# AN INPROVED ELASTO-PLASTIC SPECTRUM FOR THE SEISMIC BEHAVIOR ASSESSMENT AND DESIGN OF SHEAR WALL STRUCTURES

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**ABSTRACT :**

A simplified ductility based elasto-plastic response spectrum method to solve the seismic demand in plastic stage was introduced in this paper. Recently, the performance based seismic design method was given importance and developed rapidly. Seismic demand solving and structure assessment method was published, the IDA and N2 methods was applied more often. A simplified ductility based elasto-plastic response spectrum method which combine N2 method and the native seismic code considering the influence of site category was introduced. Ductility coefficient was used as a key parameter to solve the nonlinear seismic demand in this method which realized multi level seismic demand solving. Shear wall failure discipline was sum up and the structure performance level is divided combining with FEMA273 and the native seismic design code. A shear wall design example was enumerated to explain the process of the ductility based elasto-plastic response spectrum method. The conclusion indicated that the ductility based elasto-plastic response spectrum method could be applied to the seismic design of the performance predetermined structure, this method was simple and reliable in the seismic demand solving, and could be amended and put into practice.

**KEYWORDS:** elasto-plastic response spectrum, ductility coefficient, site category, performance based seismic design, nonlinear seismic demand

## 1. INTRDUCTION AND BACKGROUND

Structural performance-based seismic design is developed since 90s, and is accord great importance to the engineers. In resent years, seismic disaster give much more serious structural damage and property loss, current design code aims at the human safety, but is hard to protect the increasing investment of the structure establishing, so the performance-based seismic design method have developed dramatically. Though the performance-based seismic design need much improvement, it meet the needs of the present structure design, and is identify to most designers and researchers. The research results provided practical reference for seismic design. One of the methods developed for the seismic risk assessment of structures is Incremental Dynamic Analysis (IDA), this method requires a large number of inelastic time history analysis and is thus very time-consuming. N2 method is one of the simplified nonlinear methods based on the pushover analysis and inelastic response spectrum. The extended N2 method provides more precise result than the spectrum method, though this method still needs much amending to put into practice. To the structure design in China, elastic response spectrum method is used frequently, part of the structures need time history analysis, and structure displacement is used to assessment the performance or directs the design. the method of static elasto-plasticity analysis method have not widely used for the seismic behavior assessment of structures, the increasing height and more complexity of structures stake a claim of the amending of the current Code, and new Code should meet the need of effect assessment, the predetermined multilevel structural design.
In this paper, a method to assess the structure performance which can also guide the performance design and the assess standard are introduced. The solving process of performance demand details was expressed by an example of the shear wall element, and the static elasto-plasticity and elasto-plasticity response spectrum analysis method were applied in the process. The elasto-plasticity response spectrum used here is derived from FEMA356 and considering China Code. The structural static/dynamic analysis program CANNY was applied in the process of the seismic demand solving.

## 2. TARGET DISPLACEMENT SOLVING METHOD USING ELASTO-PLASTICITY DISPLACEMENT RESPONSE SPECTRUM

Deformation (displacement) is an important criterion to judge the structure performance state. It is the most practical and reliable method to define the structure performance level. Elastic response spectrum could be used in the elastic stage, and elasto-plastic response spectrum method could be considered in the inelastic stage. IN2 method which is suggested by SAC-FEMA has already put into practice in European and American Code. This method which is one of the simplified nonlinear methods based on the pushover analysis and inelastic response spectrum could provide rather precise seismic response result. Ductility demand spectrum is one of the inelastic response spectrums, if the structure displacement is given, the displacement response spectrum could be constructed to deduce the elasto-plastic displacement demand. Ductility based elasto-plastic displacement response spectrum is applied to a shear wall element to solve the inelastic target displacement in this paper. Ductility coefficient is defined as the ratio of the ultimate displacement to the yield displacement on the force-displacement curve. By the two lines inelastic model, yield displacement point and the ductility coefficient could decide the performance characteristics. The elasto-plastic displacement response spectrum mentioned in this paper is a kind of ductility demand spectrum considering different site effect. The influence of the site category and the design group were discussed in [1], in which the calculation formula set up and the related coefficient were returned. The ductility coefficient in the ductility demand spectrum can be determined as:

$$\mu = \frac{\xi_y^{-c} - 1}{c} + 1 \qquad (2.1)$$

In formula (2.1), $c = \frac{T^a}{T^a + 1} + \frac{b}{T}$ , $a$、$b$ is the return coefficient related to site category and design group; yield strength coefficient $\xi_y = \dfrac{F_y}{F_e}$, $F_e$ is the maximum inner force under earthquake action, $F_y$ is the yield baring capacity. When the basic period less than 3s, the return coefficient in table 1 could be applied, when it longer than 3s, table 2 will be adopted.

