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Energy-based Design of Steel Structures According to the Predefined Interstory Drift Ratio[†]

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ABSTRACT

The methods which take place in current building codes and used in seismic design of structures are generally linear elastic. Inelastic behavior of the structures under the effect of earthquake is considered indirectly in seismic design codes. Recent studies enable inelastic behavior of structures to be taken into account properly in the structural design. In this study, a calculation method oriented towards the design of new structures which fulfill the predefined interstory drift ratio according to the usage function of the structures was offered by considering the inelastic behavior of the structural members and by using the energy balance of the structures. Interstory drift ratios when the steel structure displacements reach the target displacements were compared with the initial interstory drift ratios and the results were interpreted.

Keywords: *Inelastic behavior, energy-based design, target displacement, performance based design.*

1. INTRODUCTION

Structures generally behave inelastic under excessive seismic loading. When earthquake loads which exceed the working load limits approach the lateral load capacity of the structures, stresses produced in structural members exceed elastic limits and displacements in structural elements become too large. Therefore, yield mechanisms of structures have a great importance in nonlinear structural behavior.

Earthquake-resistant structures are designed by using displacement-based and energy-based methods in addition to force-based methods. In the force-based design methods, it is aimed that the capacity of structural members to be higher than the internal forces of the members under external loads. The prevention of excessive displacement of the structures and structural elements under seismic loads is targeted as a design criterion in the displacement-based design methods. However, in the energy-based earthquake-resistant design methods elastic and inelastic seismic energy dissipations within the structures are aimed to be more than the earthquake input energy.

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There are many studies in literature about the energy-based seismic design of structures. The application of energy-based seismic analysis procedures in earthquake-resistant structural design was first proposed by Housner [1]. In the study, it was shown that the velocity spectra of earthquakes tend to be stable over the wide period range and also the earthquake input energy to multi-degree-of-freedom systems was expressed. Many other studies were also performed to determine the earthquake input energy and application of input energy in earthquake-resistant structural design and evaluation [2, 3, 4]. Uang and Bertero [2] offered new computation methodology to obtain the earthquake input energy to the structures and they also formulated the energy-balance equation for single-degree-of-freedom systems. Akiyama [5] defined the elastic energy dissipation in structures assuming that the structures are treated as single-degree-of-freedom systems. An energy-based methodology for earthquake-resistant design of structures was also used in Surahman's study [6]. In the methodology within the study, energy dissipations in structures and energy dissipation capacities of the structural members were emphasized. In Leelataviwat's study [7] a new method which can be used in structural design was presented by writing energy balance equations for a preselected yield mechanism. The energy-based method was used in the design of steel structures by including interstory drift ratio concept. The development of energy balance concept for multi-degree-of-freedom systems and the application of energy balance in the evaluation of structures under seismic load effects were discussed in Leelataviwat and Goel's studies [8, 9, 10]. Energy concept in earthquake-resistant structural design and performance-based design of multi-story moment resisting frames by using the energy-based approximations were researched in Shen and Akbaş's studies [11, 12, 13]. In Lee and Goel's study [14], structural design was performed by using the energy concepts and base shear force was obtained by using an energy-based design method as used in Leelataviwat's study [7]. Many studies in literature are about steel structures. In the study of Kim and Choi [15], the energy-based design of multi-story braced steel frames was performed and results were validated with nonlinear time history analyses.

Performance-based structural design is a type of design which expects fulfillment of the required criteria for the structure. In the energy-based and performance-based methodology within this study, arrangement of the method developed by Leelataviwat [7] is made to comply with the Turkish Seismic Design Code. Interstory drift ratio is chosen as a performance-based design criterion and it is taken from ATC-13 [16] report within the study. Structures are designed according to the target interstory drift ratio which is selected in line with the usage function of the structures. The energy-based base shear force that acts on the structure is determined and the structural system is designed. Beams are assumed to have the same dimensions throughout the design process. After the end of the design, nonlinear static push-over analyses are performed and pushover curves of the structures are obtained. Interstory drift ratios of all stories in the structures which are pushed up to the target displacements are obtained by using the seventh chapter of the Turkish Seismic Design Code, 2007 [17]. Interstory drift results obtained from nonlinear analyses are compared with the drifts which are preselected at the beginning of the energy-based design and the results are interpreted.

2. ENERGY-BASED DESIGN METHOD FOR MULTI-STORY STEEL STRUCTURES

In the energy-based methodolgy which is for design of new structures, it is assumed that some portion of seismic input energy are dissipated by the elastic behavior and the remaining significant portion of seismic input energy are dissipated by the inelastic behavior of the structures. Housner researched the velocity spectra of some major earthquakes in the world such as El Centro (1934, 1940), Olympia (1940) and Taft (1952) ground motions and he showed that spectra are tend to be stable over a wide period range [1]. In the energy-based design methodology within this study, Equation (1) which was defined by Housner [1] is used to calculate the seismic input energy to the multi-degree-of-freedom structural systems.

$$E_I = \frac{1}{2} M_t S_V^2 \tag{1}$$

In Eq. (1); E_I : is the total input energy to the structure with the earthquake, M_t : is the total mass of the system and S_V : is the elastic spectral velocity. The total input energy equation that was defined by Housner with Eq. (1) can be rearranged by substituting the required expressions as:

$$E_I = \frac{Wga^2T^2}{8\pi^2} \tag{2}$$

where W : is the total weight of the structure, g : is the acceleration of gravity, T : is the natural vibration period of the first mode and a : is the coefficient of the elastic spectral acceleration (dimensionless acceleration). "a" can be determined from both special design acceleration spectrum which is created by using different ground motion records and standard elastic design acceleration spectrum that is defined in the Turkish Seismic Design Code [17]. In the design methodology within the study, the Turkish Seismic Design Code [17] is considered and the coefficient of elastic spectral acceleration is calculated according to the Turkish Seismic Design Code.

The total energy input that was defined by Housner with Eq. (1) can be rewritten as in Eq. (3) assuming that the energy is dissipated by elastic and inelastic behavior.

$$E_I = E_e + E_p \tag{3}$$

In Eq. (3); E_e: is the elastic energy and E_p : is the plastic energy of the system. In the study, it is accepted that the plastic energy is dissipated in plastic hinge regions. Elastic and plastic energies of the system are given in Figure 1. Figure 1 represents the ideal elasto-plastic behavior of the structural system.

