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SEISMIC MARGIN ASSESSMENT OF SHEAR WALLS WITH DIFFERENT ASPECT RATIO

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ABSTRACT

Recent earthquake events resulting in exceedance of design basis earthquake has provided renewed thrust on seismic margin assessment (SMA) of Nuclear Power Plants (NPPs). Shear walls are commonly used for earthquake resistant design of NPP structures, and characterisation of shear wall behaviour under lateral loads is a basic requirement for seismic margin assessment of NPPs and other structures with shear walls.

In the current study, SMA of shear walls with aspect ratios that are generally encountered in NPP structures is carried out using pushover analysis procedures viz. Capacity Spectrum Method as suggested in ATC 40 (1996). A validated numerical modeling procedure using finite element software Abaqus is used to calculate the capacity curves of shear walls with low to moderate aspect ratio. It was found that application of ATC-40 method to shear walls results in over estimation of inelastic damping. Hence other reported relationships for estimation of damping, specifically applicable to shear wall structures, were evaluated, validated and used.

With the validated assessment procedures, seismic margins of shear walls with different aspect ratio (2/3, 1, and 5/3) are studied considering realistic structural configurations. These shear walls are designed following Indian Standard code of practice, corresponding to a high seismic demand (Zone-IV). Subsequently, SMA of these shear walls is carried out considering different performance objectives. The study indicates that seismic margin for shear walls reduces with decrease in aspect ratio and there is need to have a relook at the estimates of damping currently being used for analysis/ seismic re-evaluation of shear walls and shear wall type structures.

INTRODUCTION

To quantify seismic margin of any structure, many procedures are reported in literature viz. response reduction factor based approach, nonlinear response history analysis, and nonlinear static response analysis [IAEA-TECDOC-1655, (2011)]. Motivation for developing simplified procedures has essentially been to find an alternative approach to nonlinear response history analyses which is analytically complex and computational expensive/ sensitive. As a good alternative to this approach, methods of performance assessment using displacement based approach proposed in document viz. ATC-40 (1996) is applied to conventional frame structures by many of the researchers. However, use of these approaches for short period structures like low rise shear walls is still under evolution [IAEA-TECDOC-1655, (2011)].

Behavior of low-rise walls may be quite different from that of slender shear walls because of the effect of wall aspect ratio. Low rise walls with aspect ratio < 1.0 has predominant shear behavior compared to high rise walls with aspect ratio > 2.0 having predominance of flexure action. For mid rise walls behavior is combined shear and flexure. This work is aimed at quantification of seismic margin of low rise shear

walls with different aspect ratio using displacement based approach. These aspect ratio reflect configurations generally encountered in NPPs. Applicability of ATC-40 (1996) method for performance assessment of structures is reviewed and certain modifications are proposed for its applicability to shear walls.

NUMERICAL SIMULATION OF INELASTIC BEHAVIOR OF SHEAR WALLS

A realistic and practical modeling and prediction of inelastic response of RC shear wall structures under lateral loading requires analytical models capable of reproducing the nonlinear response of each structural component with reasonable accuracy and simple enough to allow computationally economic solutions. Nonlinear finite element analysis is being increasingly used to predict inelastic response of RC shear wall structures. Despite extensive experimental and analytical research on the behavior of RC wall structures subjected to lateral loads, current analytical approach of material modeling may not be simple enough to solve problem of NPP shear wall structures that have complex configurations. Simple material models are often computationally efficient but have limited accuracy of behavior predictions in nonlinear regime and complex models could land in convergence issues. Jha et al. (2013) calibrated and validated the concrete damage plasticity model of FE software Abaqus along with a modeling procedure to predict non-linear response of shear walls. In the present work this validated numerical modeling procedure for shear wall is adopted.

