

Article

Theoretical Analysis of the Plastic Property for Equal Angle Sections Subjected to Axial Force and Biaxial Bending

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Abstract: To fully harness the design development potential of plastic angle sections, this study employs a theoretical analysis approach to examine the plastic behavior of equal angle sections subjected to axial force and biaxial bending. Based on the simplified angle section results, the full plasticity correlation equations were derived. Subsequently, section shape coefficients were computed. Finally, a methodology for calculating the plastic development coefficients of angle sections was explored. The findings indicate that the full plasticity correlation equations lack the necessary safety margins in designs. Notably, the angle sections possess a greater plastic development capacity along the weak axis compared with the strong axis. It is advisable, for both regular-size and large-size angle sections, to consistently adopt the plastic development coefficients in designs as follows: $\gamma_u = 1.05$ for the strong axis and $\gamma_v = 1.15$ for the weak axis, thereby addressing the shortcomings of the specification in design.

Keywords: angle section; plastic behavior; theoretical analysis; correlation equation; plastic development coefficient



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1. Introduction

Plastic section development can improve economic efficiency when designing steel members [1–4]; however, it is important to note that, in theory, further plastic development to the point of forming plastic hinges could result in an unbounded increase in deflection, posing a significant structural security risk. To effectively utilize the plastic properties of steel members, the steel structure design specifications permit plastic design in the case of flexural or beam–column members [5–7]. Nevertheless, the extent of plastic development is typically restricted to prevent excessive radicals and the resulting significant deformations. Taking the Chinese steel structure design standard GB50017 [5] as an example, it is specified that the depth of plastic development should not exceed 1/8 of the section’s height. This means that a portion of the section transitions into an elastic–plastic working state, serving as a limit state for plasticity design. This approach not only leverages the section’s plastic performance but also ensures the section’s comprehensive safety. The design standard GB50017 employs the plastic development coefficient γ to assess the plastic properties of a section. Based on the plate width-to-thickness ratio, five grades, denoted as S1 to S5, are established to characterize the plastic development capacity. These grades also provide width-to-thickness ratio limits for the H-section, box-section, and circular pipe-section, facilitating the determination of γ values. However, it is worth noting that angle sections are not included in this classification. Consequently, utilizing the plastic properties of angle sections poses challenges, and the design may not always be economically efficient.

Angle sections are widely utilized in various engineering projects, including building structures, bridges, transmission towers, transportation machinery, and industrial settings. They serve as essential load-bearing components or connectors because of their easy fabrication and convenient assembly [8–11]. The mechanical performance of angle section members continues to be a topic of interest, attracting research efforts from multiple groups focused on studying their buckling characteristics. Design methods are constantly evolving, especially concerning high-strength steel angles, to achieve economically efficient design objectives. Shi et al. [12–14] conducted a study on Q420 high-strength steel equal angles, examining various aspects, including residual stress distribution models, local buckling, and overall buckling. Cao [15] assessed the performance of Q460 high-strength steel angle members under axial loads using a combination of numerical simulations and experimental studies. Bezas [16] explored the performance of high-strength steel angle members under both centric and eccentric compression loads while evaluating the resistance of these designed members. Zhang et al. [17–19] conducted a study on the buckling behavior of S690 and S960 high-strength equal-angle members, employing both testing and numerical simulation.

Using large-size (limb width ≥ 220 mm, limb thickness ≥ 16 mm) and high-strength steel angles has gained popularity in fulfilling engineering needs, including reducing assembly work, construction complexity, and steel consumption [20,21]. Cao et al. [22–24] investigated the buckling behavior and design methods of large-size and high-strength steel angle members subjected to axial loads. They analyzed the influence of various cross-section sizes, strength grades, and slenderness ratios, employing a combination of experimental and numerical simulation techniques. Sun [25] examined the impact of support constraints on the stability capacity of large-size and high-strength steel angle members by measuring support rotation stiffness in tested conditions. Additionally, they investigated the behavior of large-size angle steel under eccentric loads to advance the design methodology for large-size angle beam–column members [26]. Numerous researchers have progressively incorporated stainless steel into angle steel applications, mitigating issues related to corrosion. Menezes et al. [27–34] conducted a comprehensive study on the buckling behavior and design methodology of hot-rolled austenitic stainless steel angles. They employed experimental and numerical techniques to examine mechanical performance under fixed-ended and pin-ended conditions. Dobrić et al. [35–37] analyzed cold-formed stainless steel angles, enriching our understanding of relevant mechanical properties and design approaches. Sian [38] explored the material properties and local buckling behavior of extruded WAAM 316L stainless steel angles.

