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# PUSHOVER ANALYSIS OF CONCRETE SHEAR WALLS: BENCHMARKING OF CAMUS EXPERIMENT

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## ABSTRACT

A number of shake table tests have been conducted on the scaled down model of a concrete shear wall as part of CAMUS experiment in France. The experiments were conducted between 1996 and 1998 in the CEA facilities in Saclay. Benchmarking of CAMUS experiments was undertaken as a part of the coordinated research program initiated by IAEA. Technique of deflection based method was adopted for benchmarking exercise. Pushover analysis, which is an important component of deflection based method is an efficient analytical tool to look into the additional capacities to withstand seismic loading effect that a structural system can offer considering the effect of redundancies and inelastic deformation. Pushover analysis tries to determine the response of the structures against various values of base shears in order to plot the force displacement (base shear - roof displacement) curve of the structure. This is done by step-by-step static non-linear analysis of the structure with increasing value of load. For calculating the performance point of the structure corresponding to a specified input motion, established procedures like FEMA-273, ATC-40 are already available.

**Keywords:** CAMUS, Pushover, Concrete, non linear, shear wall, FEMA-273, ATC-40

## 1. INTRODUCTION

The current engineering practices followed for the design of nuclear facilities are not adequate with respect to safety implications of near field earthquakes. The recent developments in the field of design of non-nuclear facilities could provide measures for taking care of these difficulties. Many workers in this field have proposed that the effect of near field earthquake can be taken care by suitable modification of response factor. While, some have advocated to employ the deflection based method of structural design for this purpose. It has been observed from the recent records of near-fault earthquakes, that near-fault seismic waves usually have a long-period velocity pulse. These pulse-like wave could be much more destructive to structures than a large peak ground acceleration. According to the literature (Lu et. al., Hall, J.F., 1995), the characteristics of near-fault earthquakes could be elaborated as follows: (1) higher ratio of vertical-to-horizontal response spectrum compared to the far field records; (2) higher value of peak ground acceleration; (3) velocity signal consisting of pulse-like long-period wave.

A coordinated research program (CRP) has been initiated by International Atomic Energy Agency (IAEA) to evaluate the safety significance of near field earthquakes on these structures of nuclear facilities (Combescure, 2002). The CRP aims at carrying out computational modeling of objects used in the experimental background and to test the applicability of displacement based approaches for the assessment of nuclear facilitates. Pushover analysis, a deflection based method, has been successfully adopted in the seismic safety evaluation of structures of non-nuclear facilities and is believed to be useful for seismic ground motion having characteristics of NFE. One of the objectives of the CRP is to examine the suitability of pushover analysis for the seismic safety evaluation of nuclear facilities against ground motion with special emphasis on near field effects. The CRP program uses results from the shake table testing of mildly reinforced shear walls conducted as part of CAMUS experiment in France.

Effort has been made in the paper to analyse the data obtained from the experimental results in light of the results predicted using methodologies given in NEHRP Guidelines for the Seismic Rehabilitation of Buildings (FEMA 273) and Seismic Evaluation and Retrofit of Concrete Buildings (ATC-40) documents. The performance points obtained by application of each of this method to the structure are compared with respect to that observed during the experimental program for a shear wall type specimen. The applicability of these displacement-based methods to modeling the effects of near source ground motions on structures was also studied.

## 2. DEFLECTION BASED ANALYSIS METHOD

The ideal approach for non-linear analysis of a structural system against seismic motion is complete non-linear time history analysis. This method is very complex, and becomes sometimes infeasible or impractical for most of practical problems. Deflection based method, which is based on simplified non-linear analysis has been developed for calculating an approximate non linear response of the structure against seismic excitation. This method is also refereed as non-linear static analysis procedures. Pushover analysis is an important component of deflection based analysis method. There are two approaches to determine the performance of the structure during seismic excitation using pushover analysis. They are:

i) FEMA-273 method (FEMA, 1997): This method uses pushover analysis and a modified version of equal displacement approximation to estimate the maximum displacement.

ii) ATC-40 method (ATC, 1996): This method, also known as capacity spectrum method (CSM) that uses the intersection of pushover (capacity) curve and a reduced response spectrum to estimate the maximum displacement.