SEISMIC PERFORMANCE ASSESSMENT USING PUSHOVER ANALYSIS

The two key points of a performance based analysis procedure are demand and capacity. Demand is the representation of earthquake ground motion to the structure and capacity is the structure's ability to resist the seismic demand. Once capacity curve of the structure is established, performance assessment of the structure can be done using Capacity Spectrum Method (CSM). In this method capacity of structure is compared with seismic demand in acceleration displacement response spectrum (ADRS) format to assess the seismic performance of structure. In order to determine performance of a structure for a given seismic demand, displacement along the capacity curve is determined that is consistent with seismic demand. The procedure seeks to find out a point on the capacity spectrum that also lies on the appropriate demand spectrum, which has been scaled down for nonlinear effects. This point is called performance point. However this methodology is primarily applied to frame (beam-column)/ flexure dominant structures. For short period structure like shear walls, effectiveness of displacement based procedures needs to be assessed before it is used for SMA.

Application of Capacity Spectrum Method to shear walls

As per the study carried out by Gulkan et al. (2005) for performance assessment of shear walls tested on shake table, CSM significantly underestimates inelastic displacement demand. Principal reason outlined by them for this outcome was the unrealistic reduction in the demand, i.e. reduced elastic response spectrum, owing to use of very high damping values. Owing to high damping values as estimated, the inelastic displacement demand for a given ground motion is under predicted. The estimated damping value as obtained from equation of ATC-40 (1996) to take into account the inelastic behavior in the system is well above twenty percent in many of the cases. But such high damping values are not expected for shear wall structures. According to PEER/ATC 72-1 (2010), for experiments conducted on shaking table, the maximum value of damping in RC wall-frame system ranges from 6.9% - 7.5% even under significant damage conditions.

Hence it is clear that CSM in its current form cannot be applied to shear wall structures unless capability for prediction of damping value is improved. A possible remedy to overcome this problem would be to use other methods that are based on more realistic assumptions for computing the equivalent viscous damping.

Modification of CSM for its application to shear walls

Limited equations are available in literature for realistic estimation of effective damping for shear walls. Currently three formulations are assessed, (i) equation as per ATC-40, (ii) equation as per Gulkan et al. (2005), (iii) equation as per Kennedy et al. (1984). Details of these formulations can be found in the respective research paper/ document.

(i) ATC-40, 1996

$$\beta_{eff} = 0.05 + k\frac{2(\mu-1)(1-\alpha)}{\pi\mu\,(1+\alpha\mu-\alpha)};$$

Where, μ=displacement ductility ratio, α=post elastic stiffness ratio, β_{eff}= effective damping.

(ii) Gulkan et al. 2005

$$\beta_S = \frac{1+10\left(1-\frac{1}{\sqrt{\mu}}\right)}{50};$$

Where, β_s= substitute damping, μ is the ductility factor that describes the ratio of maximum displacement excursion to the displacement at the yield

(iii) Kennedy et al. 1984

$$\beta_e = \left(\frac{\frac{f_s}{f}}{\frac{f_e}{f}}\right)^2 (\beta + \beta_h);$$

Where, β_e= effective damping, β = viscous damping of shear wall structure, β_h= pinched hysteresis damping, f_s= secant frequency, f= elastic frequency, f_e= effective frequency.

To judge the effectiveness of these equations for prediction of damping for shear walls, seismic performance assessment of a shear wall specimen tested on shake table is carried out using capacity spectrum method with these three equations for evaluation of damping. Best among three that reflects experimental data is used for further assessment using capacity spectrum method. The specimen considered is a 1/3-scale model of a representative 5-story reinforced concrete building detailed according to French practice [IAEA CRP-NEF (2002)].

Specimen details

A series of shaking table experiments on shear walls were carried out in the Saclay Nuclear Center in France in 1997. One particular specimen from that program, CAMUS, was re-studied in the CRP organized by IAEA [IAEA CRP-NEF (2002)].

