Capacity Spectrum Demand Analysis Based on Proposed Bangladesh National Building Code

Ram Krishna Mazumder, Tusdid Sabur Tohfa, Md. Abdur Rahman Bhuiyan, Md. Jahangir Alam,
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***Abstract*—**Capacity spectrum method provides the capacity of a structure with respect to demand of a structure during an earthquake. A simplified approach was used to estimate seismic demand calculation based on inelastic strength and displacement spectra. Static Pushover Analysis was performed by OpenSees program to obtain capacity curve. Response of the structure was transformed into equivalent Single Degree of Freedom (SDOF) System. Response Spectra from proposed Bangladesh National Building Code (BNBC) were transformed into acceleration displacement format. Performance point was obtained from the intersection point between bi-linear pushover curve and acceleration demand spectra.

***Keywords*—**Capacity Spectra, SDOF, Pushover Analysis

I. INTRODUCTION

THE current code provision for building design and construction in Bangladesh is first prepared in 1993 which is known as BNBC 1993 [1]. For seismic design consideration, BNBC 1993 seismic zoning map was prepared based on peak ground accelerations (PGA) for a return period of 200 years. In recent years, House Building Research Institute (HBRI) undertook existing building code up gradation project in 2010. The proposed BNBC seismic zoning map is based on a return period of 2475 years [4]. This proposed map has four seismic zones with a Peak Ground Acceleration (PGA) value equal to 0.36 g [4] for seismically high risk zone. For the high risk zone, the PGA value will be increased about 1.5 times compared to the existing BNBC (1993) seismic zoning map.

In the proposed building code, soil coefficient is similar to the existing European Code. Based on this proposed design spectrum, capacity spectrum method was performed for a four storied reinforced concrete frame. The Capacity spectrum method was first developed by Freeman [3] and then this method was modified by Fajfar in 1999 [2]. This procedure is a graphical approach to compare the capacity of a structure with the demand of earthquake ground motion on the structure. Capacity of the structure is represented by a force - displacement curve whereas the curve is obtained from non-linear static pushover analysis. The typical acceleration spectrum is transformed to Acceleration Displacement Response Spectrum (ADRS) format. Then Performance of the structure is obtained from the intersection of bi-linear Capacity curve and ADRS curve.

In this method, non-linear static analysis procedures play a central role. A software name OpenSees [5] was used for performing non linear static analysis of the structure. OpenSees is a framework for simulating the seismic response of structural and geotechnical systems, which is developed by Pacific Earthquake Engineering Research Center (PEER). This study aims to identify performance of buildings using capacity spectrum method as per proposed national building code in Bangladesh.

II. DESIGN SPECTRUM AND SEISMIC DEMAND

The design spectra in proposed BNBC [4] is developed based on following relationship,

$$
\begin{aligned}
C_S(T) &= S[1+(\eta.2.5-1)\frac{T}{T_B}], 0 \le T \le T_B \\
C_S(T) &= S.\eta.2.5, T_B \le T \le T_C \\
C_S(T) &= S.\eta.2.5(\frac{T_C}{T}), T_C \le T \le T_D \\
C_S(T) &= S.\eta.2.5(\frac{T_C T_D}{T}), T_D \le T \le 4s
\end{aligned}
\qquad (1)
$$

C_s depends on S and values of T_B, T_C and T_D, which are all functions of the site class (in Figure 1). Constant C_s value between periods T_B and T_C represents constant spectral acceleration.T_D represents the starting point of constant displacement periods. η is the damping correction factors

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where $\eta=1$ for 5 percent damping of structure. The spectral acceleration is given by following equation. Z represents seismic zoning coefficient, I is the structural importance factor and R is the response reduction factor [4]. Figure 2 shows the normalized spectral acceleration spectrum S_{ae} depends on C_s, Z and R values.