Many of these studies often emphasize altering material or increasing cross-sectional dimensions to enhance the mechanical performance of angle members, aligning with practical engineering requirements. Furthermore, design methodologies primarily revolve around axial load members, with limited attention given to utilizing the plastic properties of angle sections in flexural or beam–column members. In the current steel structure design specifications, the equivalent method often transforms eccentrically compressed angle members into axially compressed members to simplify the design process. However, ensuring that members are not influenced by bending moment under complex external load conditions is challenging, especially for the superstructure, where the wind load will cause the angle member to experience both axial load and bending moment. In addition, a single-angle member bearing capacity cannot match engineering requirements, and it eventually evolves into double-combined sections. It is unavoidable for double-combined section angle members to withstand the bending moment, but this effect is typically disregarded in design, and such a design strategy may pose potential safety hazards. Consequently, effectively harnessing the plastic properties of angle sections in flexural or beam–column applications becomes challenging. Trahair et al. [39,40] examined steel angle section beams' biaxial bending and torsion behavior. Aydin et al. [4,41] investigated the mechanical performance of angle beam–column members. Vayas [3] examined the mechanical performance of angle beam–column members and discovered that angle sections categorized as Class 1

and Class 2 have a specific plastic deformation capability. Liu [42,43] et al. used the finite element method to study the angle behavior after conducting axial and eccentric compression test tests on 28 equal single-angle specimens with the section $L51 \times 6.4$. Hussain proposed a set of finite element calculations regarding steel angle members under biaxial bending [1]. The mechanical performance of angle beam–column members was studied by Chan [44–46] et al., who recommended utilizing the DSM design approach. These studies observed that angle sections exhibit plastic development ability in flexural or beam–column applications, and they believed that the existing specifications are conservative and only provide some empirical formulas without making due provisions regarding the extent of plastic development of angle steel sections, which confused many designers.

Therefore, this study employs a theoretical analysis approach to examine the plastic properties of equal-angle sections subjected to combined axial force and biaxial bending. The fully plastic development property of the angle steel section was investigated. The formula for calculating the plastic development coefficient of angle sections is derived following the methodology outlined in the GB50017 specification. Plastic development coefficients for regular-size (limb width < 220 mm, limb thickness < 16 mm) and large-size angle sections were computed, and design-recommended values were furnished. Thus, appropriate regulations are made for the extent of plastic development of angle steel sections in plastic design, thereby solving the problem of inconsistent design results and even excessive conservatism caused by replacing eccentric compression angle members with axial compression members.

2. Full Plastic Analysis of the Angle Section

2.1. Cross-Section Simplification

The angle section limb thickness t is small relative to the limb width b . For specification GB/T706-2016 [47], the range of width-to-thickness ratios for the regular-size angle section ($b < 220$ mm) is 5.0 to 18.8, whereas for large-size angle steel ($b \geq 220$ mm) is 7.1 to 13.9. To analyze the angle section mechanically better, the angle section is simplified in that the material concentrates on the center line, the two limbs equate to two intersecting straight lines, and the actual rounded corners are substituted with sharp corners [48]. The simplified angle section result is shown in Figure 1. The angle section is assumed to remain planar when subjected to tension, compression, or bending, and the axis remains perpendicular to its deformed state. The material properties of the steel are considered to exhibit ideal elastic–plastic behavior, with the material following Hooke’s law in the elastic phase and the entire section being capable of entering the plastic phase. Tension is considered positive, while compression is deemed negative. In the simplified angle section, the limb width is adjusted as $b' = b - t/2$. Consequently, this simplification process leads to a deviation in the section area due to the difference in the limb width value. When the limb width is taken as b for the regular-size angle section, the area calculation, according to Equation (1), results in an average deviation of 3.23% below the nominal value specified in the GB/T706-2016. When b' is utilized, it falls short of the nominal value by 6.91%. In the case of the large-size angle section, when the limb width is taken as b , the section area calculation, as per Equation (1), exceeds the nominal value specified in the GB/T706-2016 by an average of 4.47%. Nevertheless, when b' is employed, it falls short of the nominal value by 8.35%. Moreover, the moment of inertia between the simplified section’s strong axis (u -axis) and weak axis (v -axis) is higher than the nominal values in the standard by 0.92% and 0.13%, respectively. In the subsequent theoretical analysis of angle sections, the calculation formulas involved are applicable to both b and b' . This indicates that the errors introduced by using the simplified section for analysis are acceptable. Therefore, in the subsequent analysis, the limb width of the angle steel is considered as b .