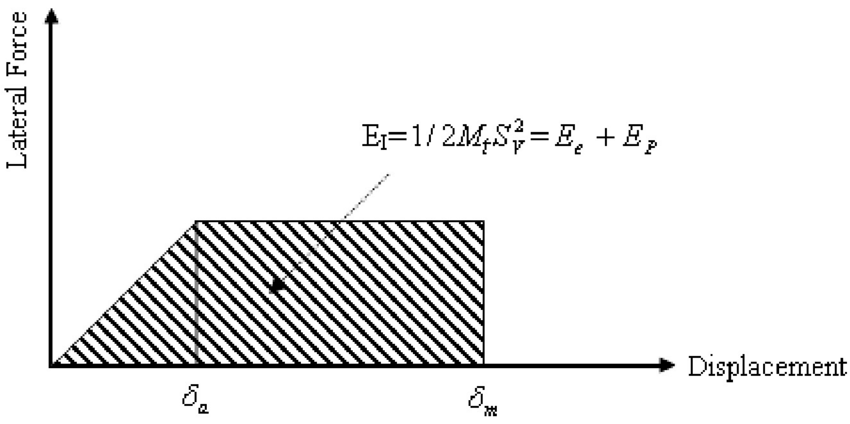

Figure 1. Elastic and plastic energy concepts from "Displacement-Lateral Force" graph (ideal elasto-plastic behavior)

In Figure 1; δ_a : is the yield displacement and δ_m :is the maximum displacement.

Akiyama [2] defined the elastic energy term with Equation (4) assuming that the structural system can be reduced into a single-degree-of-freedom system.

$$E_e = \frac{1}{2} M_t \left(\frac{T}{2\pi} \frac{V_t}{W} g\right)^2 \tag{4}$$

In Eq. (4), V_t : is the base shear force. After total and elastic energies are expressed, plastic energy E_p can be obtained by subtracting Eq. (4) from the Eq. (2) as:

$$E_p = \frac{WT^2 g}{8\pi^2} [a^2 - (\frac{V_t}{W})^2] \tag{5}$$

After the plastic energy is obtained from Eq. (5), it can be rewritten by using classical work-energy principle as in Eq. (6). In the structure, the yield mechanism is accepted as can be seen from Figure 2. The frame structure is assumed to undergo a plastic rotation "θ_p" from the base and the plastic energy equation is rewritten for the yield mechanism (6). The total plastic energy in the collapse limit state of the structure can be calculated by Eq. (6) for the preselected yield mechanism.

$$E_p = (\sum_{i=1}^{N} 2nM_{pbi} + \sum_{j=1}^{M} M_{pcj})\theta_p \tag{6}$$

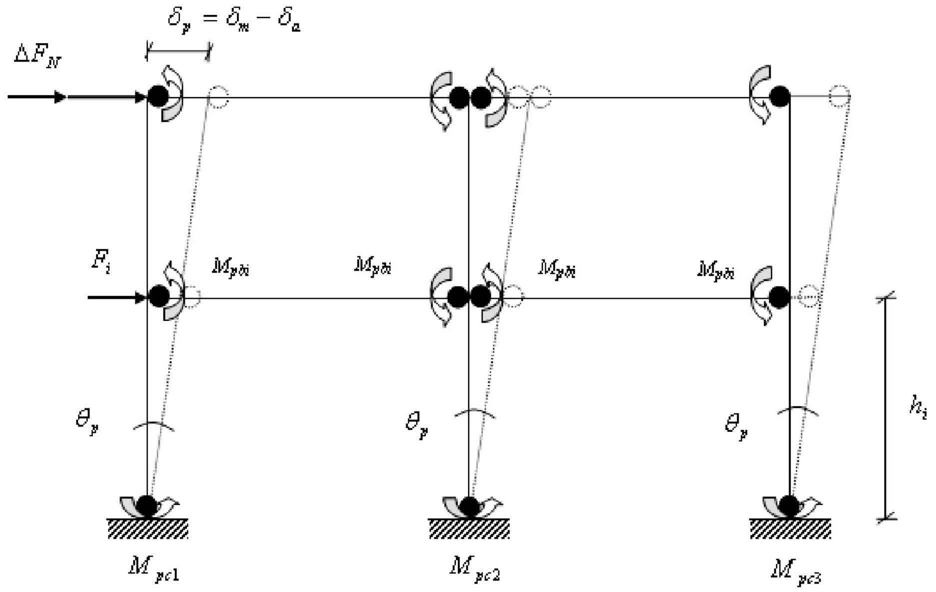

Figure 2. Yield mechanism of a two-story and two-span frame structure, plastic moment of structural members, external design loads

In Eq. (6) and Figure 2; M_{pbi} : is the plastic moment of the beams in ith story and M_{pcj} : is the base plastic moment of the columns. N : is the total number of stories, n : is the number of beams in a story and M : is the total number of columns in ground floor. In Figure 2; δ_p : is the plastic displacement of the roof story and h_i : is the height of the ith story.

Accepted yield mechanism in the design can be seen from Figure 2. In the yield mechanism it is assumed that plastic hinges occur in the beam edges and column bases. Nonlinear deformations are assumed to be in these plastic hinge regions and the other sections are accepted as linear-elastic. Eq. (7) is obtained by equating the internal work in plastic hinge regions with the external work done by the design forces of the system.

$$\sum_{i=1}^{N} 2nM_{pbi} + \sum_{j=1}^{M} M_{pcj} = \sum_{i=1}^{N} F_i h_i + \Delta F_N h_N \tag{7}$$

In Eq. (7); F_i : is the equivalent static seismic force in the Turkish Seismic Design Code [17], (Equation 8).