$$S_{ae} = (2/3)\, C_s\, ZI/R \tag{2}$$

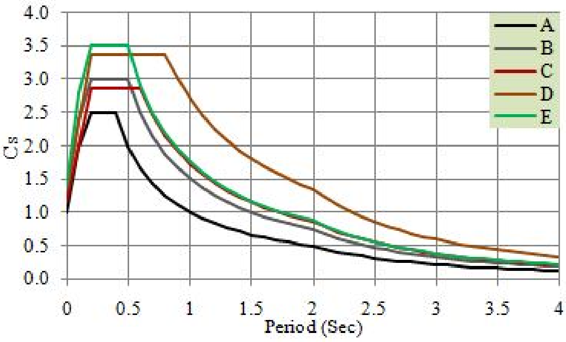

Fig. 1 Normalized acceleration response spectrum for different site classes for proposed BNBC.

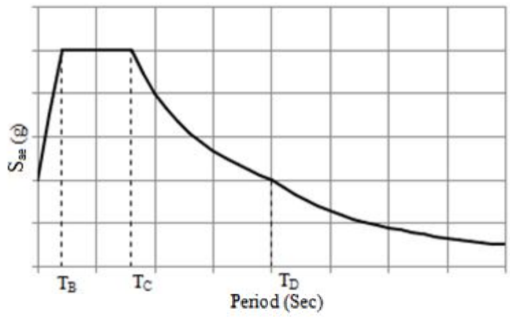

Fig.2 Typical elastic acceleration Sae (g) for 5 percent damping normalized to PGA.

For an elastic SDOF system the following relation [2] applies,

$$S_{de} = \frac{T^2}{4\pi^2} S_{ae} \tag{3}$$

For an inelastic SDOF system with a bilinear force - deformation relationship, the acceleration spectrum (S_a) and the displacement spectrum (S_d) can be determined by,

$$S_a = \frac{S_{ae}}{R_\mu} \tag{4}$$

$$S_d = d_e \frac{\mu}{R_\mu} = \frac{\mu}{R_\mu}\frac{T^2}{4\pi^2} = \mu \frac{T^2}{4\pi^2} S_a \tag{5}$$

μ is the ductility factor defined as the ratio between the maximum displacement and the yield displacement, and R_μ is the reduction factor due to ductility, i.e. due to the hysteretic energy dissipation of ductile structures [2].

$$R_\mu = (\mu - 1)\frac{T}{T_0} + 1 \quad T \le T_0, \tag{6}$$

$$R_\mu = \mu, \ T \ge T_0 \tag{7}$$

$$T_0 = 0.65\mu^{0.3} T_C \le T_C \tag{8}$$

T_C is the characteristic period of the ground motion. It is typically defined as the transition period between the constant acceleration segments of the response spectrum. An even simpler version of R_μ spectra can be obtained by fixing the transition period to T_C where $T_0 = T_C$ [2]. Figure 3 shows the displacement spectra obtained from equation 3. Equations (6) and (7) define a bilinear R_μ spectrum. In the medium- and long-period range the equal displacement rule applies (equations (5) and (7)), i.e. the displacement of the inelastic system is equal to the displacement of the corresponding elastic system with the same period. The transition period T_0 depends on the ductility (equation (8)). T_0 should not be larger than T_C [2]. Figure 4 shows acceleration demand spectra for different ductility factors.

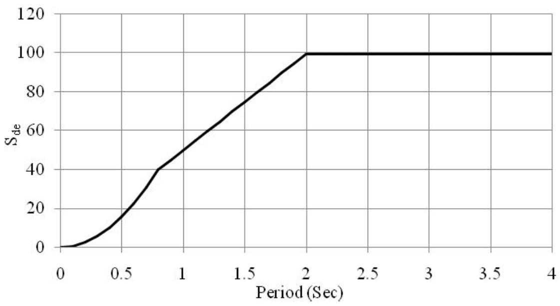

Fig. 3Typical displacement spectrum (Sde) for 5 per cent damping normalized to peak ground acceleration.