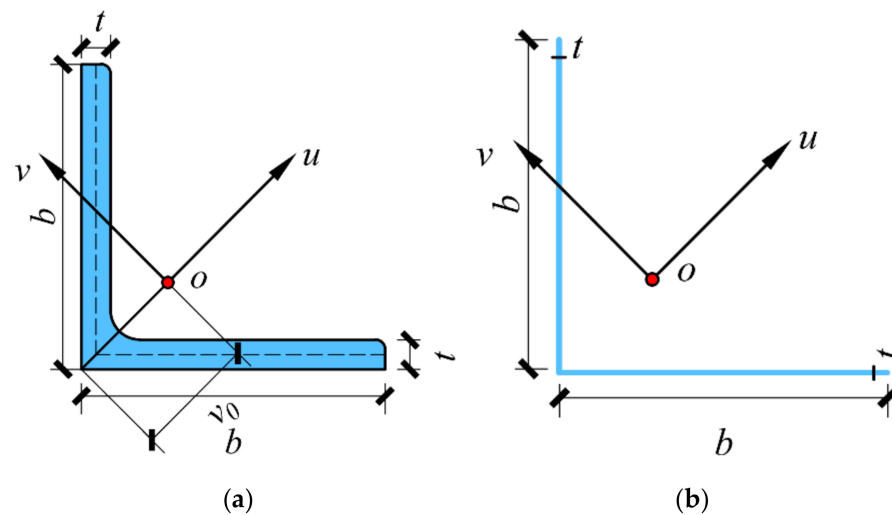


Figure 1. Simplification of angle section: (a) actual section; (b) simplified section.

2.2. Full Plastic Analysis

The simplified angle section is investigated to discuss its mechanical behaviors under axial force N and combined bending moments (M_u and M_v). The overall analysis process of this paper is shown in Figure 2.

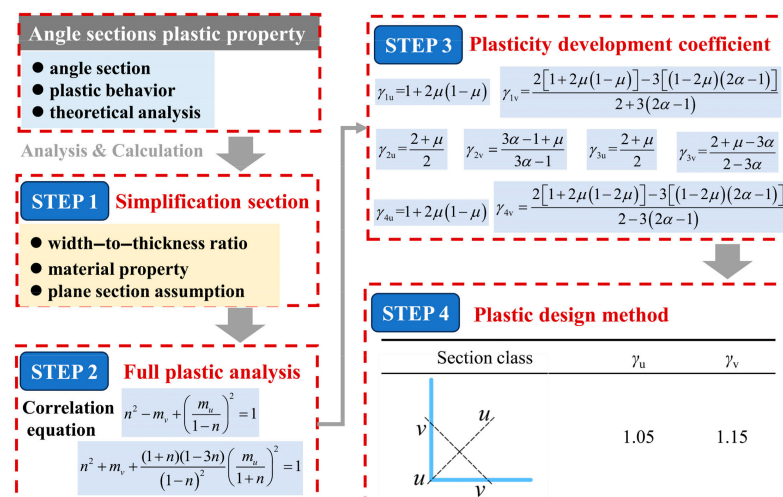


Figure 2. The process of the proposed method.

Based on the position of the neutral axis (NA axis), the stress distribution in the angle section is categorized into four cases: the neutral axis intersects both limbs with the limb back in compression (Figure 3a), the neutral axis intersects the lower limb (Figure 3b), the neutral axis intersects both limbs with the limb back in tension (Figure 3c), and the neutral axis intersects the upper limb (Figure 3d). Different stress scenarios are analyzed for each case, and the section is considered to have reached its ultimate bearing capacity when the full cross-section is yielded. The geometric parameters for the angle section's full plasticity are expressed as follows.