$$F_i = (V_t - \Delta F_N)\frac{w_i h_i}{\sum_{j=1}^{N} w_j h_j} \tag{8}$$

In Eq. (8); ΔF_N : is the additional seismic force that acts on the roof (Nth) story. w_i and w_j : are the weights of the stories i and j; h_i and h_j : are the heights of the stories i and j from the base. ΔF_N is calculated by using the equation in the Turkish Seismic Design Code [17], (Eq. 9):

$$\Delta F_N = 0{,}0075 N V_t \tag{9}$$

where N : is the total number of stories from the base. Plastic energy (E_p) equation can be rewritten by substituting Eq. (7) into Eq. (6) as:

$$E_p = (\sum_{i=1}^{N} F_i h_i + \Delta F_N h_N)\theta_p \tag{10}$$

Eq. (10) can be arranged by substituting Eq. (8) for the "F_i" force and Eq. (9) for the ΔF_N force and then energy-based base shear force "V_t" can be obtained by equating Eq. (10) with Eq. (5). V_t can be obtained from different plastic energy equalities as [7,18,19]:

$$\frac{V_t}{W} = \frac{-\alpha + \sqrt{\alpha^2 + 4a^2}}{2} \tag{11}$$

where α : is a dimensionless parameter that is based on the terms such as yield mechanism, natural vibration period for the first mode, story heights, story number and story weights. The coefficient α is calculated by using Eq. (12), [19].

$$\alpha = d - e + f \tag{12}$$

d , e and f coefficients in the α equation (Eq. (12)) are given in Eqs. (13), (14) and (15), respectively [19].

$$d = \left(\frac{\sum_{i=1}^{N} w_i h_i^2}{\sum_{i=1}^{N} w_i h_i}\right)\frac{\theta_p 8\pi^2}{T^2 g} \tag{13}$$

$$e = \left(\frac{\sum_{i=1}^{N} w_i h_i^2}{\sum_{i=1}^{N} w_i h_i}\right)\frac{0{,}06\theta_p N\pi^2}{T^2 g} \tag{14}$$

$$f = \frac{0{,}06\theta_p N h_N \pi^2}{T^2 g} \tag{15}$$

In Eqs. (13), (14) and (15); θ_p: is the preselected plastic rotation value. The total preselected rotation (θ_T) can be expressed by the sum of elastic yield rotation (θ_y) and plastic rotation (θ_p), (Eq. (16)).

$$\theta_T = \theta_y + \theta_p \tag{16}$$

In this study, θ_y which is used indirectly in the energy-based design methodology is taken as 1% considering the accepted value in the literature [18].

Interstory drift ratios will be the same in the limit collapse state of the structure. Because of this, interstory drift ratios can be used as a design criterion in determination of θ_T. Table 1 from ATC-13 report is presented to define the structural damage [16].

Table 1. Performance levels according to interstory drift ratios [ATC-13 (1985)]

Performance Level	Damage State	Interstory Drift Ratio (%)
I	None	Δ<0.2
II	Slight	0.2<Δ<0.5
III	Light	0.5<Δ<0.7
IV	Moderate	0.7<Δ<1.5
V	Heavy	1.5<Δ<2.5
VI	Major	2.5<Δ<5
VII	Destroyed	Δ>5

The total rotation (θ_T), which is used in structural design, can be determined from Table 1 according to damage state.

3. DETERMINATION OF STRUCTURAL MEMBERS

Beam and column members are chosen according to plastic design rules after determining the total base shear force within the study. The yield mechanism of the structure is accepted as shown in Figure 2. Plastic hinges are assumed to form in the beam edges and column bases as indicated in previous chapters. Plastic regions in the structural members are modeled with plastic hinges by using lumped plasticity approach. Strong column – weak beam behavior, which exists in the Turkish Seismic Design Code, is also controlled in the design within the study.

M_{pbi} moment in Eq. (7), which is obtained by equating the internal work on the plastic hinges to the external work by the design loads varies based on lateral rigidity and shear force of the story. Therefore, plastic moment of the beams in ith story can be described by Eq. (17) as the ratio of the reference moment.

$$M_{pbi} = \beta_i M_{pbr} \tag{17}$$

In Eq. (17); M_{pbi} : is the plastic moment of the beams in ith story, β_i : is the shear strength factor for the beam and M_{pbr} : is the reference plastic moment of the beamSubstituting Eq. (17) into Eq. (7);

$$\sum_{i=1}^{N} F_i h_i + \Delta F_N h_N = \sum_{i=1}^{N} 2n\beta_i M_{pbr} + \sum_{j=1}^{M} M_{pcj} \tag{18}$$

is obtained. The shear strength factor for the beam can be generally expressed by Eq. (19), [7].

$$\beta_i = (\frac{V_i}{V_N})^b \tag{19}$$

In Eq. (19); V_i : is the shear force of the story i and V_N : is the shear force of the roof story (Nth) level. b is the numerical factor and described by Lee and Goel [14] as:

$$b = 0{,}5T^{-0{,}2} \tag{20}$$

The numerical factor b in Eq. (20) was widely investigated by several researchers. In this study, Eq. (20) defined by Lee and Goel is used for the b factor depending upon the first natural period of vibration (T). β_i : The shear strength factor which is expressed by Eq. (19) is shown schematically in Figure 3. The plastic moment values (M_{pbi}), which are obtained by using β_i factor, are written in story levels in Figure 3. The plastic moment values for all beams in a story (M_{pbi}) can be calculated after determining reference plastic moment (M_{pbr}) with Eq. (18) and shear strength factor (β_i) with Eq. (19). Beams in a story are chosen according to the plastic moments (M_{pbi}) which are calculated by using Eq. (17).

Column design is performed after the design of beam. M_{pcj}, the plastic moment of column bases, can be estimated by using several approaches based on the shear force in a story. In the study Muto Method is used for determination of column plastic moments. In the beams, strain hardening effect is considered and strength increase is assumed. Therefore, plastic moments of beams are multiplied by a coefficient ξ which is called the strength increase factor within the study. The increased plastic moment (ξM_{pbi}) is used in the column design instead of beam plastic moment (M_{pbi}). Assuming the strength increase ratio to be approximately equal to 5%, ξ is taken as 1.05 within this study. ξ is taken 1 because; in the roof story level plastic hinges do not affect the behavior of the mechanism.

In the study, column axial loads and bending moments are obtained in the limit collapse (yield) state. Steel column sections which are under the effect of combined bending and axial loads are chosen by using the yield surfaces [20] of the sections. Application steps of the design methodology can be seen from Figure 4 (flow chart).