Two terminologies are used in deflection based methods to specify the performance of a structure under earthquake loading effects. They are, performance point and target displacement. Both are, in effect, the same parameters, i.e., the expected top displacement of the structure under the effect of design earthquake, also considering the non-linear behavior of the structure. This term ‘performance point’ is widely used in ATC-40 method, where as the FEMA 273 approach defines this parameter as target displacement.

Both the methods have basically two steps, 1) determination of pushover curves and 2) determination of maximum displacements. The pushover curve of a structure is determined by a step-by-step non linear equivalent static analysis of the structure and are same for both the methods. FEMA 273 uses the displacement coefficient method to determine the maximum displacement. ATC-40 methods for determination of target displacement or maximum displacement are based on the reduction of seismic demand for increasing values of displacement.

### 2.1 Determination of Pushover Curve

Basic objective of pushover analysis is to determine the response of the structures (generally the top displacement or roof displacement) against various values of base shears in order to plot a force displacement (base shear - roof displacement) curve of the structure. This is done by step-by-step static non-linear analysis of the structure with increasing value of load (base shear). The method is summarized below,

i) Capacity curve is generally constructed considering the fundamental mode of vibration of the structure.
ii) Develop a suitable analytical model of the structure.
iii) Depending on the degree of sophistication to be adopted in pushover analysis, load forms like a single concentrated load applied at the top, or lateral forces proportionately applied in inverted triangular form is considered. The lateral storey forces can be applied to the structure in proportion to the product of mass and fundamental mode shape also. This is generally considered valid for buildings with fundamental periods of vibration up to about one second.
iv) Record the base shear and roof displacement of the structure for each applied lateral load step for the chosen distribution of applied lateral forces.
v) If the strength degradation of the structural elements are implicitly incorporated in the FEM model, the incremental loads could be applied without making any changes to the model. Otherwise, check the structural elements for strength degradation/yielding and revise the model using zero (or very small) stiffness for the yielding elements. Then an incremental load is applied to the revised structure till another element (or group of elements) yields.
vi) Repeat steps (iv) and (v) until the structure reaches an ultimate limit such as instability from P-$\Delta$ effects; distortions considerably beyond the desired performance level, an element or group of elements reaching a lateral deformation at which significant strength degradation begins etc.

### 2.2 Determination of maximum displacement demand using FEMA 273 method.

The deflection coefficient method has been adopted to determine the maximum displacement, or the target displacement or the displacement demand. The step-by-step procedure to calculate target displacement using FEMA 273 is as follows:

1. Perform the pushover analysis of the structure subjected to a lateral loading based on the assumed loading pattern.
2. Draw the load deformation curve based on the applied base shear and the calculated roof deformation.
3. Calculate the effective elastic stiffness: Construct a straight line that is representing the post-elastic stiffness, $K_s$, where the structure strength has leveled off (ATC-40, 1996). Construct an effective elastic stiffness line $K_e$, by drawing a line passing through a point on the capacity curve corresponding to a base shear of $0.6V_y$, where $V_y$ is the base shear corresponding to the point defined by the intersection of lines $K_s$ and $K_e$.
4. Calculate the fundamental period '$T_e$' of the structure as

$$T_e = T_i \sqrt{\frac{K_i}{K_e}} \tag{1}$$

Where, $T_i$ is the elastic fundamental period

$K_i$ is the elastic lateral stiffness of the wall under consideration

$K_e$ is the effective lateral stiffness of the building in the direction under consideration

5. Calculate the target displacement ($\delta t$)

$$\delta_t = C_0 C_1 C_2 C_3 S_a \left( \frac{T_e}{2\pi} \right)^2 \tag{2}$$

Where $C_0$ to $C_3$ : Different modification factors which relates the spectral displacement and likely building response, expected maximum inelastic displacements to displacements calculated for linear elastic response, the effect of stiffness degradation and strength deterioration on maximum displacement response, and displacements due to dynamic P-$\Delta$ effects.

### 2.3 Determination of maximum displacement demand using ATC-40 method

The methodology described in ATC-40 to determine maximum displacement demand is known as the capacity spectrum method. The method calls for plotting both the demand and capacity curves in terms of spectral acceleration and spectral displacement.

