CHAPTER 3 PERFORMANCE-BASED PLASTIC DESIGN OF BRKB-TMF

In this study, a Performance-Based Plastic Design (PBPD) procedure (Goel and Chao, 2008) for BRKB-TMF was developed. The design starts by selecting a yield mechanism and a target drift for the structure. For design purposes, structural elements are classified either as Designated Yielding Members (DYMs) or non-Designated Yielding Members (non-DYMs). This classification is used to distinguish elements which will be used to dissipate seismic energy and those which will remain elastic. Design base shear and lateral force distribution are determined from the energy balance equation. The required strength of DYMs is determined using virtual work equation. The non-DYMs are designed to remain elastic under the forces generated by the fully yielded and strain hardened DYMs. In this chapter, a step-by step PBPD design procedure for BRKB-TMF system is presented.

3.1 Design Yield Mechanism

Figure 3.1 shows the design yield mechanism of BRKB-TMF subjected to design lateral forces and pushed through the design target plastic drift, θ_p. All major inelastic deformation is intended to be confined within the BRBs. The desired global yield mechanism of BRKB-TMF consists of plastic deformation of braces and plastic hinges at the column bases. The plastic hinges at the column bases are required for the frame to form a complete mechanism.

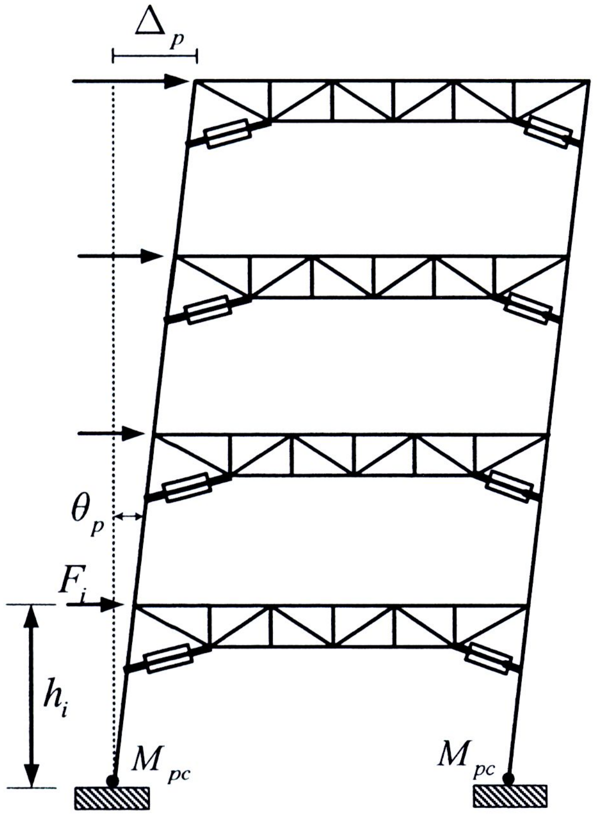

Figure 3.1 Pre-selected Yield Mechanism of BRKB-TMF

3.2 Selection of Target Drift and Design Base Shear

The design of BRKB-TMF in this study is based on the PBPD approach. This method directly accounts for inelastic behaviour and considers the internal force distribution at ultimate limit state. The design concept uses pre-selected target drift and yield mechanism as key performance limit states. The required design base shear is derived corresponding to a target drift level and a selected yield mechanism using the energy balance concept. Plastic (limit) design is then used to design the structure to achieve the selected mechanism.

The PBPD method begins by selecting a target yield mechanism with a set of designated yielding members (DYMs). For BRKB-TMF system, the selected mechanism consists of the yielding of the BRBs and the flexural hinging at the bases of the columns as illustrated in Figure 3.1. A target drift corresponding to a chosen hazard level is then selected. The target drift depends on the performance objective, and is selected mainly to limit system and elements ductility demands to prescribed limits. To assure satisfactory behavior, the inelastic deformation expected to occur in the BRBs in a severe earthquake should not exceed the inelastic deformation capacity of the BRBs. This can be done by choosing an appropriate value for the target drift to limit the deformation demands of the BRBs. Inelastic deformation demand for a BRB can be calculated approximately from the target drift by assuming that the system will deform in a rigid-plastic manner. Using the selected mechanism and neglecting any elastic deformation in the frame members, plastic deformation of a BRB can be computed based on the truss configuration along with the law of cosines (Figure 3.2). For a special case where the depth of the truss at the face of the column is chosen to be twice the depth of the truss at mid span ($D=2D_o$), the plastic strain in the BRB, ε_p, simply becomes

$$\varepsilon_p = \frac{\delta}{l_o} = \frac{\theta_p D \sin(\varphi)}{l_o} \qquad (3\text{-}1)$$

where θ_p is the target plastic drift of the frame, l_o is the undeformed length of the BRB, φ is the acute angle between the first diagonal member and the column, and D is the depth of the truss at the face of the column. For more details on the relationship between the target drift and the brace deformation, the reader should refer to Appendix A.