Table 1 Return value of parameter a、b（T belongs to 0.1～3s）

| Design group | Site Ⅰ | | Site Ⅱ | | Site Ⅲ | | Site Ⅳ | |
|---|---|---|---|---|---|---|---|---|
| | a | b | a | b | a | b | a | b |
| The 1 group | 0.7307 | 0.2363 | 1.8618 | 0.3190 | 0.2729 | 0.2740 | 2.7879 | 0.4276 |
| The 2 group | 1.3431 | 0.3190 | 0.2997 | 0.2505 | 0.3584 | 0.3669 | 1.2508 | 0.4567 |
| The 3 group | 0.7115 | 0.3640 | 0.6675 | 0.4578 | -0.3956 | 0.4253 | 0.3847 | 0.5267 |

Table 2 Return value of parameter a、b（T belongs to 0.1～3s）

| Design group | Site Ⅰ | | Site Ⅱ | | Site Ⅲ | | Site Ⅳ | |
|---|---|---|---|---|---|---|---|---|
| | a | b | a | b | a | b | a | b |
| The 1 group | 0.3747 | 0.2174 | 0.8968 | 0.2937 | 0.0691 | 0.2606 | 1.4444 | 0.4094 |
| The 2 group | 0.6019 | 0.2914 | -0.0552 | 0.2275 | -0.1863 | 0.3315 | 0.6975 | 0.4359 |
| The 3 group | 0.3535 | 0.3446 | 0.4395 | 0.4453 | -0.063 | 0.4460 | 0.2116 | 0.5160 |

Ductility demand spectrum is the statistic curve of the structure ductility and the basic period, the ductility demand curve diagram shows in figure 1.

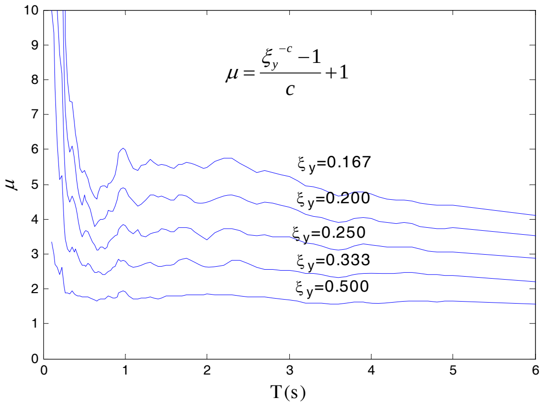


Figure 1 Schematic diagram of ductility demand

The elasto-plastic displacement response curve can be expressed as the formula below:

$$S_{dp} = \mu x_y \qquad (2.2)$$

in formula (2.2),

$\mu$ —ductility demand;

$x_y$ —system yield displacement。

so the displacement demand of the single degree of freedom system can be given as:

$$D_n = \mu D_{ny} \qquad (2.3)$$

in the formula,, $D_n$ 、$D_{ny}$ $D_n$ 、$D_{ny}$ is the equivalent system displacement demand and yield displacement, $S_a$ is the acceleration of the spectrum at the period T.

## 3. PERORMANCE TARGET DIVIDING AND ELSTO-PLASTICAL DISPLACEMENT DEMAND

The damage level is determined by the damage degree of the structure, when it suffers an earthquake action, and the structure damage level can be divide from general structure and element level. Based on FEMA273 [2] and FEMA368 [3], the earthquake damage level can be divided into 4 levels, the details of each level Is described in table 3.