The capacity curve obtained after a pushover analysis will be in terms of base shear and roof displacement. In order to use the capacity spectrum method, this curve is converted into one representing the capacity in acceleration displacement response spectra (ADRS). The maximum demand on the structure corresponding to a given input motion is arrived at by determining the performance point of the structure. The performance point obtained should satisfy two relationships: 1) the point should lie on the spectrum with the reduced amount of damping. 2) the point must lie on the capacity spectrum curve (ADRS conversion of pushover curve). In order to satisfy the above criteria, the determination of the performance point requires trial and error approach. ATC-40 provides three procedures for calculation of performance point. Though these procedures are developed on same concepts and mathematical relationships, they differ in their dependence on analytical and graphical approaches.

In the present paper, Procedure B, as per ATC-40 has been used of for the calculation of performance point. This procedure assumes that not only the initial slope of the bilinear representation of the capacity curve remains constant but also the point at which the structure starts yielding as well as the behavior after yielding post yield slope) remains constant.

## 3. DESCRIPTION OF THE EXPERIMENTS

The test specimen of the CAMUS experimental programme consists of two structural walls interconnected by 6 floors at different elevations; see Fig. 1. Each wall is 6.26 cm (mean value of measured thickness) thick and has a height of 4.5m. A heavily reinforced footing of 10 cm thickness connects each of these walls to the shake table.

Apart from the dead weight of the floors, additional masses have been added to each floor by means of concrete blocks and steel blocks kept at both upper and lower sides of the slab. To avoid failure of the wall in undesired mode, the out of plane stiffness of the walls have been augmented by means of a triangular bracing provided between the two walls.

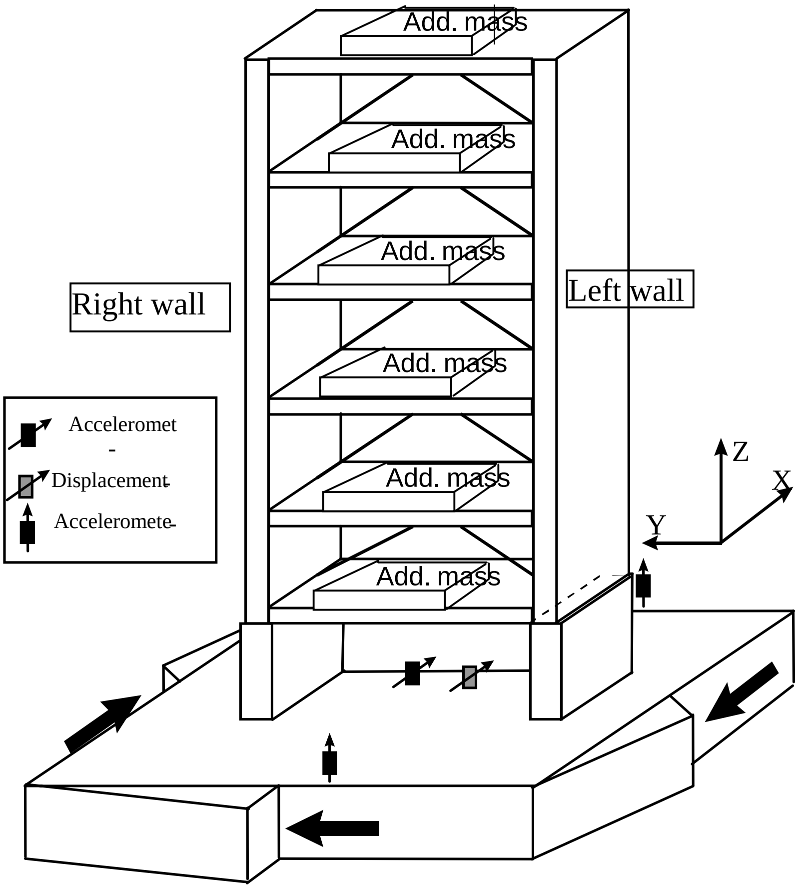



*Figure 1: Diagrammatic representation of test set up (modified from Combescure, 2002)*

The reinforcement provided in the wall is concentrated in three zones, namely middle zone and two end zones, Fig. 2. The area in between these zones is unreinforced. Lateral reinforcement in the form of stirrups has also been provided in the middle and two end zones at a spacing of 6 cm c/c.