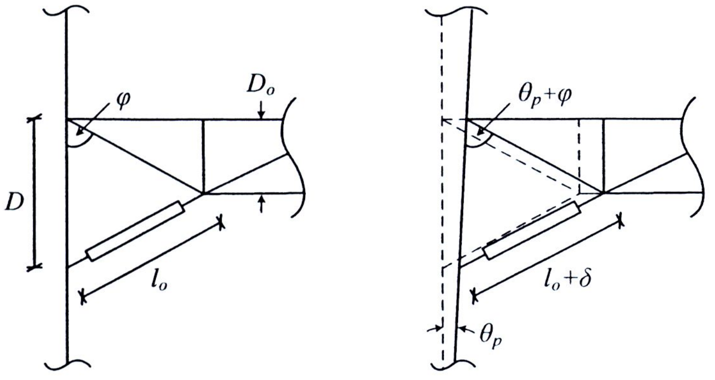

Figure 3.2 Plastic Deformation of BRB

Figure 3.3 shows brace strain demand versus φ angle for different plastic drift ratios. The strain demand was largest at 45°. This figure can be used to select a target drift depending on BRBs' strain capacity.

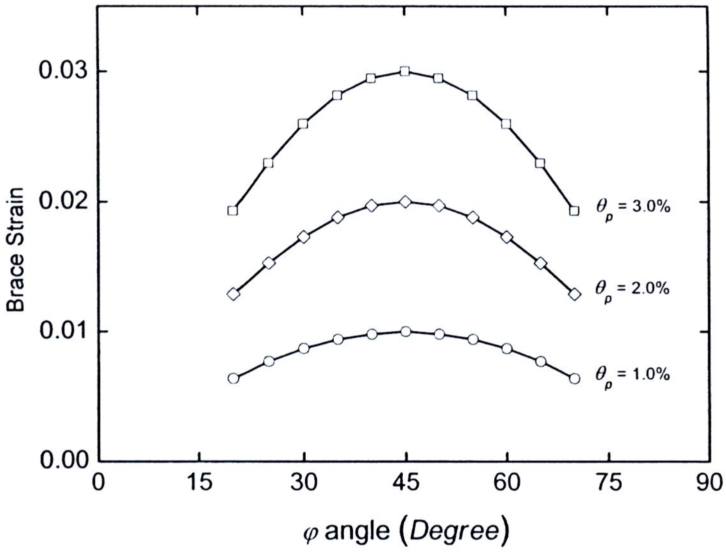

Figure 3.3 Brace Strain Demand for Different Plastic Drift Ratios

Numerous uniaxial and subassemblage BRB tests have been performed over the years. Based on some of test results (Table 2.1), the maximum strain for a BRB appears to be in the range of 2%-3% depending on the length and configurations of the BRB. Knowing the deformation capacity of the BRBs, Equation 3-1 can be used to select an appropriate value for the target drift as well as the truss configuration. Once these are determined, the strength of the system, or design base shear, required for a selected hazard level is calculated using energy balance concept, i.e., by equating the work needed to push the structure monotonically up to the target drift to that required by an equivalent elastic-plastic single degree of freedom system to achieve the same state (Lee and Goel, 2001). It can be shown that the required base shear (Equation 2-3), V, is given by:

$$\frac{V}{W} = \frac{-\alpha + \sqrt{\alpha^2 + 4\gamma C_e^2}}{2}$$

where W is the weight of the structure, C_e is normalized design pseudo acceleration (S_a/g), γ is the energy modification factor defined as the ratio between the work needed to push the structure up to the target drift and elastic input energy (Goel and Chao 2008), and α (Equation 2-4) is a parameter given by:

$$\alpha = \left(\sum_{j=1}^{n} \lambda_i h_i \right) \frac{\theta_p 8\pi^2}{T^2 g}$$

in which T is the period, and h_i is the height from the ground of floor level i, and λ_i is the lateral force distribution factor such that:

$$F_i = \lambda_i V$$

In general, the lateral force distribution should closely represent an actual pattern that occurs under earthquake ground motions. In this study, a distribution (Equation 2-6) proposed by Choa et al. (2007) for a moment frame is used and is given by:

$$\lambda_i = (\beta_i - \beta_{i+1})\left(\frac{w_n h_n}{\sum_{j=1}^{n} w_j h_j}\right)^{0.75T^{-0.2}}$$

where w_n is the weight of the structure at the top level n, h_n is the height from the ground to the top level, and β_i (Equation 2-7) is ratio of the story shear at level i to that of the top story (level n).

$$\beta_i = \frac{V_i}{V_n} = \left(\frac{\sum_{j=i}^{n} w_j h_j}{w_n h_n}\right)^{0.75T^{-0.2}}$$

The derivation of the above equations has been discussed in detail (Goel and Chao, 2008) and has been omitted herein. Once the design base shear and lateral forces have been determined, the required strength of the BRBs and the truss members can be calculated as discussed in Topics 3.3 and 3.4.

3.3 Design of BRBs (Designated Yielding Members)

The principle of virtual work is used to determine the required strength of BRBs. The relative strength of the BRBs in each floor level is initially assigned based on the ratio of the story shear, β_i. Using the plastic mechanism in Figure 3.1 and assuming that the tension and compression forces acting on the BRBs at each floor level are equal, the virtual work equation can be written as

$$\sum_{i=1}^{n} F_i' h_i \theta_p = 2M_{pc}\theta_p + \sum_{i=1}^{n} 2(\beta_i N_{BRB})\delta \qquad (3\text{-}2)$$

where F'_i is the lateral force for one bay at level i, N_{BRB} is the axial strength of the BRB at the roof level, and M_{pc} is the plastic moment of the columns at the bases. The above equation applies to BRKB-TMF with one-bay; however, it can be easily extended to cover a multi-bay structure. By assigning the values for the plastic moment of columns in the first story, the required strength of BRBs at each level ($\beta_i N_{BRB}$) can be calculated. One possible approach is to assign the value of the plastic moment of the columns to prevent soft-story mechanism, that is:

$$M_{pc} = \frac{1.1Vh_{c1}}{4N} \qquad (3\text{-}3)$$

where h_{c1} is the clear height of the first story. The factor 1.1 is used to account for the possible strain-hardening in the plastic hinges (Leelataviwat et al., 1999). The above approach has been found to provide adequate column strength leading to an acceptable seismic performance for many structural systems designed by the PBPD method (Goel and Chao, 2008). The required brace strength of BRBs at each level is given by

$$\phi P_{ysc} = \beta_i N_{BRB} \tag{3-4}$$

3.4 Design of Trusses and Columns (non-Designated Yielding Members)

For this structural system, truss members and columns are designed to be elastic. These members are selected so that they remain in elastic range, even against severe earthquake ground motions. Conventional elastic design can be utilized for these members.

3.4.1 Design of Truss Members

After the sizes of the BRBs have been determined, the trusses are designed to remain elastic under the largest forces generated by the BRBs. The adjusted strengths for a BRB accounting for material overstrength, compression overstrength, and strain-hardening are given by:
for tension

$$P_{pr}^{+} = \omega R_y P_{ysc} \tag{3-5}$$

and for compression:

$$P_{pr}^{-} = \omega \beta R_y P_{ysc} \tag{3-6}$$

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In Equations 3-5 and 3-6, ω, β, and R_y are factors accounting for strain hardening, compression overstrength, and material overstrength respectively. R_y has a value of 1 if the yield stress is determined based on a coupon test. The values for ω and β are generally best assigned based on test results of BRBs with similar length, configurations, and restraining mechanisms to those that will be used in the structure. Using the backbone curve from a test, one can extract the strength adjustment factors ω and $\omega\beta$ comparable to the level of deformation demands expected to occur in the BRBs. It is important to note that the deformation demands experienced by the BRBs will generally be larger than those expected for conventional braced frames because the BRBs in BRKB-TMF system are generally short. Therefore, the values for ω and $\omega\beta$ for BRKB-TMF system will be larger than those used in a conventional braced frame. An example illustrating the selection of those factors is provided in Chapter 4.