$$A = 2 \cdot b \cdot t \quad (1)$$

$$N_p = A \cdot f_y \quad (2)$$

$$M_{up} = W_{up} \cdot f_y \quad (3)$$

$$M_{vp} = W_{vp} \cdot f_y \quad (4)$$

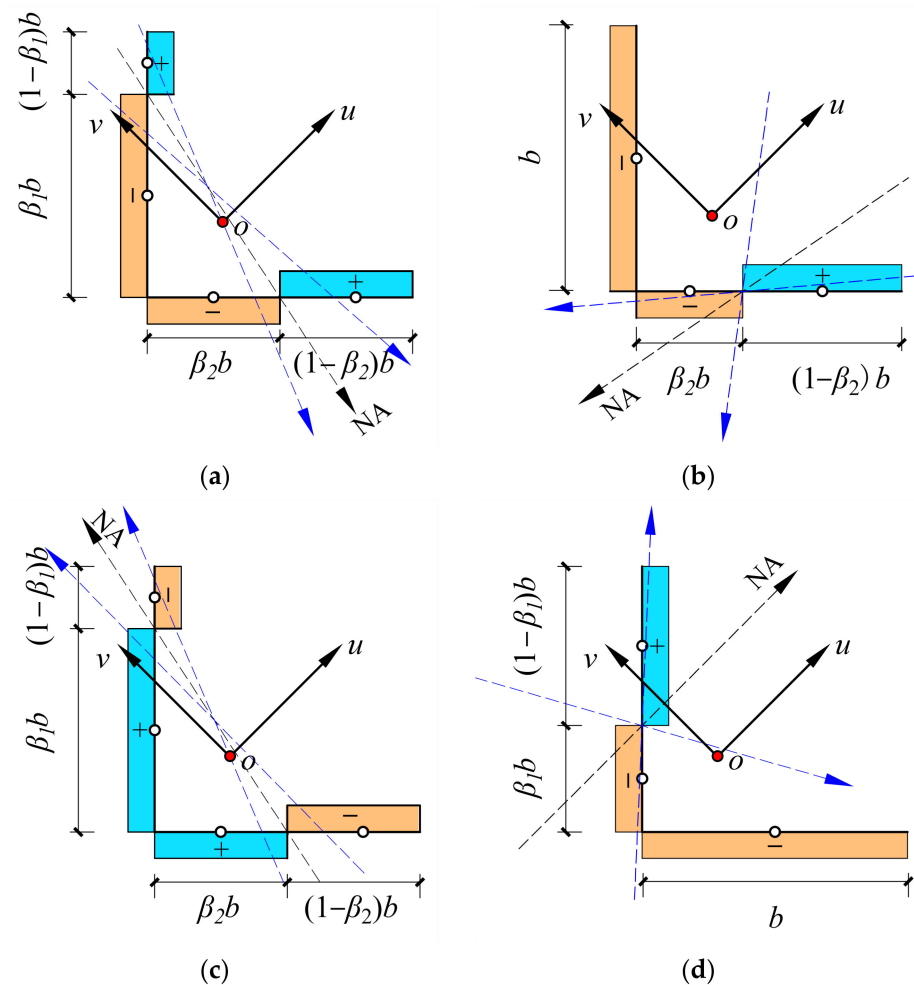


Figure 3. Stress distribution with the different neutral axis positions: (a) intersects the two limbs, which limb back in compression; (b) intersects the lower limb; (c) intersects the two limbs, which limb back in tension; (d) intersects the upper limb.

N is the axial force applied to the angle section. M_u is the bending moments applied to the angle section along the strong axis (u -axis). M_v is the bending moments applied to the angle section along the weak axis (v -axis). A is the section area, f_y is the yield strength, N_p is the axial plastic bearing capacity, W_{up} and W_{vp} are the plastic section moduli of the strong and weak axes, respectively, and M_{up} and M_{vp} are the plastic bending moments of the strong and weak axes, respectively.

The stress distribution of the angle section in Figure 3a is analyzed. $\beta_1 b$ and $\beta_2 b$ are the distances from the intersection point of the neutral axis and the two limbs to the limb back, respectively. To satisfy the equilibrium of the force on the angle section, β_1 and β_2 have to satisfy the relationship in Equation (5).

$$\frac{N}{N_p} = 1 - (\beta_1 + \beta_2) \quad (5)$$

The bending moment for the strong axis (u -axis):

$$M_u = bt f_y \left[\frac{(1 + \beta_1)b}{2\sqrt{2}}(1 - \beta_1) - \frac{\beta_1 b}{2\sqrt{2}}\beta_1 + \frac{\beta_2 b}{2\sqrt{2}}\beta_2 - \frac{(1 + \beta_2)b}{2\sqrt{2}}(1 - \beta_2) \right] \quad (6)$$