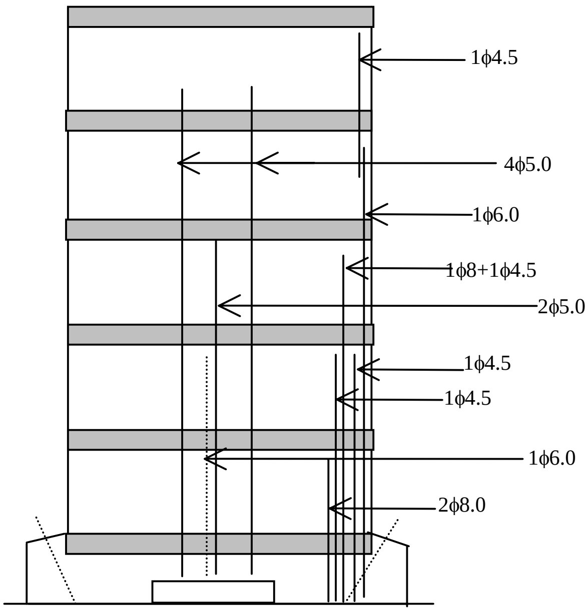
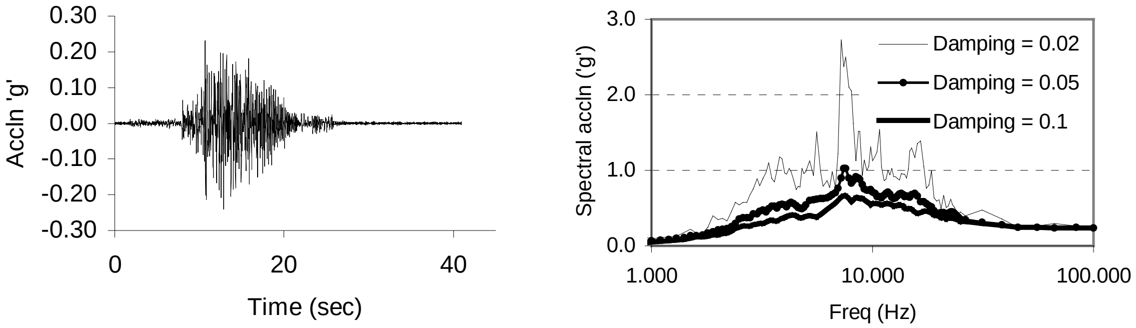



*Figure 2: Reinforcement detailing of the specimen (elevation)*

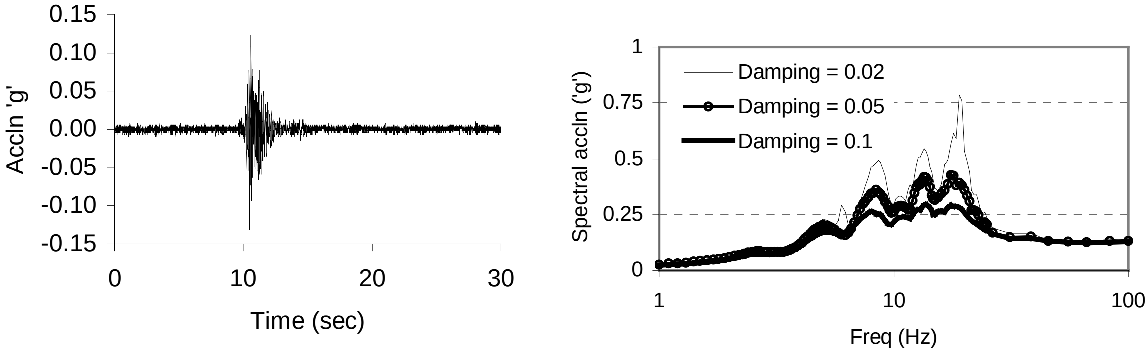
The accelerograms used in the experiments consisted of an artificially generated ground motion representing a far field earthquake (named as ‘Nice’) and one recorded near the fault rupture region (termed as ‘San Francisco’). These input motions have been scaled to different PGA values. The current paper discusses the outcome of the following two analyses.