The 1/3rd scaled model, CAMUS, consist of two parallel 5-floor R/C walls without opening linked by 6 square floors (1.7m x 1.7m) (including the floor connected to the footing). The specimen had a total mass of 36 tons with additional masses attached to it. A heavily reinforced concrete footing allowed anchorage to the shaking table. Total height of the model was 5.10 m. Width of shear wall is 1.7 m and thickness is 6 cm. The specimen had a measured fundamental natural frequency of 7.24 Hz. Details of the specimen including reinforcement detailing and material properties can be found in IAEA CRP-NEF (2002). Total five time history analyses, Run-1 to 5, were performed on shake table for CAMUS specimen. This specimen was modeled using FE software Abaqus for pushover analysis with validated input parameters as discussed in previous section. FE model of the specimen and pushover curve are shown in Figure-1.

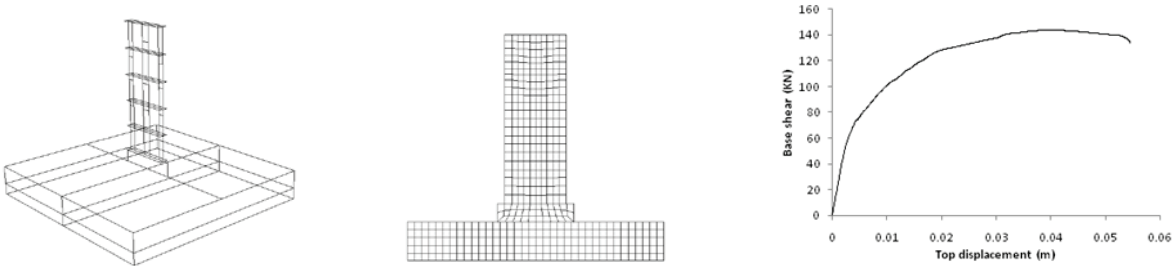


Figure-1 Idealized FE model of CAMUS specimen and a typical pushover curve corresponding to the idealization

Calculation of damping at various drift levels

Table-1 shows calculated damping values as per the above mentioned equations at different displacement demands. It can be seen that the damping values as per equation proposed by Gulkan et al. (2005) are generally lower compared to those obtained from ATC-40 (1996) but are still on higher side with respect to reported value in PEER/ATC 72-1 (2010). The equation proposed by Kennedy et al. (1984), takes into account the specific behavior of shear walls and predicts damping values very close to experimentally observed values.

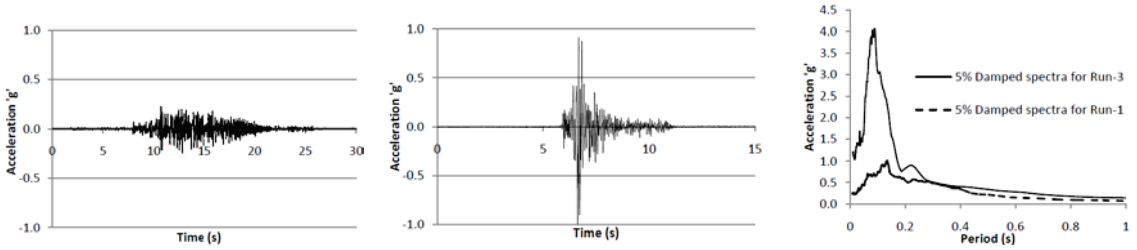
Table-1 Comparison of damping values estimated by different equations

% Drift (fraction of drift at ultimate load)	Damping value as per ATC-40, (1996)	Damping value as per equation of Gulkan et al. (2005)	Damping value as per Kennedy R.P et al. (1984)
24.6	11.25%	12.80%	5.80%
38.4	18.68%	11.83%	6.92%
56.5	21.08%	12.91%	7.78%
82.2	22.25%	14.10%	7.92%

From the above discussions it is clear that equation of Kennedy et al. (1984) for calculation of effective damping for shear wall structures gives reasonable approximation of the amount of energy dissipated when compared to experimentally observed value reported in PEER/ATC 72-1 (2010). It is expected that the inelastic demand can be approximated with more accuracy using this equation. This conclusion is verified from the outcome of CAMUS test and analysis data described in the following subsection.