Collating the above equation obtains:

$$M_u = \frac{(\beta_2 + \beta_1)(\beta_2 - \beta_1)}{\sqrt{2}} b^2 t f_y \quad (7)$$

The plastic bending moment for the strong axis:

$$M_{up} = 2 \cdot \frac{b}{2\sqrt{2}} b t f_y = \frac{1}{\sqrt{2}} b^2 t f_y \quad (8)$$

The bending moment for the weak axis (v -axis):

$$M_v = b t f_y \left[-\frac{\beta_1 b}{2\sqrt{2}} (1 - \beta_1) - \frac{(1 - \beta_1)b}{2\sqrt{2}} \beta_1 - \frac{(1 - \beta_2)b}{2\sqrt{2}} \beta_2 - \frac{\beta_2 b}{2\sqrt{2}} (1 - \beta_2) \right] \quad (9)$$

Collating the above equation obtains:

$$M_v = \frac{(\beta_1^2 + \beta_2^2) - (\beta_1 + \beta_2)}{\sqrt{2}} b^2 t f_y \quad (10)$$

The plastic bending moment for the weak axis:

$$M_{vp} = 4 \cdot \frac{1}{2} \cdot \frac{b}{2\sqrt{2}} \cdot \frac{1}{2} b t f_y = \frac{1}{2\sqrt{2}} b^2 t f_y \quad (11)$$

From Equations (5)–(11), the full plasticity correlation equation for the angle section under the combined action of axial force and biaxial bending moment can be obtained, as shown in Equation (12).

$$\left(\frac{N}{N_p} \right)^2 - \frac{M_v}{M_{vp}} + \left(\frac{M_u/M_{up}}{1 - N/N_p} \right)^2 = 1 \quad (12)$$

The stress distribution of the angle steel section in Figure 3b is analyzed. $\beta_2 b$ is the distance from the intersection point of the neutral axis with the lower limb to the limb back, and the parameter β_2 is related to the axial force exerted on the section, shown in Equation (13).

$$\beta_2 = -\frac{N}{N_p} \quad (13)$$

The bending moment for the strong axis:

$$M_u = b t f_y \left[-\frac{b}{2\sqrt{2}} + \frac{\beta_2 b}{2\sqrt{2}} \beta_2 - \frac{(1 + \beta_2)b}{2\sqrt{2}} (1 - \beta_2) \right] \quad (14)$$

Collating the above equation obtains:

$$M_u = \frac{(\beta_2^2 - 1)}{\sqrt{2}} b^2 t f_y \quad (15)$$

The plastic bending moment for the strong axis:

$$M_{up} = 2 \cdot \frac{b}{2\sqrt{2}} b t f_y = \frac{1}{\sqrt{2}} b^2 t f_y \quad (16)$$

From Equations (13)–(16), the full plasticity correlation equation of the axial force and bending moment about the strong axis can be obtained, as shown in Equation (17).

$$\left(\frac{N}{N_p} \right)^2 - \frac{M_u}{M_{up}} = 1 \quad (17)$$

The bending moment for the weak axis:

$$M_v = btf_y \left[-\frac{(1 - \beta_2)b}{2\sqrt{2}}\beta_2 - \frac{\beta_2 b}{2\sqrt{2}}(1 - \beta_2) \right] \quad (18)$$

Collating the above equation obtains:

$$M_v = \frac{-\beta_2(1 - \beta_2)}{\sqrt{2}} b^2 t f_y \quad (19)$$

The plastic bending moment for the weak axis:

$$M_{vp} = 4 \cdot \frac{1}{2} \cdot \frac{b}{2\sqrt{2}} \cdot \frac{1}{2} b t f_y = \frac{1}{2\sqrt{2}} b^2 t f_y \quad (20)$$

From Equations (13), (19), and (20), the full plasticity correlation equation of axial forces and bending moments about the weak axis can be obtained as shown in Equation (21).

$$2 \left(\frac{N}{N_p} + \frac{N^2}{N_p^2} \right) - \frac{M_v}{M_{vp}} = 0 \quad (21)$$

The same approach can be employed to analyze the stress distribution in the cases depicted in Figure 3c,d, deriving the full plasticity correlation equation for the angle section as shown in Equations (22)–(24).

