building Model B_{i5} is kept same as in Building Model B_{i3} in Y direction except windows is removed and replaced by wall along grid D-D. There is no window along grid D-D.

Description of Building Model B_{i6} for 3, 4 and 5 storey.

Every details of Building Model B_{i6} is kept same as in Building Model B_{i3} in Y direction except all windows of size 5ft is increased to 6ft along Y direction. Every details of Building Model B_{i6} is kept same as in Building Model B_{i3} in X direction except windows of size 5ft is increased to 6ft along grid 1-1 and windows of size 3ft is replaced by wall along grid 3-3 in X direction.

Description of Building Model B_{i7} for 3, 4 and 5 storey.

Every details of Building Model B_{i7} is kept same as in Building Model B_{i3} in Y direction except all windows of size 5ft is increased to 6ft along Y direction and wall is removed from grid B3-B2 in Y direction. Every details of Building Model B_{i7} is kept same as in Building Model B_{i3} in X direction except windows of size 5ft is increased to 6ft along grid 1-1 and windows of size 3ft is replaced by wall along grid 3-3 in X direction.

Material Properties

Grade of concrete used = M20
Rebar used = Fe500 TMT bars
Tie Beams
Size of beam = 230 mm x 230 mm
Reinforcement details: 3-12mm ϕ at top and 3-12mm ϕ bars at bottom
1% of concrete area
6mm ϕ stirrups @ 150mm c/c
Clear cover = 30 mm
Tie Columns
Size of column = 230 mm x 230 mm
Reinforcement details: 4-10mm ϕ at corners and 4-10mm ϕ at edges
8mm ϕ ties @ 100mm c/c
Clear cover = 30 mm
Slab
Thickness of slab = 125 mm
Wall
230 mm full brick masonry type wall.

III. MODELLING AND ANALYSIS

Different literatures were reviewed for the modelling of the system with various assumptions for the ease of the model and without much variation in results. For ease and to avoid much analytical complexity without much loss of accuracy of the analysis the assumption made for simplification is that only the main structural elements such as slab, tie beam, tie column and masonry panels are taken as main participating components. In this particular Study following steps were undertaken for the modelling and analysis:

a) Literature review and selection of the Plan of the building.
b) Calculation of the wall density index [1] as wall density index = area of wall / area of slab
   Wall densitiy criteria also satisfies the criteria of Meli. R, which states that Exterior walls should be ≥ 50 % of the building dimension in that direction[1] .

$$\%\text{ of exterior wall} = \frac{\text{Exterior length of (wall + column) only}}{\text{total length of building in that dimension}} \times 100$$

c) Model was formed in SAP 2000 “Integrated software for analysis and design”. For the modelling of the building strut and tie model (STM) [2] was selected. Live load of 2 KN/m2, Floor finish of 1 KN/m2 were assigned to the model and mass source as per IS code.
d) Equivalent width of the diagonal strut for URM infill walls without any opening is taken as [12]

$$w_{ds} = 0.175\alpha_h^{-0.4} L_{ds}$$

where,

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

where, Em and Ef are modulii of elasticity of materials of unreinforced masonry infill and Moment resisting frame, Ic is the moment of inertia of the adjoining column, t the thickness of infill wall, and θ be the angle of diagonal strut with the horizontal, h is the height clear height of the wall.

modulus of elasticity of materials of masonry infill Em =	1335.73	MPa
grade of concrete fck =	20	MPa
modulus of elasticity of materials of frame Ef =	22360.68	MPa

thickness of wall t =	0.23	m
height of wall h =	2.75	m
moment of inertia of adjoining column Ic = $bd^3/12$	0.000233	m^4

e) For the analysis of the strut, material properties that was considered is below:
Stress Strain Data for Masonry [3]
Modulus of Elasticity of brick masonry can be idealised as Em = 550 fm'
Where, fm' = modulus of elasticity of brick masonry, fm' = $0.63\ f_b^{0.49}\ f_j^{0.32}$
Minimum class of Brick for load bearing Masonry is class B and Minimum Mortar grade of cement sand Mortar is 1:6 [14]. So, following masonry properties were obtained.
fb = crushing strength of brick = 7.5 N/mm2
fj = mortar strength = 3.1 N/mm2
Therefore, Masonry strength of class B brick in cement sand mortar of 1:6 and Modulus of elasticity of Brick Masonry are
fm = 2.4286 N/mm2
and Em = 1335.73 N/mm2
Stress strain data for masonry with class B brick and cement sand mortar of 1:6 is obtained as follow:

Stress fm N/mm2	strain
0	0
0.80143859	0.0009
1.821451342	0.0021
2.18574161	0.0029
2.428601789	0.0036
1.457161073	0.0059

f) Design base shear was calculated as per IS 1893:2016 [7] and for pushover analysis FEMA 356 [13] was followed. Hinges were auto assigned for the frame and for strut axial hinge was assigned at half length of the diagonal and pushover curve was generated. After generating pushover curve yield base shear, maximum displacement, yield displacement was noted.

g) Calculation of Response reduction Factor
Response reduction factor R = $R_d * R_0$
R_d is ductility related force modification factor, R_0 = overstrength related force modification factor = Yield base shear / Design Base shear
Structural Ductility factor μ = Maximum displacement / elastic displacement.
R_d = ductility related force modification factor, $R_d = \sqrt{(2\mu-1)}$

h) Data analysis

Response reduction factor was then related with wall density index in both X and Y direction which can be used to predict the response reduction factor on the basis of wall densities for this Regression analysis [9] was done.

IV. ANALYSIS RESULT AND DISCUSSION

Wall densties for different model is tabulated below (in the subscript i refers to the storey number and j refers to model number).

Model	Wall density index along X – dir %)	Wall density index along Y – dir (%)
A_{i1}	6.89	7.691
A_{i2}	6.89	6.384
A_{i3}	6.89	6.297
A_{i4}	6.89	5.948
A_{i5}	6.89	5.774
A_{i6}	6.7	6.384
A_{i7}	4.19	5.948
B_{i1}	5.73	8.655
B_{i2}	5.2	8.655
B_{i3}	5.73	6.89
B_{i4}	5.2	6.545
B_{i5}	5.37	7.75
B_{i6}	5.9	6.545
B_{i7}	5.2	5.9

Response reduction factor for different models is tabulated below

Model	Ro	μ	Rd =	R= Ro*Rd
A31	4.280	1.711	1.556	6.660
A32	4.107	1.665	1.526	6.268
A33	3.837	1.742	1.576	6.048
A34	3.664	1.784	1.603	5.873
A35	3.525	1.879	1.660	5.854
A36	4.097	1.7675	1.533	6.282
A37	3.213	1.440	1.371	4.406

B31	4.323	1.790	1.606	6.943
B32	4.272	1.753	1.583	6.764
B33	4.173	1.479	1.399	5.840
B34	3.964	1.428	1.362	5.400
B35	4.212	1.486	1.404	5.914
B36	4.118	1.616	1.494	6.153
B37	3.722	1.380	1.327	4.939

3 – storey building both Models A and B were introduced with openings and sizes of openings were varied and 7 different models were obtained with different in wall densities. All together 14 different models were generated and analysis was done and results have been presented in the table above. Base shear decreases with decrease in wall densities. It was obtained that as the wall densities decreases, overstrength factor R_0 also decrease significantly while Ductlity factor R_d don't decrease significantly compared to as that of overstrength factor. However, overall R value decreases with decrease in wall densities.

Model	Ro =	μ	Rd	R= Ro*Rd
A41	3.112	2.083	1.780	5.537
A42	2.957	2.071	1.772	5.241
A43	2.752	2.155	1.819	5.006
A44	2.681	2.065	1.769	4.743
A45	2.566	2.028	1.748	4.485
A46	2.924	2.11	1.799	5.262
A47	2.456	2.023	1.745	4.285
B41	3.201	2.177	1.831	5.862
B42	3.178	2.117	1.798	5.714
B43	2.976	1.795	1.610	4.790
B44	2.922	1.580	1.469	4.294
B45	3.138	1.963	1.710	5.368
B46	2.986	1.909	1.679	5.012
B47	2.737	1.851	1.644	4.499

For 4 storey building, after analyzing results of 14 different models of namely A and B, it was obtained that as the wall densities decreases, overstrength factor(R_o) also decrease significantly while Ductlity factor(R_d) don't decrease significantly compared to as that of overstrength factor. However, overall R value decreases with decrease in wall densities.

Model	Ro	μ	Rd =	R= Ro*Rd
A51	2.315	2.790	2.140	4.955
A52	2.215	2.694	2.095	4.639
A53	2.155	2.664	2.081	4.483
A54	2.060	2.549	2.024	4.169
A55	1.967	2.621	2.060	4.050
A56	2.199	2.710	2.102	4.624
A57	1.967	2.378	1.938	3.813
B51	2.539	2.595	2.047	5.198
B52	2.551	2.045	1.758	4.485
B53	2.297	2.352	1.925	4.422
B54	2.215	2.332	1.914	4.240
B55	2.444	2.341	1.919	4.689
B56	2.323	2.219	1.854	4.307
B57	2.097	2.127	1.804	3.783

For 5 storey building, after analyzing results of 14 different models of namely A and B, it was obtained that as the wall densities decreases, overstrength factor(Ro) also decrease significantly while Ductlity factor(Rd) don't decrease significantly compared to as that of overstrength factor. However, overall R value decreases with decrease in wall densities.