Once the sizes of the BRBs have been determined, the truss at each level is designed to be elastic mainly under gravity loads and the adjusted BRB forces. In addition, because the truss is normally connected to the column by welding, the moment generated by the fixity of the top chords should also be taken into account. These end moments create additional flexural forces in the chords and axial forces in the vertical members. The truss is thus subjected to the forces as shown in Figure 3.4. In the figure, $M_{p\text{-}ch}$ is the plastic moment of the top chord and the factor 1.2 is used to account for strain-hardening of material. The analysis of the truss under the given load can be easily

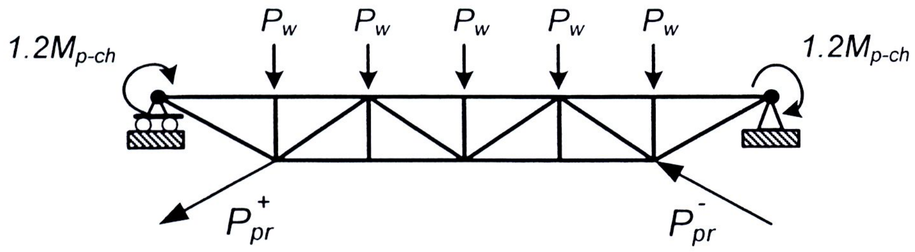

Figure 3.4 Truss Design Concept

If calculations are carried out by hand, the method of superposition can be used. The primary axial tension/compression forces in the truss members can be analyzed under gravity loads and the adjusted BRB strengths. The secondary effects due to plastic moments of the chord members can be approximated using a continuous beam model as illustrated in Figure 3.5. External moments are determined from the plastic moment of the chord multiplied by the overstrength (ξ).

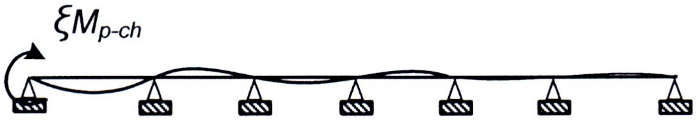

Figure 3.5 Equivalent Multi-span Beam with Subjected to End Moment

3.4.2 Design of Columns

The columns in BRKB-TMF systems are also designed to remain elastic except at the column bases where plastic hinges are required to complete the yield mechanism of the frame. To do so, the columns are designed to resist the adjusted BRB forces given by Equations 3-5 and 3-6 and the forces generated by the truss members connected to the columns. Based on the PBPD approach (Goel and Chao, 2008), a capacity design method that considers the equilibrium of the entire column subjected to forces generated by the BRBs and the trusses can be used to design the columns. Alternatively, a pushover analysis can be carried out up to an expected displacement demand level assuming elastic columns. The forces obtained from such analysis can then be used in the design of the columns. Capacity design of column trees are carried out separately for exterior and interior columns as follows.

1) **Exterior Columns**
   Consider the equilibrium of the entire column tree as shown in Figure 3.6. When the frame deformation reaches the target drift, the internal forces reach the maximum values with the BRB forces assumed to be equal to the adjusted strengths and the column moments at the bases assumed to be equal to M_{pc}. At this state, a set of external forces must be acting on the frame to maintain equilibrium. Static equilibrium analysis can be used to determine these balancing lateral forces. By assuming that the distribution of these balancing forces are the same as what used earlier in the design, the sum of the

balancing forces F_R and F_L to the right and left of the column can be determined from Figure 3.6 (a) and 3.6 (c) and can be expressed as

$$\left(F_R\right)_{ext}=\frac{\sum_{i=1}^{n}\left(T_{R,i}-D_{R,i}\sin\varphi\right)h_i-\sum_{i=1}^{n}\left(P_{pr}^{+}\sin\varphi\right)\left(h_i-D\right)+M_{pc}}{\sum_{i=1}^{n}\alpha_i h_i} \tag{3-7}$$

$$\left(F_L\right)_{ext}=\frac{\sum_{i=1}^{n}\left(T_{L,i}-D_{L,i}\sin\varphi\right)h_i-\sum_{i=1}^{n}\left(P_{pr}^{-}\sin\varphi\right)\left(h_i-D\right)+M_{pc}}{\sum_{i=1}^{n}\alpha_i h_i} \tag{3-8}$$