1. Run 1: Nice with 0.24 g PGA,
2. Run 2: San Francisco with 0.13 g PGA




*(a) Input acceleration measured on the shake table* *(b) Response spectrums corresponding to horizontal acceleration*

*Figure 3: Input characteristics of ground motion corresponding to Run-1*




*(a) Input acceleration measured on the shake table* *(b) Response spectrums corresponding to horizontal acceleration*

*Figure 4: Input characteristics of ground motion corresponding to Run-2*

## 4. ANALYTICAL MODEL OF CAMUC TEST SPECIMEN FOR PUSHOVER ANALYSIS

Nonlinear analysis of concrete structures is carried out by conducting a complete progressive failure analysis of the structure up to its collapse using the non-linear characteristics of material in each step of the analysis. Non-linear response of reinforced concrete structures is caused by four major material effects:

i) Cracking of concrete,
ii) Plasticity of the reinforcement and of compression of concrete,
iii) Bond slip between steel and concrete, aggregate interlock, dowel action by vertical reinforcement steel, etc., and
iv) Time dependant effects such as creep, shrinkage, temperature and load history.

There are a number of methods available for nonlinear analyses to establish pushover curve for concrete frame structures. However a very scanty literature is available for non-linear pushover analysis of concrete shear wall type structures, which is the generic configuration of the CAMUS-I test specimen. The nonlinear static analysis approach using arc-length algorithm provided in the ANSYS software were used for the analysis. Cracking of concrete, plasticity of the reinforcement and the compression concrete were considered.

### 4.1 Analytical Model of the Structure

The analytical models generally used to predict the nonlinear response of structural walls can be categorised into two:

(a) Detailed models: These are derived based on the concept of mechanics of solids. This requires detailed modeling of the structure to include local behaviour and hence called microscopic approach.
(b) Line Models, which are based on simplifying idealisation (macroscopic models). These models are capable of predicting the global behaviour of the structure to a satisfactory extent.

Total configuration of the experimental model as well as the applied excitation were symmetric. Hence, only one wall is considered in the analytical model. The masses from each floor have been apportioned accordingly. Similarly, the half portion of base slab of the shake table below the wall is modeled and symmetry boundary conditions are applied on the plane of symmetry. The support struts of the shake table are also modeled.

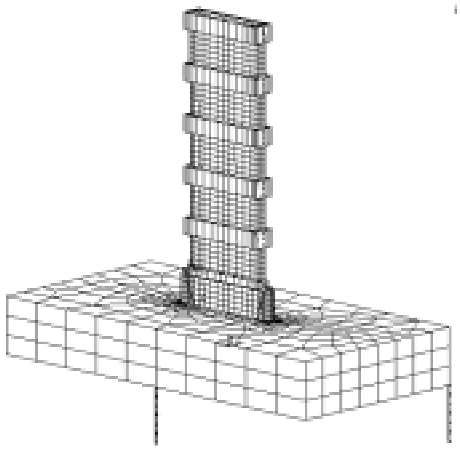


*Figure 5: View of the additional masses applied on the wall to account for loads from the floor slab*