Estimation of performance point and comparison with experimental result

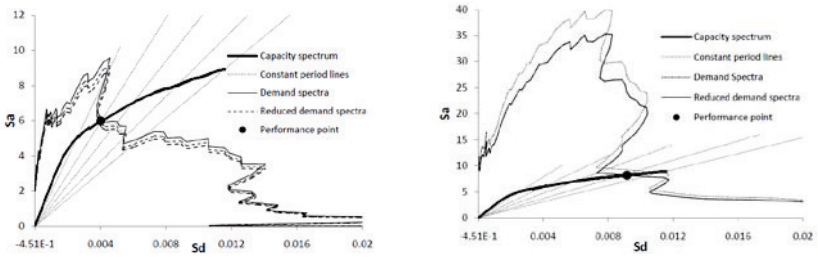
To validate the equation of Kennedy et al. (1984) for use in CSM, performance assessment of the CAMUS specimen is carried out for Run-1 & Run-3 time history analysis. Figure-2 shows the input time histories and corresponding response spectra (5% damped) for Run-1 and Run-3.



(a) Run-1 Time History (b) Run-3 Time History (c) Response spectra for Run-1&3

Figure-2 Input time histories and response spectra for Run-1 and Run-3

Performance assessment for estimation of performance point of CAMUS specimen for Run-1 and Run-3 is represented in graphical form in Figure-3.



(a) Run-1 (b) Run-3

Figure-3 Performance assessment of CAMUS specimen for Run-1 and Run-3

Calculated performance points using the proposed modified procedure show good match with peak displacement and corresponding base shear obtained from the experiment during dynamic testing. Comparison of experimental values and the values predicted by analysis using proposed modified CSM is shown in Table-2. It is seen from Table-2 that there is a very good match between experimental and predicted values.

Table-2 Comparison between the observed and predicted displacement and base shear for Run1 and Run3

No.	Performance Analysis		Experiment(time history)	
	Δ(mm)	V(KN)	Δ(mm)	V(KN)
Run-1	5.60	80.4	7	69.4
Run-3	12.84	109.8	13	112.0

CASE STUDY FOR SEISMIC MARGIN ASSESSEMNT

Study on seismic margin in shear walls with different aspect ratios is carried out in this work using the seismic performance assessment procedure outlined in previous section. Three structures having shear

walls as major lateral load resistant member with aspect ratios (height/width) 0.67, 1.0 and 1.67 respectively designed as per Indian Standard codes [IS:456 (2000), IS:1893 (2002), and IS:13920 (1993)] are considered for the study. The structures are analyzed for dead load plus live load, by static analysis and for earthquake load using response spectrum method. For response spectrum analysis IS:1893 (2002) specified zone-IV response spectrum for rocky and hard soil sites is used. As the aim of the study is to evaluate available seismic margin, importance factor and response reduction factor as per IS:1893 (2002) are taken to be unity in the current work. For the same reason, load factors used for design are also considered as unity. Pushover analysis is carried for the walls using validated numerical model of Jha et al. (2013) with lateral load distribution proportional to first fundamental mode for estimating seismic margin.

General description of structures considered in this study

RCC structures considered in the study have plan dimension of 24m x 24m with a grid size of 6m x 6m and floor height of 4m in each case. To capture change in aspect ratio of shear wall, number of floors are varied. Structures are of 5, 3, and 2 stories with total height of 20m, 12m and 8m respectively. General layout of structure and finite element model of structure with 20m height are shown in Figure-4 and Figure-5. Columns of dimension 500mm x 500mm and beams of 300mm x 600mm are considered. Thickness of shear walls is taken as 230mm.