where $T_{R,i}$ and $T_{L,i}$ are the axial forces in the top chord at any floor level i, $D_{R,i}$ and $D_{L,i}$ are axial forces in the diagonal member at any level i, h_i is the height from column base, φ is the angle between a diagonal member and a column, and α_i is the distribution factor given by:

$$\alpha_i=\frac{(\beta_i-\beta_{i+1})}{\sum_{i=1}^{n}(\beta_i-\beta_{i+1})} \tag{3-9}$$

when $i = n$, $\beta_{n+1} = 0$

Note that the moments due to plastic hinges in the top chords have been neglected because they are much smaller than those generated by the axial force in the truss members and the BRBs. Once the balancing forces are determined, column moment at any given point can be computed.

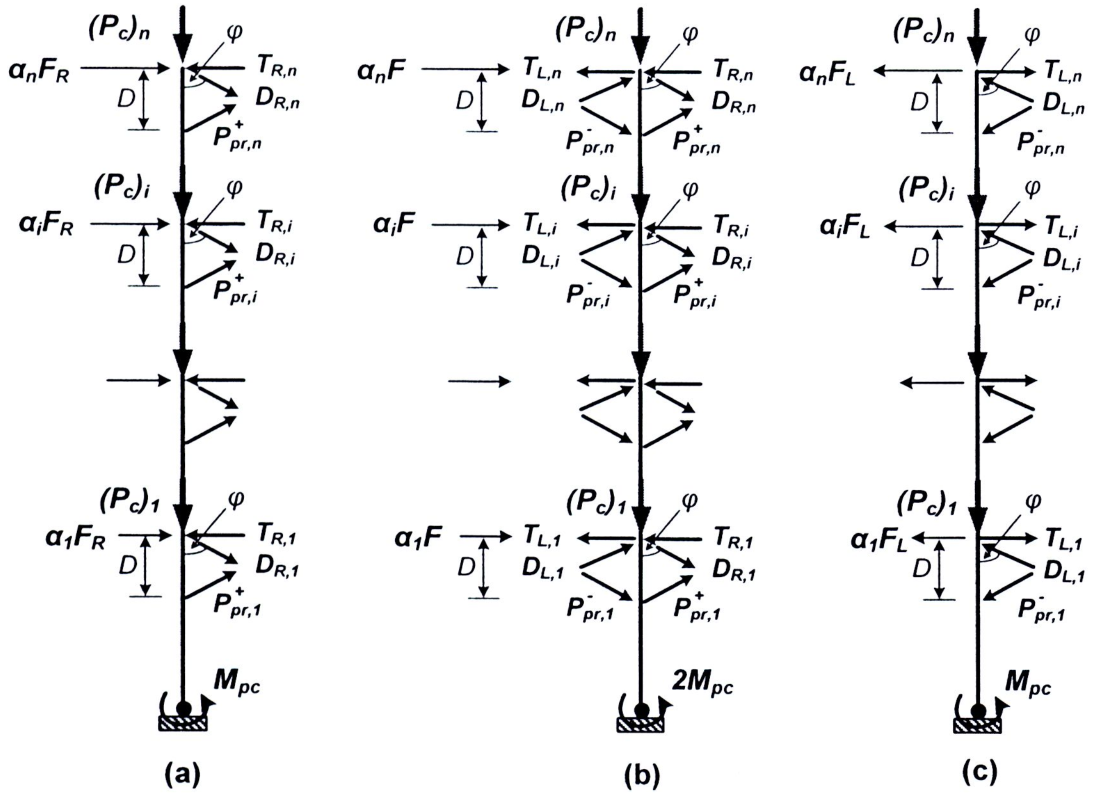

Figure 3.6 Free Body Diagram of Column Tree: (a) Exterior Column Tree (Lateral Forces Acting to the Right), (b) Interior Column Tree, (c) Exterior Column Tree (Lateral Forces Acting to the Left)

2) **Interior Columns**

   A similar approach can be applied to the interior columns. Interior column tree analysis can be done by using summation of forces acting to the left and right as shown in Equation 3-10.

$$(F)_{int} = \frac{\sum_{i=1}^{n}\left(T_{R,i} + T_{L,i} - (D_{R,i} + D_{L,i})\sin\varphi\right)h_i - \sum_{i=1}^{n}\left((P^+_{pr} + P^-_{pr})\sin\varphi\right)\left(h_i - D\right) + 2M_{pc}}{\sum_{i=1}^{n}\alpha_i h_i} \tag{3-10}$$

Note that the plastic moment of the base is taken as $2M_{pc}$ for the interior column.