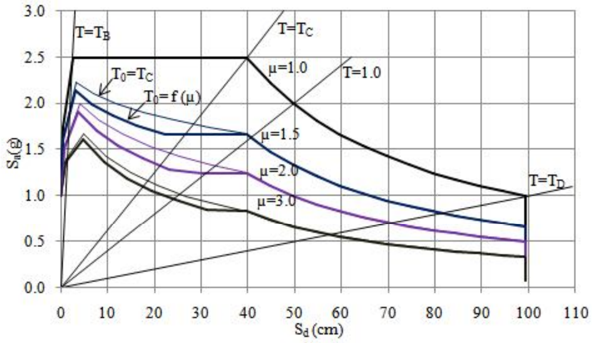

Fig. 4 Demand spectra for constant ductilities in ADRS format.

III. BUILDING MODEL

A four storied typical Reinforced Concrete Frame was taken for this study as shown in Figure 5. Columns and beams length were 3.05 m and 3.66 m, respectively. Frame was modeled in OpenSees using Uniaxial Concrete 02 [5] and Uniaxial Steel 01[5] material. Fig. 6 represents stress-strain hysteretic behavior of both materials. Concrete compressive strength and crushing strength were 20 MPa and 4 MPa, respectively. The yield strength of steel was 40 Ksi. Structural section was built as fiber reinforced section. Each section is separated into confined and unconfined concrete region. There are 3.8 cm covers around the entire section.

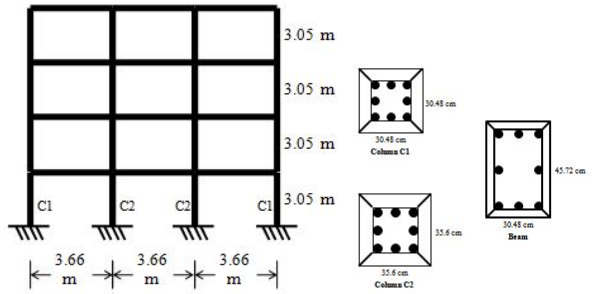

Fig.5 Reinforced Concrete Frame

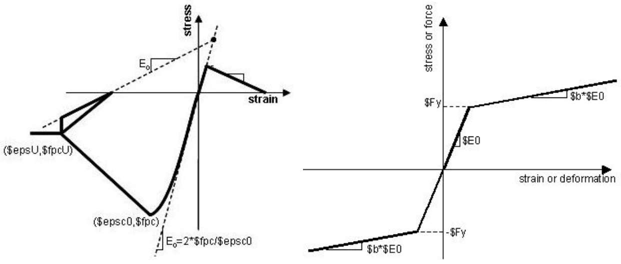

Fig. 6 OpenSees material for concrete 02 (left) and steel 01

Pushover analysis was performed under application of gravity loads. The capacity curve is determined by pushover analysis for values of the control displacement ranging between zero and the value corresponding to 1.5 times of the target displacement [2]. Pushover analysis provides non-linear force-displacement relationship of the Multi Degree of Freedom (MDOF) system. The target displacement is determined from the elastic response spectrum. Relation between Normalized lateral forces $\overline{F}_i$ and normalized displacements Φ_i are assumed as below,

$$\overline{F}_i = m_i \Phi_i \tag{9}$$

m_i is the mass in the i-th storey. Displacements are normalized in such a way that $\Phi_n = 1$, where n is the control node whereas n denotes roof level. The mass of an equivalent SDOF system m^* and transformation factor Γ are determined by [2],

$$m^* = \Sigma m_i \Phi_i = \Sigma \overline{F}_i, \quad \Gamma = \frac{m^*}{\Sigma m_i \Phi_i^2} = \frac{\Sigma \overline{F}_i}{\Sigma\left(\frac{\overline{F}_i^2}{m_i}\right)} \tag{10}$$