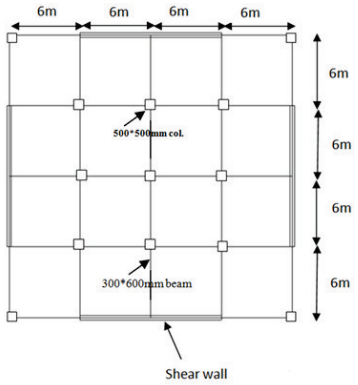


Figure-4 Layout of structure

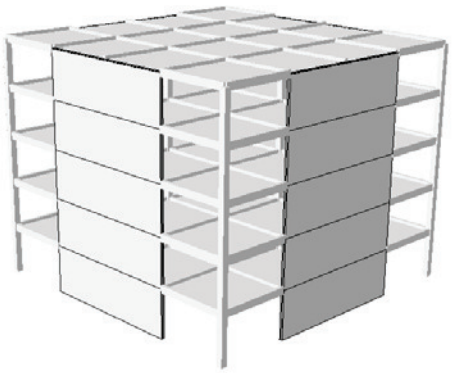
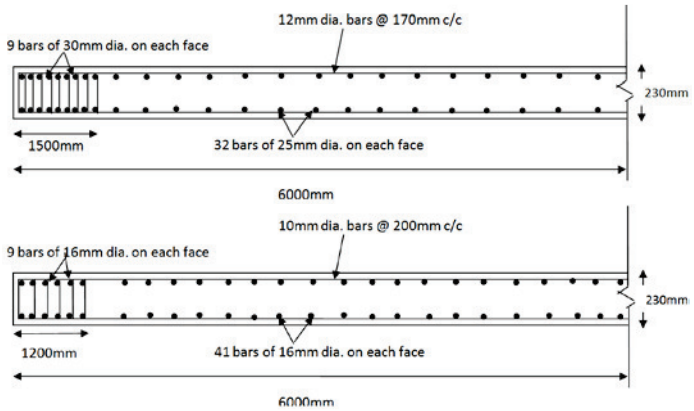


Figure-5 Geometric model of structure with 20m height

The shear walls are designated as SW-I, SW-II, and SW-III with corresponding aspect ratio (H/W) of 1.67, 1.0 and 0.67 respectively. Reinforcement detailing of the walls is shown in Figure-6.



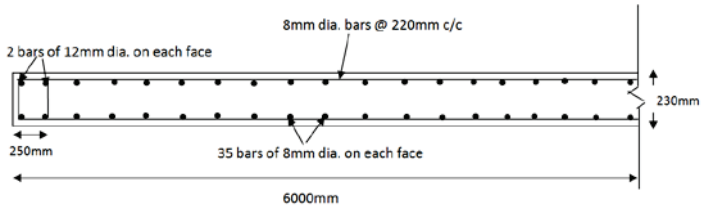


Figure-6 Reinforcement detailing of SW-I (top), SW-II (middle), and SW-III (bottom)

In all the cases, 8mm dia. cross ties are provided at a spacing of 115mm c/c in boundary elements as per the detailing requirement of IS-13920 (1993). Reinforcement detailing is done in such a way that amount of reinforcement provided is just equal to required reinforcement, ensuring that the comparison of seismic performance is on a common platform.

Pushover analysis of walls

Pushover analysis of the FE model of walls under monotonically increasing load is carried out with lateral load distribution corresponding to the first mode of the wall. Details of first mode of shear wall are given in Table-3.

Table-3 Modal details of the shear walls

Wall	Mode	Frequency of only shear wall (Hz)	% Mass participation
SW-I	I	4.62	67.5
SW-II	I	6.85	71.6
SW-III	I	10.98	75.0

Size of finite elements ranges from 0.7m to 0.9m. FE mesh for pushover analysis is shown in Figure-7. Capacity curves of the walls are shown in Figure-8.