Table 3 Description of each performance level

| | Structure performance level | | | |
|---|---|---|---|---|
| | Operational Level | Immediate Occupancy Level | Moderate Damage Level | Near Collapse |
| General description | No permanent drift. Structure substantially retains original strength And stiffness. Minor cracking of facades, partitions, and ceilings as well as structural elements. All systems important to normal operation are functional. | No permanent drift. Structure substantially retains original strength and stiffness. Minor cracking of facades, partitions, and ceilings as well as structural elements. Elevators can be restarted. Fire protection operable. | Some residual strength and stiffness left in all stories. Gravity-load bearing Elements function. No out-of plane failure of walls or tipping of parapets. Some permanent drift. Damage to partitions. Building may be beyond | Little residual stiffness and strength, but load bearing columns and walls function. Large permanent drifts. Some exits blocked. Infill and untraced parapets failed or at incipient failure. Building is near collapse. |
| Shear wall structural components | A little tinny crack appears on the shear wall surface. The crack no wider than 1mm, no longer than 10mm | A little crack appears on the wall surface. The crack no wider than 1mm, no longer than 50mm | Lots of cracks appear on the wall surface. The crack no wider than 2mm, no longer than 100m | There appears run-through crack, and wider than 2mm, wall dislocated, concrete on the surface fall down, bars exposed but not buckled. |
| Nonstructural components | Negligible damage occurs. Power and other utilities are available, possibly from standby sources. | Equipment and contents are generally secure, but may not operate due to mechanical failure or lack of utilities. | Falling hazards mitigated but many architectural, mechanical, and electrical systems are damaged. | Extensive damage. |

The top horizontal load and top displacement of the 15 test walls which tested in Tongji University in China [4]. These 15 walls have different section characteristic individually. The test indicates that most shear walls with different section parameters should experience 3 stages when it suffers lateral load: elastic stage, plastic develop stately stable and plastic develop unstable stage.
To sum up the failure process of the walls and the criteria of determination for shear wall performance level the top force-displacement curve can be simplified into 3 lines and 4 stages. To match Operational Level to the minor earthquake stage in Chinese code, it can be expressed with the elastic line of the curve; the moderate stage can be divided into Immediate Occupancy Level and Moderate Damage Level with yield point; and to the boundary point of the moderate damage Level with the Near Collapse Level, it can be divided by peak point on

the curve. About the partition of concrete structures, Zixiong Guo and Hongwang Ma have discussed in [5, 6]. The same as Chinese Code, the "could be repaired" moderate stage is defined between the minor earthquake stage and the severe earthquake stage. Though the "could be repaired" moderate stage is still remain vague, and structural element will experience rather long plastic deform process in this crack developing stage, so the "could be repaired" moderate stage is divided into two part with the yield point: the minor earthquake stage and the severe earthquake stage.
15 shear walls with different parameters were tested in State Key Laboratory for Disaster Reduction in Civil Engineering of Tongji University. These specimens are different at axial compressive ratio, aspect ratio, concrete strength, boundary length, reinforcement bar ratio and stirrup ratio. Element performance is decided by the section parameter, and so the relation between the performance parameter and the section parameter can be set up. The yield rotate angle can be expressed by $\theta_y = \theta(n, r, \eta, ...)$; The peak point rotate angle can be expressed by $\theta_p = \theta(n, r, \eta, ...)$, and The ultimate rotate angle can be expressed by $\theta_u = \theta(n, r, \eta, ...)$. $n, r, \eta, ...$ stand for axial compressive ratio, aspect ratio, concrete strength, boundary length and so on. Details of the set up process of the formula stated in [6].

## 4. APPLICATION EXAMPLE

To make the performance assessment and design method mentioned in this paper more clear, an assessment example of 8-story shear wall is enumerated below, the general situation and the solving process details is showed in the example (figure 2).

### 4.1. Project Profile

A 8-story concrete shear wall structure, which has story height of 2.9m, and the width of the wall is 2.0m, the project specific as follows (according to Chinese Code):

（1）seismic fortification intensity: 7degree
（2）Design group: the first group; the site category: III category
（3）Thickness of the shear walls: 200mm; Infill wall thickness:120mm, 1.2 kN/m$^2$
（4）Dead load of the floor: 4.5kN/m2; live load of the floor: 2.0kN/m$^2$
（5）No human abundance roof, same with the other floor, 40mmrigid waterproof layer
（6）Concrete grade: C30