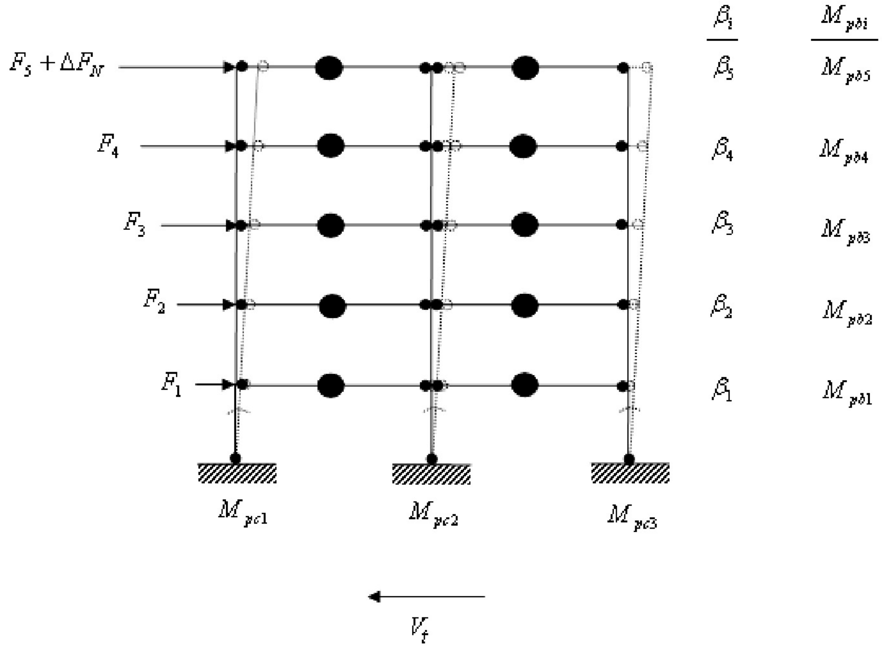

Figure 3. β_i parameters and plastic moments for the beam design

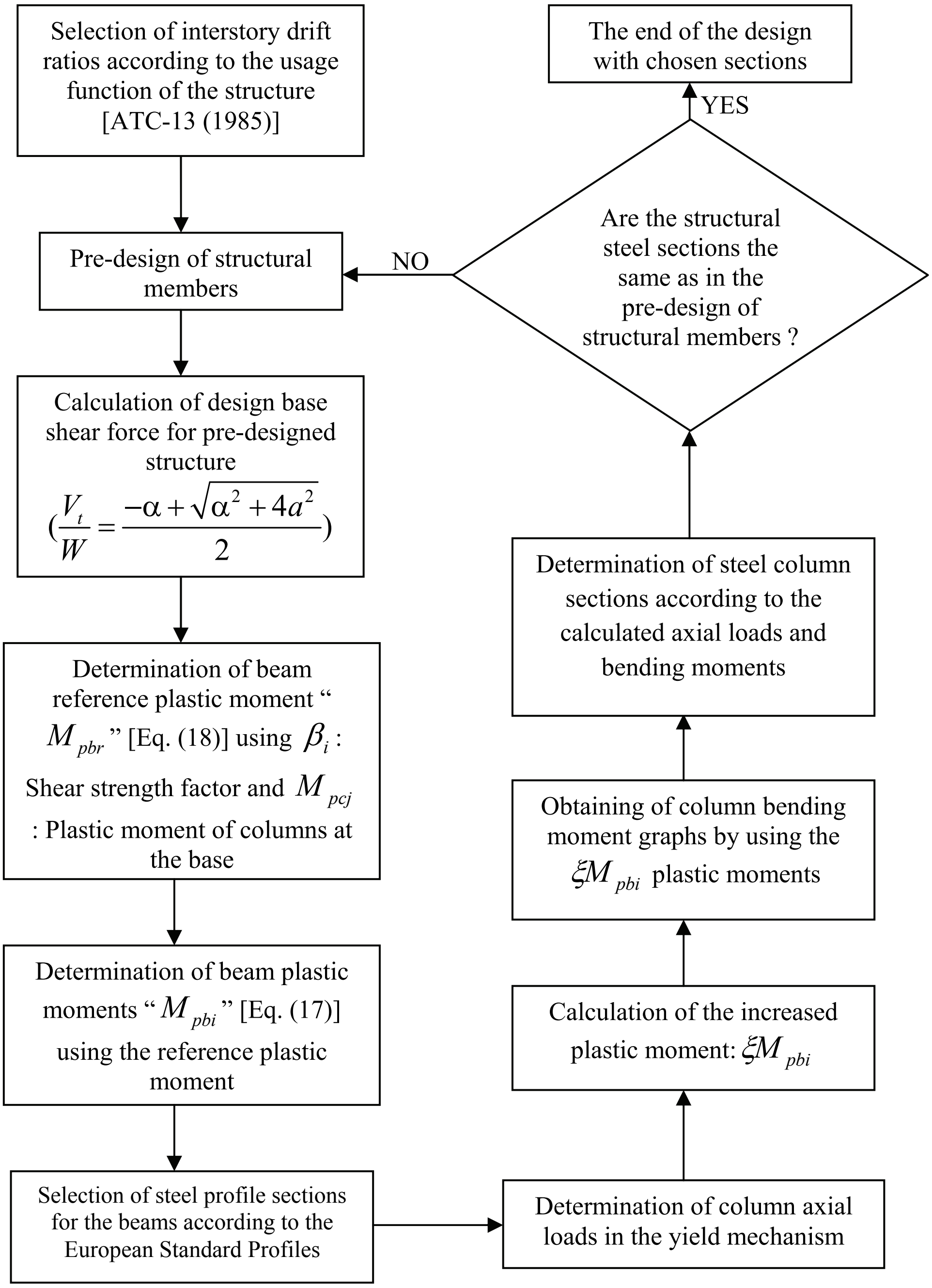

Figure 4. Flow chart of the energy-based structural design methodology

4. CASE STUDY

2, 5 and 8-story steel frames are designed according to the different preselected interstory drift ratios using the energy-based methodology within the study. In the design; 1.5%, 2% and 3.5% interstory drift ratios are chosen from the ATC-13 report to represent the moderate, heavy and major damage states (Table 1).

In the application of the design methodology, steel profiles which have the yield strength of 240 MPa and modulus of elasticity of 210000 MPa are used. Steel structures are designed by using the European Standard Profiles. HEB profiles are used for the columns and IPE profiles are used for the beam sections. Regular steel frames with uniform mass and stiffness along the buildings are used in the application of the design methodology. All story heights are 3 meters and all beam spans are 6 meters. Distributed load on the beams is taken as 30 kN/m and the weights of the frames are ignored. Structures are assumed to be in the first degree earthquake zone and soil type Z4 is assumed. Building importance factor is taken as I=1.0 for the usage function of the structures [17].