As the storey increases, overstrength factor (Ro) decreases and ductility factor(Rd) increases. However, overall R value for 3 storey is more than 4 storey and 4 storey is more than 5 storey. Therefore, it was studied that Response reduction factor decreases with decrease in wall densities.

Mario O. Moroni [4] concluded reduction factor decreases with increase in wall densities which contradicts the result obtained from this analysis. For his conclusion he analysed four different building plans with difference in wall densities. Mario O. Moroni's conclusion was based on the study of different buildings. Each Buildings were different in size and different in orientation of the walls and also have different numbers of bay in X and Y directions due to which buildings have different seismic weight and wall densities. So the value of reduction factor is for different types of building of which he concluded that Reduction factor decreases with decrease in wall densities. However in this research, analysis was done in two different plans and wall densities were varied in both X and Y direction for both plans to obtain different analytical models, it is concluded from the result herein that R value decreases with decrease in wall densities and vice versa for the same building and it does mean that as the percentage of wall increases in the building ability of the building to dissipate the energy through inelastic behavior increases.

Similarly, Response reduction factor value ranges from 2.25 to 3 according to different codes which is way below the analysis result obtained in this

research. Wisnumurti, S.M. Dewi and Soehardjono from their experiment have concluded R value from the code is way below than that of actual value obtained from the tests. Similarly Mario O. Moroni's value for overstrength factor ranges from 2.94 to 7.91 which when multiplied with ductility factor gives value more than 3. This suggests the value used in codes is very conservative.
R value acts as dependent variable while wall density index in X and Y direction acts as independent variables. Regression analysis was done in Microsoft excel and equations were obtained.

For 3 storey building

R = -1.129606213 + 0.533583935 X% + 0.57162426 Y%, (X% > 2.5, Y% > 2.5)
From analysis data,
Adjusted r^2 = 0.9226
92.26% of the response reduction factor can be explained by the wall density index in X and Y direction.

For 4 storey building

R = 0.311329656 + 0.242921156 X% + 0.476209254 Y%, (X% > 2.5, Y% > 2.5)
From analysis data, regression coefficient is
Adjusted r^2 = 0.8420
84.20% of the response reduction factor can be explained by the wall density index in X and Y direction.

For 5 storey building

R = 0.690470769 + 0.232453222 X% +0.343319927 Y%, (X% > 2.5, Y% > 2.5)
From analysis data, regression coefficient is
Adjusted r^2 = 0.7859
78.89% of the response reduction factor can be explained by the wall density index in X and Y direction.

V. CONCLUSIONS AND RECOMMENDATIONS

Overstrength factor and ductility reduction factor has been calculated by using non-linear static analysis for 42 models with varying wall densities and storey. Over strength factor and ductility reduction factor has been further used to calculate Response Reduction Factor. From the analysis of these data following conclusions are made.

a) From the analysis result it has been observed that as the wall density index decreases, Overstrength factor decreases significantly, however ductility reduction factor don't decrease significantly this is due to added confining element in the openings.
b) As the wall density index decreases, response reduction factor also decreases. Main decrease in response reduction factor is due to the significant decrease in Overstrength factor.
c) Overstrength factor decrease with the increase in storey while ductility factor increases with increase in storey, however overall response reduction factor decreases when storey increases.
d) Response reduction factor calculated is greater than the value that is being used in codes and only come closer if wall density is way below regular construction practice of buildings.
e) R value for 3 storey building based on wall densities in X and Y direction is
R = -1.151409813 + 0.542135069 X% + 0.568675378 Y%
f) R value for 4 storey building based on wall densities in X and Y direction is
R = 0.292230378+ 0.250411684 X% + 0.473626125 Y%
g) R value for 5 storey building based on wall densities in X and Y direction is
R = 0.690470769 + 0.232453222 X% +0.343319927 Y%

VI. LIMITATION OF THE STUDY

a) Only two building models were selected and wall densities were varied for the analysis.
b) Walls were modeled using strut and tie model, however walls below and above openings were not considered.
c) Only non – linear static analysis was carried out for the study.
d) Default hinge was used in Members.
e) Soil structure interaction was not considered.
f) Effect of bands that are proposed for the construction are not considered during analysis.

VII. RECOMMENDATION FOR FURTHER STUDY

a) Study can be done by using different typical buildings.
b) Other methods like Equivalent frame method and finite element method can also be employed for the analysis to verify results.
c) Non-linear time history analysis can be used for the analysis to verify the results.
d) Study can be further done by taking account of the wall below and above the openings and also intermediate bands that have been proposed during the construction.

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