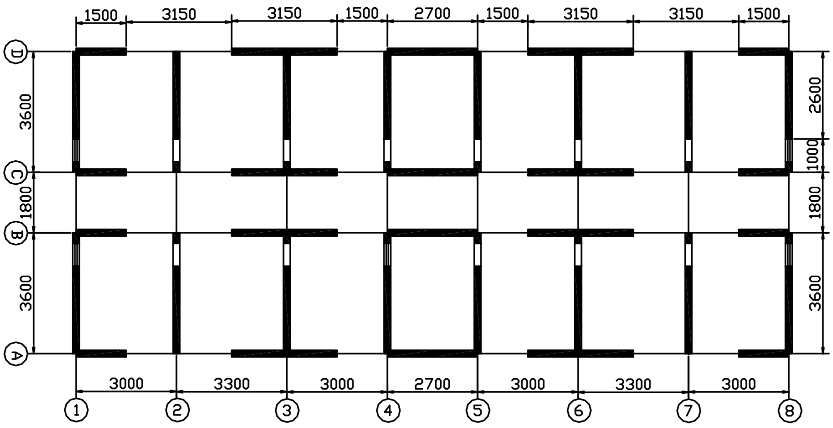


Figure 2 The shear wall structure plan

### 4.2. Define the Displacement Demand

（1） To simplify the process, axial2 is selected to be the analysis target. On axial 2, there are two symmetrical walls; the rigidity is assigned on average, the details of dynamic parameter of the structure showed in table 4.

Static elasto-plastic analysis (Pushover analysis) gives out the relation curve of the top displacement and the base shear force. The structural static/dynamic analysis program CANNY was applied in the Static elasto-plastic analysis [7]. Figure 3 shows the pushover curve and the irregular curve.

table 4 The modal analysis result of axial 2

| floor | lever（m） | story gravity（kN） | $\phi_1$ | minor earthquake action（kN） | moderate earthquake action（kN） | severe earthquake action（kN） |
|---|---|---|---|---|---|---|
| 8 | 23.2 | 100 | 1.0 | 10.00 | 27.50 | 62.48 |
| 7 | 20.3 | 120 | 0.8376 | 10.05 | 27.64 | 62.79 |
| 6 | 17.4 | 120 | 0.674 | 8.08 | 22.22 | 50.53 |
| 5 | 14.5 | 120 | 0.5136 | 6.16 | 16.94 | 38.50 |
| 4 | 11.6 | 120 | 0.3624 | 4.35 | 11.96 | 27.17 |
| 3 | 8.7 | 120 | 0.2274 | 2.73 | 7.51 | 17.05 |
| 2 | 5.8 | 120 | 0.1165 | 1.40 | 3.85 | 8.73 |
| 1 | 2.9 | 120 | 0.03786 | 0.45 | 1.24 | 2.84 |
| modal participate coefficiant: 1.47; equvilant mass: 115 kN; basic period: 0.9263s | | | | | | |

（2） Equivalent the MDOF structure to SDOF structure
The parameters of the equivalent SDOF are described as follows:

modal participate coefficient: $$\gamma_j = \frac{\sum_{i=1}^{n} m_i \Phi_{ji}}{\sum_{i=1}^{n} m_i \Phi_{ji}^2} \quad (4.1)$$

equivalent mass: $$M_{eq1} = \frac{\left(\sum_{i=1}^{n} m_i \Phi_{ji}\right)^2}{\sum_{i=1}^{n} m_i \Phi_{ji}^2} \quad (4.2)$$

equivalent displacement: $$D = u_r / X_r \quad (4.3)$$

equivalent force: $$V = V_b / \sum_{i=1}^{n} X_i m_i \quad (4.4)$$

equivalent period: $$T_1 = 2\pi \sqrt{u_{1ry} \sum_{i=1}^{n} X_{1i} m_i / X_{1r} V_{by}} \quad (4.5)$$

Transform the force-displacement curve to capacity curve:

acceleration: $$A = \frac{V_b}{M_{eq1}} \quad (4.6)$$

displacement: $$D = \frac{u_r}{\gamma_1 \Phi_{1m}} \quad (4.7)$$

In the formula above, $\Phi_{1m}$ is equivalent height.

The equivalent period of the elastic stage on the irregular curve is 1.15s; the earthquake influent coefficient is 0.0929g. As indicated in China earthquake Code [8], the earthquake influent coefficient is 0.5g.