The force F^* and displacement d^* of the equivalent SDOF system are computed as,

$$F^* = \frac{F_b}{\Gamma}, \quad d^* = \frac{d_n}{\Gamma} \tag{11}$$

F_b and d_n are base shear force and control node displacement of the MDOF system, respectively. The yield force F_y^*, which represents also the ultimate strength of the idealized system, is equal to the base shear force at the formation of the plastic mechanism. The initial stiffness of the idealized system is determined in such a way that the areas under the actual and the idealized force – deformation curves are equal [2]. Based on this assumption, the yield displacement of the idealized SDOF system d_y^* is given by,

$$d_y^* = 2\left[d_m^* - \frac{E_m^*}{F_y^*}\right] \tag{12}$$

E_m^* is the actual deformation energy up to the formation of the plastic mechanism. The period T* of the idealized equivalent SDOF system is determined by,

$$T^* = 2\pi\sqrt{\frac{m^* d_y^*}{F_y^*}} \tag{13}$$

The target displacement of the structure with period T^* and unlimited elastic behavior is given by,

$$d_{et}^* = S_e(T^*)\left[\frac{T^*}{2\pi}\right]^2 \tag{14}$$

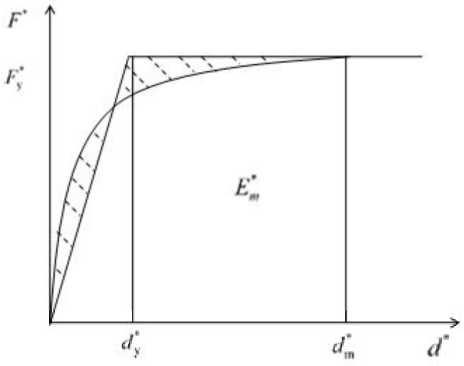

Fig. 7 Idealized elasto - plastic force –displacement relationship.

Figure 7 shows the idealized bi-linear curve obtained from pushover curve. S_e (T^*) is the elastic acceleration response spectrum at the period T^*. For the determination of the target displacement d_t^* for structures in the short-period range and for structures in the medium and long-period ranges different expressions are used as indicated below. The end period between the short- and medium period range is T_C [2].

For short period range ($T^* < T_C$): If $F_y^*/m^* \geq S_e$ (T^*), the response is elastic [6],

$$d_t^{*} = d_{et}^{*} \tag{15}$$

If $F_y^{*}/m^{*} < S_e(T^{*})$, the response is nonlinear [6],

$$d_t^{*} = \frac{d_{et}^{*}}{q_u}\left[1+(q_u-1)\frac{T}{T_C}\right] \ge d_{et}^{*} \tag{16}$$

q_u is the ratio between the acceleration in the structure with unlimited elastic behavior $S_e(T^{*})$ and in the structure with limited strength F_y^{*}/m^{*}.

$$q_u = S_e(T^{*})\frac{m^{*}}{F_y^{*}} \tag{17}$$

For medium and long period range ($T^{*} \ge T_C$):

$$d_t^{*} = d_{et}^{*} \tag{18}$$

d_t^{*} shall not be exceed 3 d_{et}^{*}. Figure 8a and 8b are plotted in acceleration - displacement format for short period range and medium to long period range, respectively. Period T* is represented by the radial line from the origin of the coordination system to the point at the elastic response spectrum define by coordinates $d^{*} = S_e(T^{*})(T^{*}/2\pi)^2$ and $S_e(T^{*})$ [2] [6]. Finally target displacement for the MDOF system is determined by:

$$d_t = d_t^{*}\Gamma \tag{19}$$

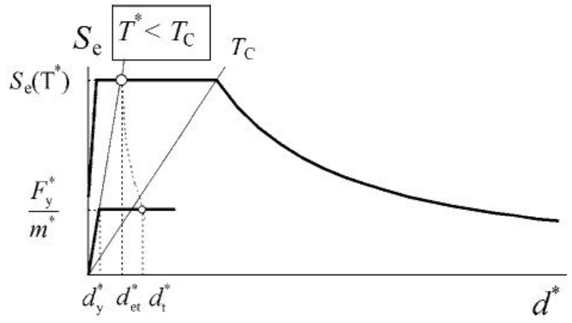

Fig. 8a Determination of target displacement for the equivalent SDOF for shorter period range period [6].