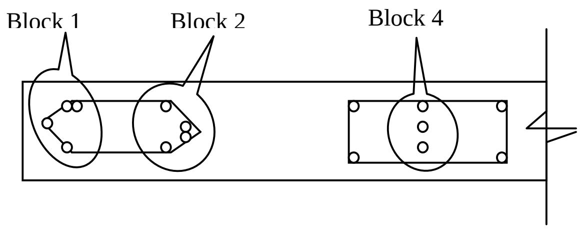



*Figure 6: Different blocks defined in the model*

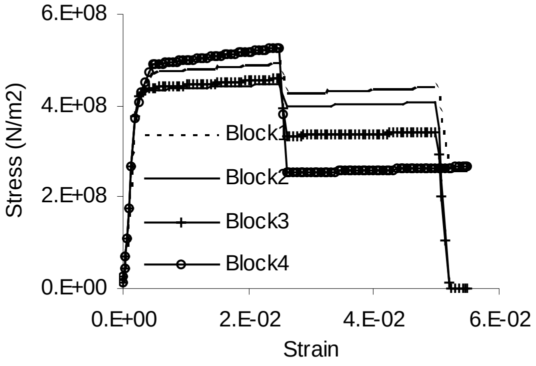
As the scope of study also included local behavior, the wall elements have been modeled using specialized three-dimensional solid (brick) elements, the Solid65 element of ANSYS. These elements are capable of modeling cracking as well as crushing of concrete. Moreover the reinforcement can be modeled as embedded in to concrete element. The aspect ratio of the concrete elements in the model has been kept around 2 but less than 2.5 for majority of the elements while generating the finite element mesh. The finite element model of the specimen is depicted in Fig.5.

Moreover, each wall of the test specimen consists of 3 zones of reinforcement (left zone, middle zone and right zone), which is in turn linked by plain cement concrete wall only. Since the tensile strength of plain cement concrete is poor, in an ideal situation; the wall should have vertically split into different vertically standing units due to the cyclic application of lateral load. As this had not been observed during testing, it can be concluded that the floors at each levels has acted as rigid links which interconnects the different zones of reinforcement ensuring monolithic action of the wall. Hence the links which have been used to simulate the floor mass have been assigned very high axial stiffness.

### 4.2 Modeling of reinforcing steel

The yield strengths and ultimate strengths of the reinforcement have been provided as input (Combescure, 2002). Due to existence of a single element at the locations where more than one type of reinforcement bars existed, some bars had to be grouped together, Fig. 6. This grouping in turn modifies the stress-strain behavior, which was also taken into account Fig. 7.



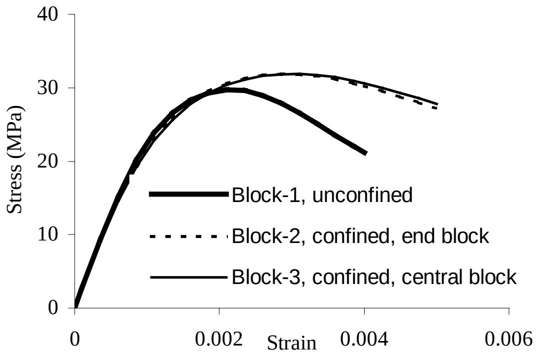




*Figure 7: Equivalent stress-strain curves for different blocks*

*Figure 8: Stress strain curve of concrete used in the analysis*

### 4.3 Modeling of concrete:

It has been well documented in the literature that the properties of concrete namely ductility and strength is considerably increased due to the presence of confining pressure.

The stress-strain curve proposed by Popovics (1973), has been used to calculate the effect of confinement of lateral reinforcement on concrete. The stress-strain curve is given by:

$$f_c = \frac{f'_{cc}\left(\frac{\varepsilon_c}{\varepsilon_1}\right)r}{r-1+\left(\frac{\varepsilon_c}{\varepsilon_1}\right)^r},\ \varepsilon_c < \varepsilon_1 \ \&\ f_c = \frac{f'_{cc}\left(\frac{\varepsilon_c}{\varepsilon_1}\right)r_o}{r_o-1+\left(\frac{\varepsilon_c}{\varepsilon_1}\right)^{r_o}},\ \varepsilon_c \geq \varepsilon_1 \tag{3}$$

where

$$r_o = r^{(1+1/r)};\ r = \frac{E_c}{E_c - E_{\sec}}.$$

$f'_{cc}$ is the maximum compressive stress in concrete

$f_c$ compressive stress in concrete corresponding to a strain of $\varepsilon_c$

$\varepsilon_1$ is the strain at which compressive stress attains the maximum value

Since it has been reported that the falling branch becomes too flat and remains above the experimental uniaxial stress-strain data, the expression beyond the peak strength has been modified (Goswami, 2002). The stress-strain curve corresponding to different zones also considering the lateral confinement offered by ties are given in Fig. 8.

### 4.4 Modeling of loading on the structure

The lateral load is applied up to the maximum capacity of the specimen for two types of load distribution.