$$\left(\frac{N}{N_p} \right)^2 + \frac{M_v}{M_{vp}} + \left(\frac{M_u/M_{up}}{1 + N/N_p} \right)^2 = 1 \quad (22)$$

$$\left(\frac{N}{N_p} \right)^2 + \frac{M_u}{M_{up}} = 1 \quad (23)$$

$$2 \left(\frac{N}{N_p} + \frac{N^2}{N_p^2} \right) - \frac{M_v}{M_{vp}} = 0 \quad (24)$$

where Equation (22) represents the correlation equation for the stress distribution state in Figure 3c, Equations (23) and (24), conversely, pertain to the correlation equations for the strong and weak axis of the stress distribution state in Figure 3d, respectively.

2.3. Full Plastic Correlation Equations

To conduct a more in-depth analysis of the full plastic correlation equations for the angle section's axial force and biaxial bending moment, we introduce the following dimensionless parameters: $n = N/N_p$, $m_u = M_u/M_{up}$, and $m_v = M_v/M_{vp}$. Consequently, we can simplify the fully plastic correlation equations presented in Equations (12), (17), (21)–(24) as follows.

The correlation equation for the stress distribution state depicted in Figure 3a was simplified as Equation (25).

$$n^2 - m_v + \left(\frac{m_u}{1 - n} \right)^2 = 1 \quad (25)$$

Similarly, the correlation equation for the stress distribution state in Figure 3b was simplified as Equations (26) and (27).

$$m_u = n^2 - 1 \quad (26)$$

$$m_v = 2(n^2 + n) \quad (27)$$

Similarly, the correlation equation on the stress distribution state in Figure 3c was simplified as Equation (28).

$$n^2 + m_v + \left(\frac{m_u}{1+n} \right)^2 = 1 \quad (28)$$

Furthermore, we simplify the correlation equation for the stress distribution state in Figure 3d, resulting in Equation (29) and (30).

$$m_u = 1 - n^2 \quad (29)$$

$$m_v = 2(n^2 + n) \quad (30)$$

The relationship curves for the fully plastic correlation equations range from (25) to (30) at various values of n , as illustrated in Figure 4. The full plasticity relationship curves exhibit a distinct convex shape. When a fixed value of n is considered, Equations (25) and (28) correspond to the lower and upper segments of the curve—meanwhile, Equations (26), (27), (29), and (30) denote the red angular points indicated in the graph. Notably, these angular points do not completely coincide with the curve itself, thus requiring modifications to the full plasticity relationship curves. In Figure 3b,d, where the neutral axis intersects a single limb of the angle section, although the neutral axis can rotate over a wide range, the lengths of the tensile and compressive zones need to remain constant to satisfy the equilibrium conditions. Therefore, during the rotation process, Figure 3b,d correspond to only one point on the full plasticity relationship curves, specifically the angular points marked in Figure 4. Moreover, in both of these scenarios, the neutral axis and the angle limb are nearly perpendicular, making the stress distribution of the simplified angle section very similar to that of the actual section. Particularly when $v_0 \cong \frac{b}{2\sqrt{2}}$ it can be considered that the simplified angle section centroid is the same as that of the actual section. Hence, these angular points can be used to modify the curve.

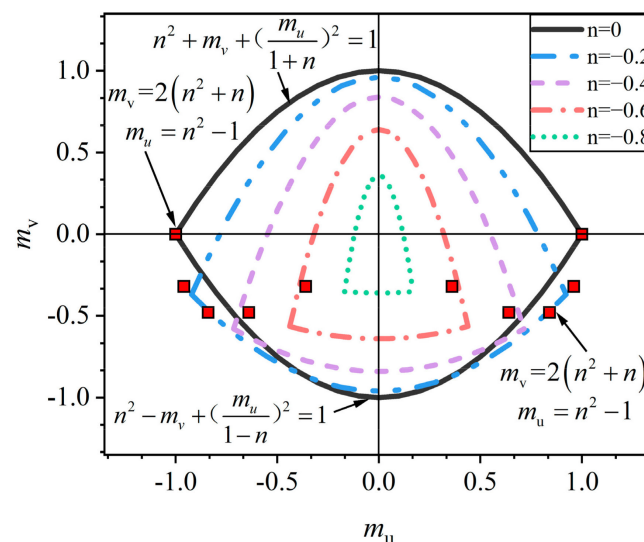


Figure 4. Fully plastic correlation equation curve with different n values.