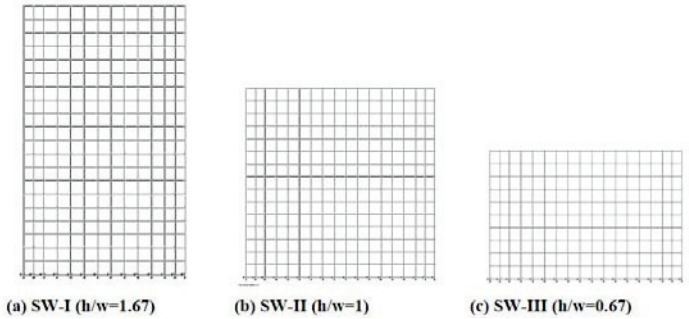


Figure-7 FE mesh of shear walls

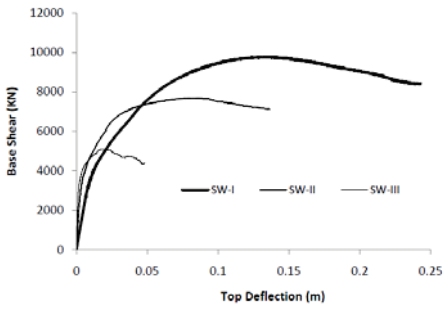


Figure-8 Pushover curves of shear walls

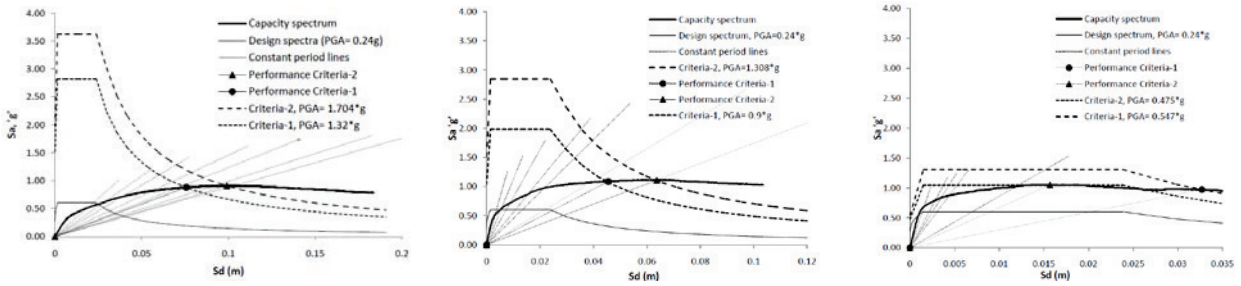
Analysis shows that post elastic behavior significantly depends on the aspect ratio of the wall. As expected, wall with higher aspect ratio shows better ductility than that of low aspect ratio shear walls due to predominant flexure action. Load-deformation response of shear walls also gives sufficient information about failure modes. Wall SW-III, with aspect ratio of 0.67, due to shear mode of failure has least amount of inelastic deformation capabilities indicating shear failure mode. Wall SW-I with aspect ratio of 1.67 on the other hand has shown significant inelastic deformation capabilities before failure.

Seismic performance and margin assessment

Capacity spectrum method with proposed modification in damping estimation as discussed in previous section is used for performance assessment in the fundamental mode. Effect of higher mode is not considered in this study. Capacity curve of the structure is converted into capacity spectrum (ADRS format) and is superimposed with the demand spectrum to establish performance point after taking into account effect of hysteretic damping.

Seismic margin is evaluated for the predefined performance objective specified in EPRI-TR-103959 (1994), for NPP structures. This document specifies that drift in shear wall should not exceed 0.5% in case where safety related equipments are attached. In addition, drift at peak/ ultimate load is also considered as one of the performance objective in the present study to check the collapse limit state of the walls. It is seen that for SW-I and SW-II, drift at peak load is more than 0.5% (0.66% and 0.70% respectively), whereas for low aspect ratio wall SW-III, drift at peak load is only 0.24%. So the structure with wall SW-III will reach collapse state before 0.5% drift. Seismic margin for these two performance objectives is estimated by scaling up the design response spectrum with respect to PGA till target performance objective on the capacity curve is reached. These performance objectives are designated as Criteria-1 (0.5% drift) & Criteria-2 (drift at peak/ ultimate load). Seismic margin is estimated as the ratio of scaled up PGA to the design PGA.

Performance assessment for estimation of seismic margin for shear walls is represented in graphical form in Figure-9.



(a) SW-I (b) SW-II (c) SW-III

Figure-9 Calculation of PGA values meeting performance objectives

Table-4 shows the comparison of design values of PGA with demand values meeting the performance objectives.