1) Assuming an inverted triangular distribution for lateral loads. It was noted that the distribution of storey forces corresponding to first mode of vibration closely followed a distribution representing an inverted triangle. As, many of the pushover analysis procedures recommend the use of storey shear corresponding to the significant mode of vibration as the lateral force distribution, inverted triangular distribution was considered as one of the loading patterns. The diagrammatic representation of the distribution is shown in Fig. 9

2) The second model of loading consisted of application of forces on each floor such that they are proportional to the mass of that floor. As the floor masses did not vary much, application of this approach resulted in almost a uniform distribution of forces across each floor.

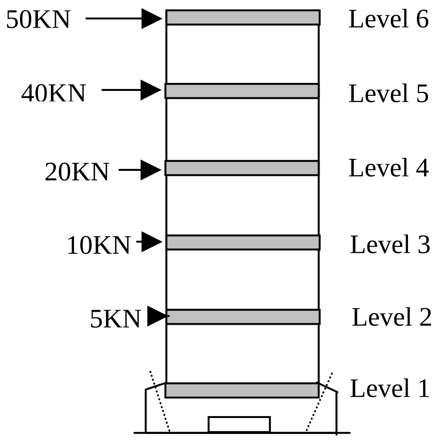



*Figure 9: Distribution of triangular load for the pushover analysis.*

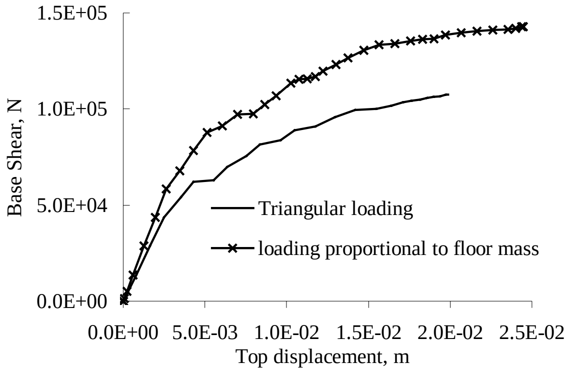



*Figure 10: Load -displacement curve corresponding to different load distributions*

## 5. RESULTS AND DISCUSSIONS

The analysis was started for a target base shear of 150 KN. The failure was observed at a base shear value of approximately 108KN for triangular load distribution and 143KN for the load distribution which was proportional to floor mass.

The maximum deflection is approximately 20mm and 24.5mm respectively for the two types of loading models. The plots depicting the variation of displacement with base shear for the two loading models are given in Fig. 10. The propagation of the cracks in the specimen corresponding to failure load (triangular loading model) is given in Fig. 11. Major crack pattern observed during the experimental investigations is shown in Fig. 12. The target displacements or performance points have been calculated using the procedure of FEMA-273 and ATC-40. These results along with other calculated parameters like expected acceleration, shear force, bending moment, strains, etc., are given in Table 1. Comparison of the calculated target displacements with the experimentally measured values is given in Table2.

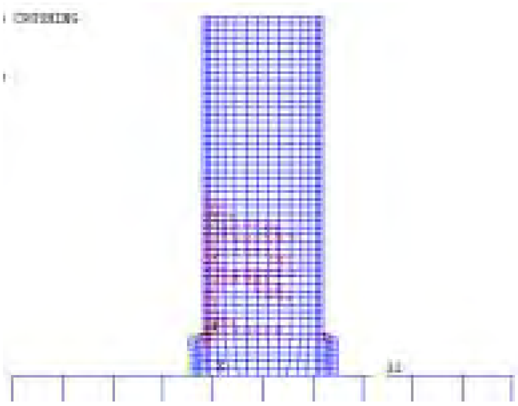


*Figure 11: Distribution of cracks at ultimate load for triangular load distribution.*

*Figure 12: Distribution of cracks as observed at the end of one typical time history run.*

### 5.1 Observations of deflection-based analysis

1. *General*

(i) The observed crack pattern as well as the location of major cracks compares well for both types of loading model.
(ii) The uniform loading pattern results in higher value of ultimate displacement compared to that of triangular loading.
(iii) Capacity of the specimen is lower in case of triangular load distribution

2. *Deflection based analysis with load distribution proportional modal mass (triangular load)*
   (i) The top displacements predicted by analysis compares well with the experimental value for Run 1, Run 2.
   (ii) Analytically predicted bending moment is lower than the experimental value for Run 1, but the difference is larger in case of Run 2. However, shear force predicted by analysis compares better with the experimental values for both runs
   (iii) The bending moments predicted by analysis are 40 to 50% higher than that observed during analysis
   (iv) When compared to the experimentally observed values, the top acceleration predicted for Run-1 is higher by about 10% whereas it is lower by the same amount for Run-2.
   (v) The analytically predicted strain is generally less than the experimentally observed values.