Base shear forces acting on the steel frame structures are calculated initially in the design. Parameters and V_t/W ratios for the 1.5%, 2% and 3.5% of θ_T are given in Table 2, 3 and 4 for the 2, 5 and 8-story steel frame structures in the limit state. Final beam and column sections are shown in Figures 5, 6 and 7.

Table 2. Design parameters of the 2-story frames

Story Number	T (sec.)	a	θ_y	θ_p	α	V_t/W
2	0.48	1.000	0.01	0.005	0.867	0.656
2	0.56	1.000	0.01	0.01	1.298	0.543
2	0.67	1.000	0.01	0.025	2.262	0.379

Table 3. Design parameters of the 5-story frames

Story Number	T (sec.)	a	θ_y	θ_p	α	V_t/W
5	0.63	1.000	0.01	0.005	1.136	0.582
5	0.74	1.000	0.01	0.01	1.655	0.470
5	0.92	0.981	0.01	0.025	2.638	0.325

Table 4. Design parameters of the 8-story frames

Story Number	T (sec.)	a	θ_y	θ_p	α	V_t/W
8	0.69	1.000	0.01	0.005	1.484	0.503
8	0.86	1.000	0.01	0.01	1.905	0.429
8	1.24	0.774	0.01	0.025	2.283	0.238

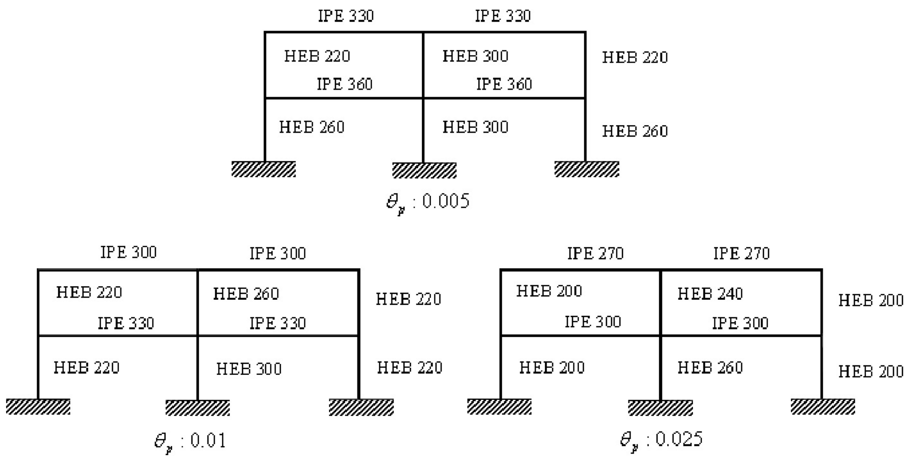

Figure 5. Energy-based design of 2-story frames according to the interstory drift ratios of 1.5%, 2% and 3.5%

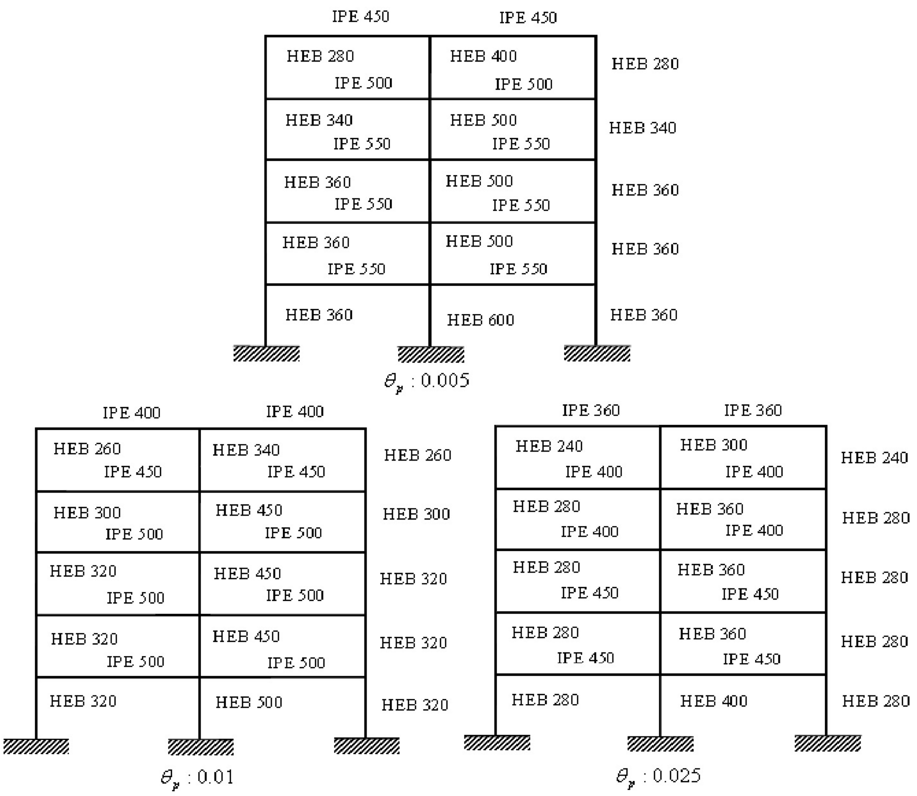

Figure 6. Energy-based design of 5-story frames according to the interstory drift ratios of 1.5%, 2% and 3.5%