The design procedure of BRKB-TMF can be summarized into a flowchart as illustrated in Figure 3.7.

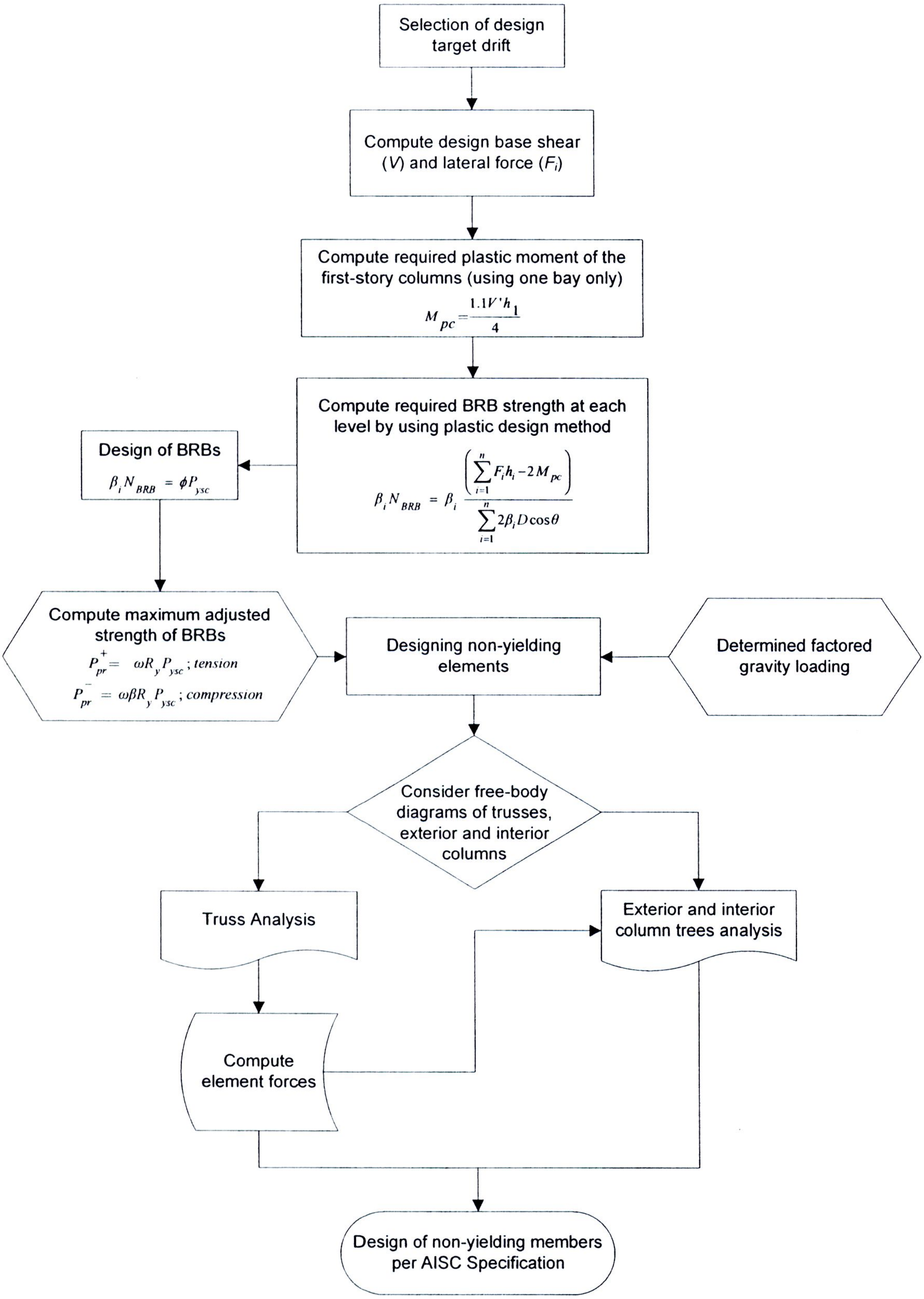

Figure 3.7 Performance-Based Plastic Design Flowchart for BRKB-TMF System