*Table 1: Outputs for target displacement predicted by FEMA-273 approach corresponding to different force distributions and comparison of the various parameters with respect to experimentally observed ones.*

| | Triangular force distribution | | Uniform force distribution | | Experiment | |
|---|---|---|---|---|---|---|
| | RUN 1 | RUN 2 | RUN 1 | RUN 2 | RUN 1 | RUN 2 |
| Top relative displacement x $10^{-3}$ (m) | 7.93 | 1.73 | 5.41 | 1.49 | 7.01 | 1.54 |
| Top absolute horizontal acceleration (m/sec$^2$) | 7.50 | 2.41 | 6.62 | 1.82 | 6.64 | 2.78 |
| Level 1 Bending moment x $10^3$ (N-m) | 298.62 | 115.82 | 282.24 | 105.86 | 211 | 75.5 |
| Level 1 Shear force x $10^3$ (N) | 78.58 | 30.48 | 88.785 | 33.33 | 65.9 | 23.5 |
| Strain in the external R-bar, level 4 (x $10^{-5}$) | 4.24 | -6.12E-03 | 2.05 | -0.920 | 0 | 0 |
| Strain in the external R-bar, level 3 (x $10^{-5}$) | 8.11 | 1.18 | 5.67 | -0.154 | 2100 | 2230 |
| Strain in the external R-bar, level 2 (x $10^{-5}$) | 117 | 2.58 | 10.0 | 1.10 | 1450 | 1310 |
| Strain in the external R-bar, level 1 (x $10^{-5}$) | 4.46 | 0.889 | 3.95 | 0.681 | 1620 | 1430 |

*Table 2: Comparison of maximum deflection at level-6 calculated by FEMA – 273 and ATC - 40.*

| Run No. | Maximum displacement determined from test (mm) | Maximum horizontal displacement (mm) | |
|---|---|---|---|
| | | FEMA - 273 | ATC - 40 |
| 1 | 7.01 | 7.939 | 2.8 |
| 2 | 1.54 | 1.733 | 1.3 |

3. *Deflection based analysis with load distribution proportional to floor mass*
   (i) Cracking pattern in this case is similar to that of triangular load distribution but spread more evenly.

(ii) Top displacement is less than the experimental values for both the runs.
(iii) The bending moments predicted by analysis are 30 to 40% higher than that observed during analysis
(iv) The top acceleration predicted for Run-1 matches closely with experimental values whereas it is lower by about 35% for Run-2.
(v) Analytically predicted strain values are less than that of experimental values.

4. *Comparison between FEMA 273 and ATC-40 methods*
(i) For Run-1, the displacement predicted by FEMA-273 is close to the observed value where as the one predicted by ATC-4 is very low
(ii) For Run-2, the target displacements predicted by both methods are closer to the observed value. The difference is almost same, but predictions using FEMA-273 procedure results in higher displacements where as ATC-40 approach predicts values on the lower side.
(iii) There is high amount of subjectivity in application of ATC-40 method for a response spectrum generated from time history. While using non-smoothened ADRS, there could be multiple points where response spectrum coincides with capacity curve, and hence multiple performance points. Also, there could be instances where a small shift in the performance curve results in significant variation in target displacements.

## 6 CONCLUSIONS

(i) It is found that the displacement based approaches can be used to rationally predict the behaviour of shear wall type reinforced concrete structures during earthquakes.
(ii) Target displacements predicted using FEMA –273 procedure matches well with the experimental values for seismic ground motions including that of near field earthquakes.
(iii) The application of ATC-40 approach is very demanding and depends on subjective judgment when acceleration displacement response spectrum is not a smooth one.

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