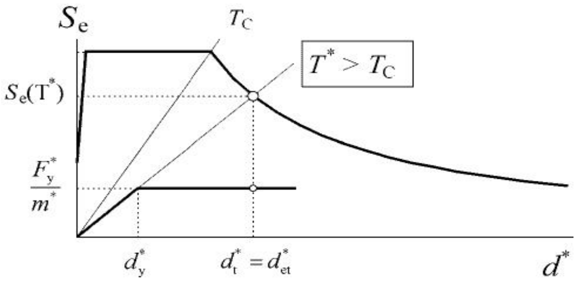

Fig. 8b Determination of target displacement for the equivalent SDOF for medium and long range period [6].

IV. RESULTS

The story masses from the ground floor to top amount to 121.6, 121.6, 121.6 and 112.6 lb. A linear displacement shape was assumed for the pushover analysis; $\Phi^T = [0.27, 0.54, 0.81, 1.00]$. The force and displacement of equivalent single degree of freedom system are correlated with the multiple degree of freedom systems of the building. The capacity curve reduced into a SDOF system. The equivalent mass amount is m^{*}= 309.6 lb and the transformation constant Γ is equal to 1.3. Figure 9 shows the pushover curve obtained from OpenSees results. Then a bilinear curve has been obtained for F_y^{*} = 810 kN and D_y^{*}=13.97cm. The elastic period is T^{*}=1.31s.

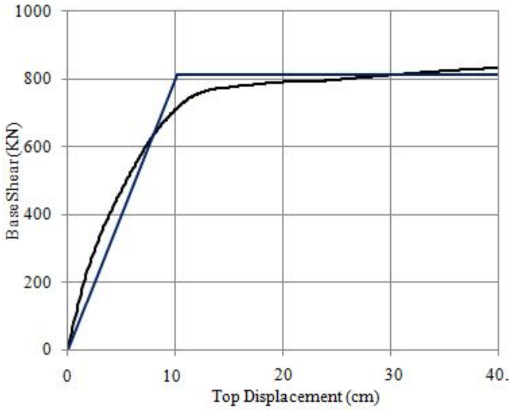

Fig. 9 Capacity curve obtained from Pushover analysis.

The capacity curve is obtained by dividing the forces in the idealized pushover curve by the equivalent mass. The acceleration at the yield point amounts to $S_{ay}=F_y^{*}/m^{*}=810/309.6=0.27$ g.

In the case of unlimited elastic behavior of the structure, seismic demand is represented by the intersection of the elastic demand spectrum and the line corresponding to the elastic period (T^{*}=1.31 s) of the equivalent SDOF system. The values S_{ae} = 0.45 g and S_{de} =65 cm are obtained. The reduction factor R_μ amounts to R_μ =. S_{ae} /S_{ay} = 0.45/0.29 = 1.70. The period T* is greater than T_C, so equal displacement rule apply S_d=S_{de} = 65 cm.

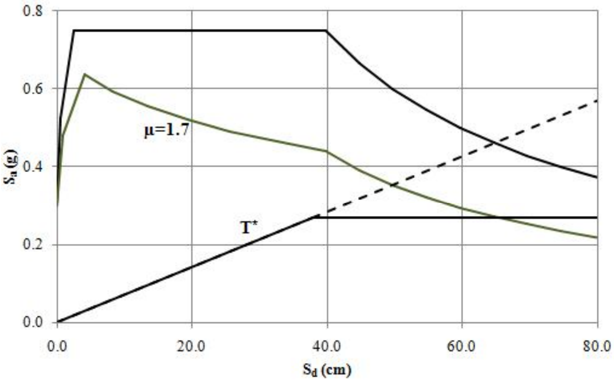

Fig. 10 Demand and capacity spectra for 4 storied RC frame

V. CONCLUSION

It was shown that performance evaluation procedure can be formulated in the format of the capacity spectrum method. Non-linear static analysis result obtained from OpenSees was reasonably acceptable for a broad range of design spectra. This procedure can be performed for seismic performance of existing structures.

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