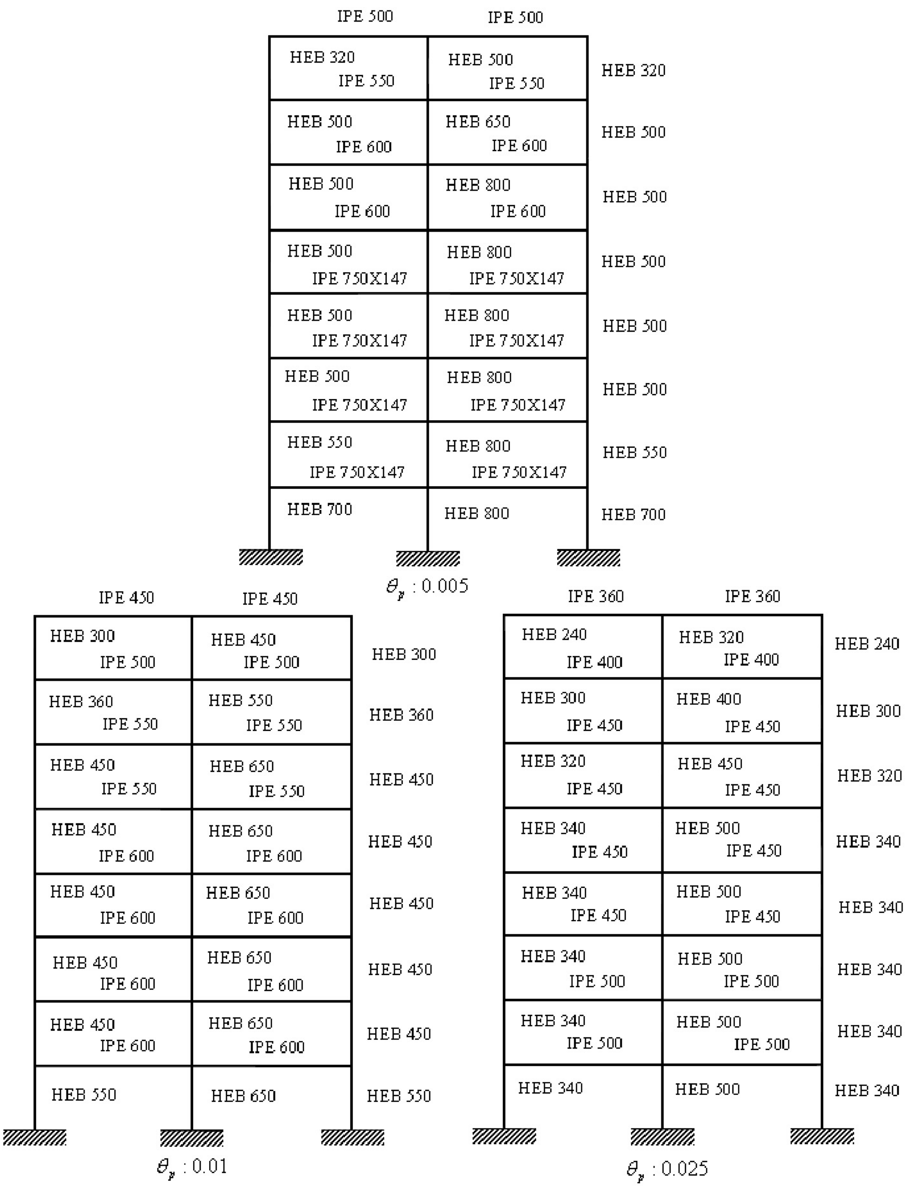

Figure 7. Energy-based design of 8-story frames according to the interstory drift ratios of 1.5%, 2% and 3.5%

5. EVALUATION OF ENERGY-BASED DESIGN

In this chapter, 2, 5 and 8-story steel frames which are designed by using the method explained in previous chapters are controlled by performing nonlinear static analyses to see if the frames satisfy the target interstory drift ratios or not. SAP2000, a structural analysis program, is used in the analyses. Section moment-rotation relations are defined as ideal elasto-plastic and second-order effects are neglected in the nonlinear analyses. Graphs which are obtained by converting pushover curves to modal capacity curves [21] for the 2, 5 and 8-story frame structures designed according to the interstory drift ratios of 1.5%, 2% and 3.5% can be seen from Figures 8, 9 and 10. Displacement demands of the frames obtained by using the method in the Turkish Seismic Design Code are shown in the same figures.

Because the interstory drift ratios are used in the design methodology as design criteria, when interstory drift ratios are reached the displacement demands are compared with the interstory drift ratios which are preselected in the design. Interstory drift ratios obtained from nonlinear static analyses and target interstory drift ratios in the design are given in Figure 11, 12 and 13. It can be seen from the results that the interstory drift ratios are exceeded in 2-story frames. In 5 and 8-story frames, the target interstory drift ratios are not exceeded and remain smaller than the preselected target drift ratios.

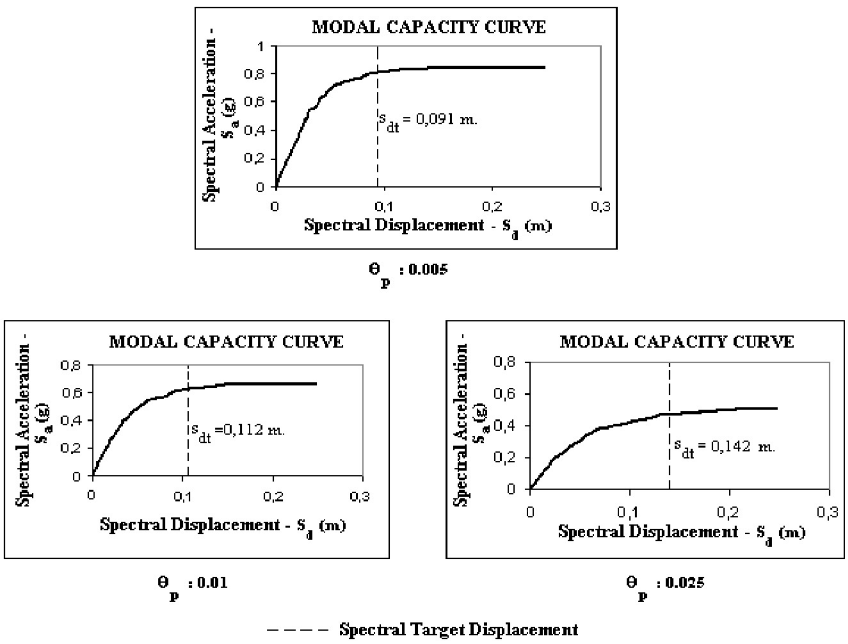

Figure 8. Modal capacity graphs of 2-story frames (Interstory drift ratios:1.5%, 2% and 3.5%)