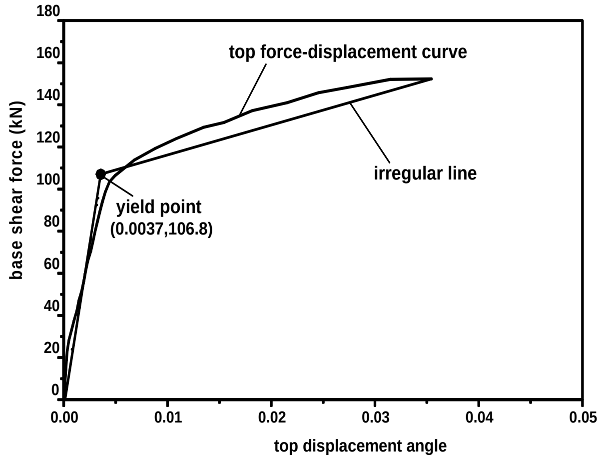


Figure 3 Schematic diagrams of the base force-displacement curve and the irregular line

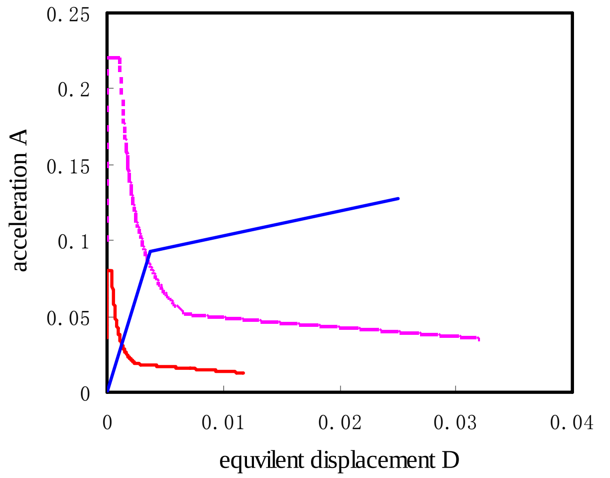


Figure 4 Response spectrums and the capacity

If it is supposed that the damage degree should be controlled within “moderate damage degree”, displacement ductility demand is $\mu_e$ , and the related coefficient in the ductility calculation formula: a=0.3232，b=0.2775, the calculation process is list:

$$c=\frac{T^a}{T^a+1}+\frac{b}{T}=1.05 \tag{4.8}$$

$$\xi_y=\frac{F_y}{F_e}=0.0929g/0.2142g=0.4337 \tag{4.9}$$

$$\mu_e=\frac{\xi_y^{-c}-1}{c}+1=2.337 \tag{4.10}$$

$$D=\mu_e D_y=2.337\times 23200\times 0.00292=158.3\,\text{mm} \tag{4.11}$$

$D$ is the equivalent displacement of the equivalent SDOF structure, transformed into the original displacement:

$$\Delta_i=D\phi_1 \tag{4.12}$$

The calculated displacement showed in table 5, the demand of other performance level could be solved through this way also:

Table 5. The displacement demand result

| floor | demand displacement $\Delta$ （mm） | demand displacement angle $\theta$ | story drift $\Delta_d$ （mm） | story drift angle $\theta_d$ |
|---|---|---|---|---|
| 8 | 95.90 | 1/30 | 15.57 | 1/186 |
| 7 | 80.33 | 1/36 | 15.69 | 1/185 |
| 6 | 64.64 | 1/45 | 15.38 | 1/189 |
| 5 | 49.25 | 1/59 | 14.50 | 1/200 |
| 4 | 34.75 | 1/83 | 12.95 | 1/224 |
| 3 | 21.81 | 1/133 | 10.64 | 1/273 |
| 2 | 11.17 | 1/260 | 7.54 | 1/385 |
| 1 | 3.63 | 1/799 | 3.63 | 1/799 |

## 5. CONCLUSIONS

The elasto-plastic response spectrum method-N2 method which is proposed in Europe and America has been developed recently. Most elasto-plastic response spectrum method combined the static elasto-plastic analysis and the elastic response spectrum.The improved ductility based elasto-plastic response spectrum method mentioned in this paper connects the structural capacity curve and the displacement demand with ductility coefficient. This method combine the other elasto-plastic response spectrum method and the native seismic code, also considering the influence of different site characteristics. In the design practice, the elastic response spectrum method suggested in native seismic code is still applied in elastic stage design, the ductility based elasto-plastic response spectrum method is used in plastic stage including moderate earthquake stage and sever earthquake stage. It is convenient to apply this method in practical design. To performance level dividing, it combined the international dividing method and the minor, moderate and severe earthquake style in China, the performance level dividing style suggested in this paper can provided efficient basis to structure design and performance assessment in elasto stage.

There still remains much space to be mended about the ductility based elasto-plastic response spectrum method currently, for example, the standardization of different structures, the amendment of the spectrum considering different damp and so on. Uncertainties need to be found in the further research.

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