Table-4 Comparison of design PGA and PGA meeting performance objective

Wall	Design PGA 'g'	PGA 'g' at Performance objective		Ratio of PGA at performance limit to design PGA (Seismic Margin)	
		Criteria-1	Criteria-2	Criteria-1	Criteria-2
SW-I	0.24	1.320	1.704	5.50	7.10
SW-II	0.24	0.90	1.308	3.75	5.45
SW-III	0.24	0.547*	0.475	2.28*	1.98

* This point lies beyond the peak load (assumed as collapse load)

It is observed that damping of shear walls due to inelastic deformations decreases with reduction in the aspect ratio of the walls resulting in higher seismic demand. Variation of hysteretic damping with aspect ratio of shear walls considered in this study is shown in Figure-10. It is found that seismic margin in terms of ratio of PGA decreases with decrease in aspect ratio of the wall, as shown in Figure-11.

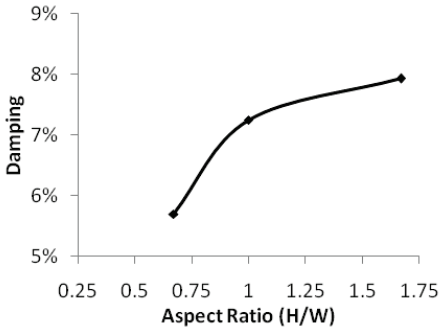


Figure-10 Hysteretic damping against aspect ratio

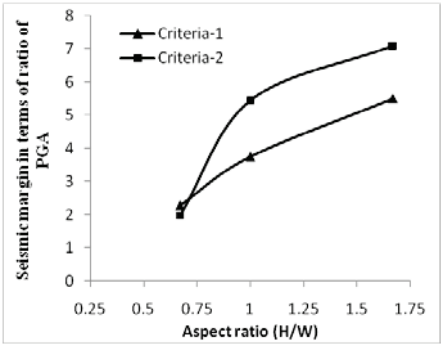


Figure-11 Variation of seismic margin with aspect ratio

CONCLUSIONS

Following are the conclusions drawn from this work:

- Direct application of Capacity Spectrum Method to short period structures like shear walls may give misleading results as inelastic demand due to seismic loading is significantly underestimated by use of damping values as per ATC-40. Present study reveals that the damping value calculated using ATC-40 equation is as high as 22% for shear walls at ultimate load. Experiments conducted on shaking table [PPER/ATC 72-1-2010] shows that under significant damage conditions the maximum value of damping in RC-wall-frame system ranges from 6.9% - 7.5%.
- Equation based on Kennedy et al. (1984) for estimation damping value while using ATC-40 method for shear walls has been proposed in the current study.
- Performance assessment of a 5 storey 1/3 scale model shear wall tested on shake table for two time history inputs using CSM with proposed modification shows effectiveness of the proposed method. The modified method is found to provide much better match than the results predicted by ATC-40 equation for damping estimation.
- Proposed modified CSM can effectively predict performance point of shear wall structure subjected to seismic ground motion and hence can be used for seismic margin assessment.
- Pushover analysis of three shear walls with different aspect ratio shows that, as expected, wall with higher aspect ratio has better ductility as compared to low aspect ratio shear wall.
- For SW-I and SW-II (with aspect ratio 5/3 and 1 respectively), drift at peak base shear is more than 0.5% hence the structures have additional margin against collapse. Whereas SW-III (aspect ratio of 2/3) has lesser drift capacity (0.24%) than 0.5% criteria. Hence 0.5% drift criteria seem to be un-conservative for very low aspect ratio walls.
- Shear walls with different aspect ratio designed according to Indian Standard Codes, shows that walls with lesser aspect ratio has lesser seismic margin in terms of PGA level meeting the performance limit of the structure.
- Damping due to inelastic deformation is lesser for low aspect ratio walls. This is due to lesser inelastic deformation capacity of short shear walls, behavior of which is dominated by shear deformation.

- While designing short shear walls it is not advisable to use response reduction factors because they undergo lesser energy dissipation before failure.
- Seismic capacity of low aspect ratio shear wall saturates at low level of drift, so due attention needs to be given to the level of damage such walls have undergone while deciding their performance limit.

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