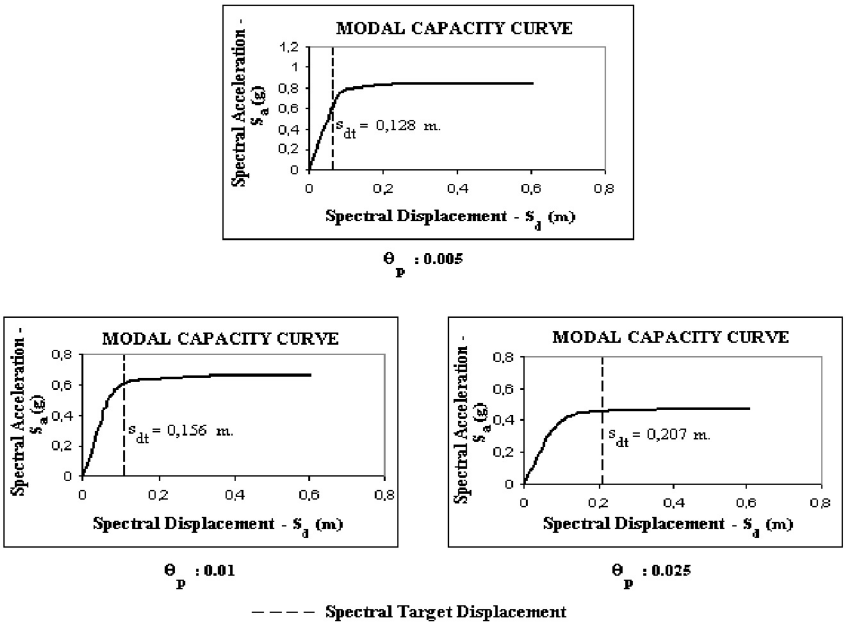

Figure 9. Modal capacity graphs of 5-story frames (Interstory drift ratios:1.5%, 2% and 3.5%)

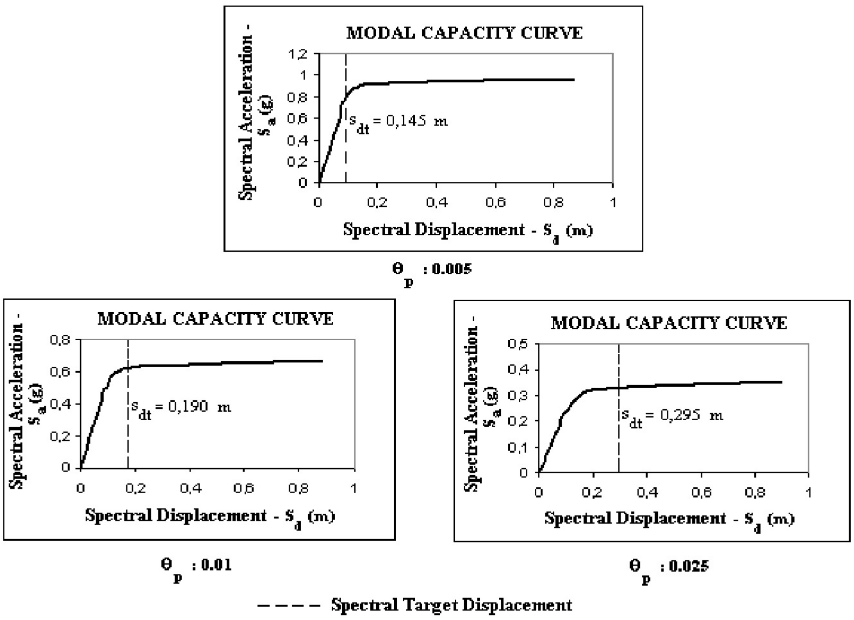

Figure 10. Modal capacity graphs of 8-story frames (Interstory drift ratios:1.5%, 2% and 3.5%)

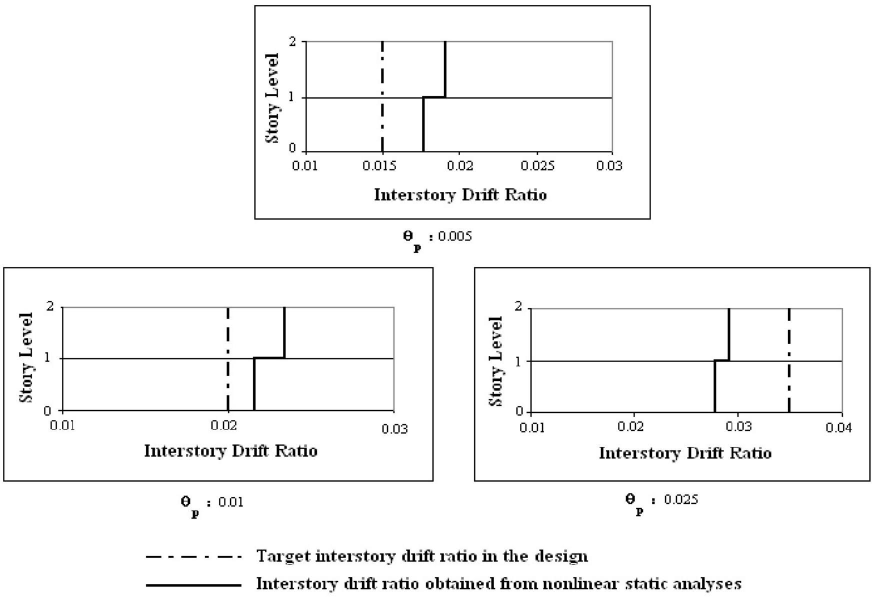

Figure 11. Interstory drift ratios of 2-story frames designed with the energy-based method

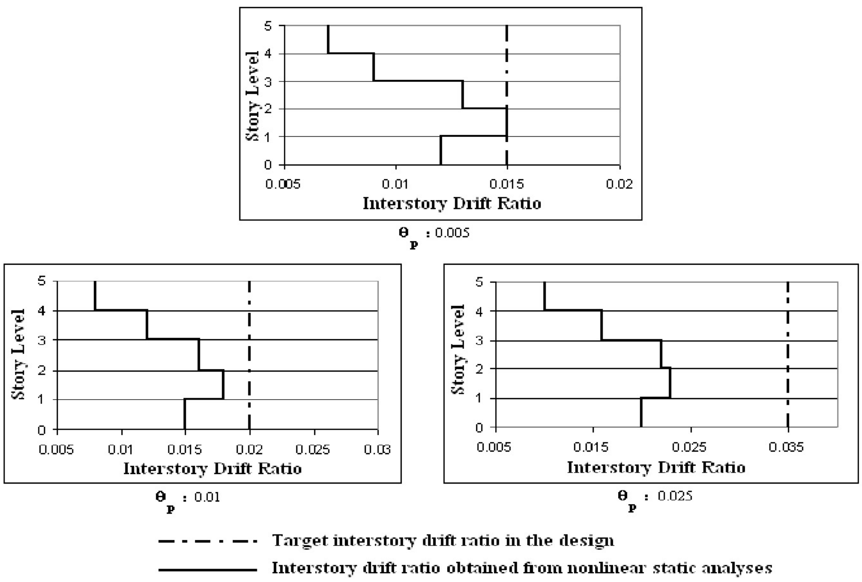

Figure 12. Interstory drift ratios of 5-story frames designed with the energy-based method

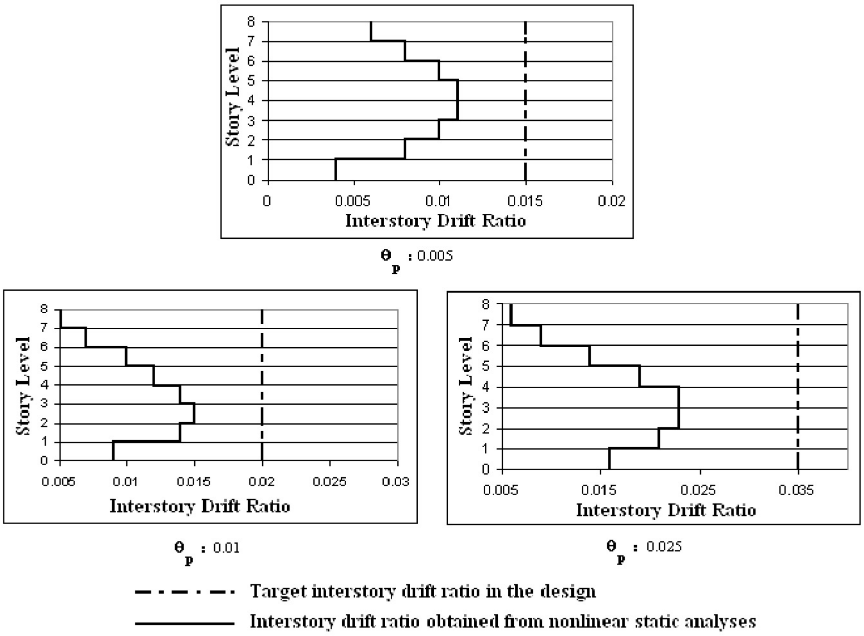

Figure 13. Interstory drift ratios of 8-story frames designed with the energy-based method

6. CONCLUSIONS

Energy-based design methodology according to the predefined interstory drift ratio is presented within the study. 2, 5 and 8-story steel frame structures are chosen to investigate the applicability of the methodology. Nonlinear static analyses are performed to check the target interstory drift ratios preselected in the design to see whether the target drift ratios are exceeded or not. A computer software that consists of proper calculation algorithms is needed because the design methodology is an iterative methodology. Microsoft Excel program is used to reduce the time-consuming computation processes and hence the design results are obtained in a shorter period of time. The flow chart explaining the methodology is seen in Figure 4. Inelastic behavior of the structures is considered within the design methodology. The design is performed by using the energy concept differing from the force-based and displacement-based designs. Energy concept is supported with the yield mechanism and interstory drift ratio concepts and so the energy-based methodology is developed.

It is seen from the nonlinear analyses that target displacements of the 2-story steel frames are exceeded in all story levels for the interstory drift ratios of 1.5% and 2%. The interstory drift ratio values which are obtained from nonlinear analyses remain less than the targeted drift ratios in the design of 2-story frames according to the drift ratios of 3.5%. In the design of 5-story frames, target interstory drift ratios are not exceeded in all story levels and it can be seen from the nonlinear analyses that interstory drift ratios are close to the targeted drift ratios in the designs. Target interstory drift ratios are not exceeded in 8-story frames, too, and drift ratios obtained from nonlinear analyses remain less than the targeted values. It can be observed from the study that the energy-based design methodology gives better results for medium height frame structures.

Further research should be done to obtain better results from the energy-based existing design methodology. The calculation procedure is developed for the first-mode dominated structures. First mode shape of the structure is used in the design. It is necessary to study the design methods that consider higher modes of the structures. The design methodology can be developed by evaluating parameters such as span number, interval length and story height. Elastic rotation of the structure is accepted as 1% in this study. It will be very useful to develop the accepted elastic rotation according to the height and the other properties of the structure.

Symbols

a : Coefficient of the elastic spectral acceleration

b : Numerical factor used in the calculation of shear strength factor for the beam

d : Coefficient which is based on several structural properties and used in the calculation of coefficient "α"

e : Coefficient which is based on several structural properties and used in the calculation of coefficient "α"

E_e : Elastic energy of the system

E_I : Seismic input energy of the system

E_p : Plastic energy of the system which is assumed to be dissipated in plastic hinge regions

f : Coefficient which is based on several structural properties and used in the calculation of coefficient "α"

F_i : Equivalent earthquake force which acts on the ith story

g : The acceleration of gravity

h_i : The height of the ith story

h_N : The height of the Nth story

M : Total column number on the ground floor

M_p : Plastic moment of the column

M_{pbi} : Plastic moment of the beams in the ith story level

M_{pbr} : Reference plastic moment of the beams

M_{pcj} : Plastic moment of the column at the base level on j axis

M_t : Total mass of the multi-degree-of-freedom system

n : Beam number in a story

N : Total story number from the base

N_p : Plastic axial load of the column

s_{dt} : Spectral target displacement

S_V : Elastic spectral velocity

T : Natural vibration period of the first mode

V_i : Shear force of the i^{th} story

V_t : Energy-based base shear force

V_N : Shear force of the roof story

w_i : The total weight of the i^{th} story

W : The total weight of the structure

α : Dimensionless parameter which is used in the calculation of energy-based base shear force

β_i : Shear strength factor for the beam

δ_a : Yield displacement

δ_m : Maximum displacement

δ_p : Plastic displacement

Δ : Interstory drift ratio in the ATC-13 report

ΔF_N : Additional earthquake load which acts on the roof level of the structure

θ_p : Preselected plastic rotation

θ_T : Preselected total rotation

θ_y : Elastic yield rotation

ξ : Strength increase factor for the beams

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