Introducing correction coefficients ρ_1 and ρ_2 , we can rewrite Equations (25) and (28) as follows.

$$n^2 - m_v + \rho_1 \left(\frac{m_u}{1-n} \right)^2 = 1 \quad (31)$$

$$n^2 + m_v + \rho_2 \left(\frac{m_u}{1+n} \right)^2 = 1 \quad (32)$$

By substituting Equations (26) and (27) into Equation (31) and substituting Equations (29) and (30) into Equation (32), we obtain:

$$\rho_1 = 1 \quad (33)$$

$$\rho_2 = \frac{(1+n)(1-3n)}{(1-n)^2} \quad (34)$$

The calculation results of ρ_1 and ρ_2 are substituted in Equations (29) and (30) to obtain Equations (35) and (36) and depict the full plasticity relationships of angle sections under different n values as shown in Figure 5.

$$n^2 - m_v + \left(\frac{m_u}{1-n} \right)^2 = 1 \quad (35)$$

$$n^2 + m_v + \frac{(1+n)(1-3n)}{(1-n)^2} \left(\frac{m_u}{1+n} \right)^2 = 1 \quad (36)$$

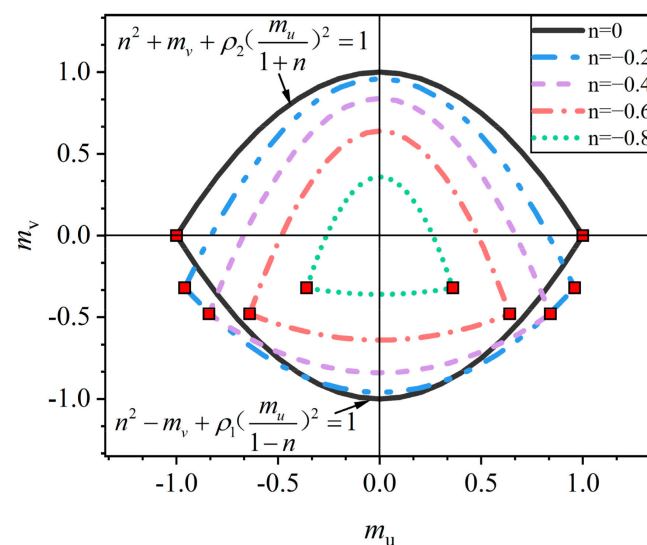


Figure 5. Fully plastic correlation equation modified curve with different n values.

From Figure 5, it can be observed that the relationship curves remain convex, with Equation (35) representing the lower portion of the curve and Equation (36) representing the upper portion. Moreover, both curves encompass the angular points, indicating that Equations (35) and (36) can serve as the full plasticity correlation equation for the angle section under the combined action of axial force and biaxial bending moment. In standard GB50017, to facilitate the design and consider unfavorable factors, the strength design formula for members subjected to axial force and biaxial bending moment, whether in tension or compression, is presented in a linear form, as shown in Equation (37).

$$\frac{N}{N_p} \pm \frac{M_x}{M_{px}} \pm \frac{M_y}{M_{py}} \leq 1 \quad (37)$$

where, $N_p = A_n f_y$, $M_{px} = \gamma_x W_{nx} f_y$, $M_{py} = \gamma_y W_{ny} f_y$. A_n is the net cross-section area, W_{nx} and W_{ny} are the x -axis and y -axis net cross-section moduli, and γ_x and γ_y are the x -axis and y -axis cross-section plasticity development coefficients.

Comparing the relationship curves of the derived full plasticity correlation equations for the angle section with the relationship curves of the strength design formula in the standard GB50017, as shown in Figure 6. It can be observed that the full plasticity equation results in a convex curve, whereas the standard design formula follows a linear relationship.

Furthermore, the standard design formula is relatively conservative compared with the full plasticity equation. This conservative formula arises from the fact that the standard employs a linear simplified formula, utilizing the section plastic development coefficient γ to restrict the section plastic development depth. This approach ensures that members can utilize the plastic properties of the section while maintaining an adequate margin of safety, fully leveraging the material's performance. Therefore, for structural design safety considerations, it is also possible to refer to the linear relationships in the standard and discuss the values of the section plastic development coefficient γ , which reflects the plastic performance of angle sections.

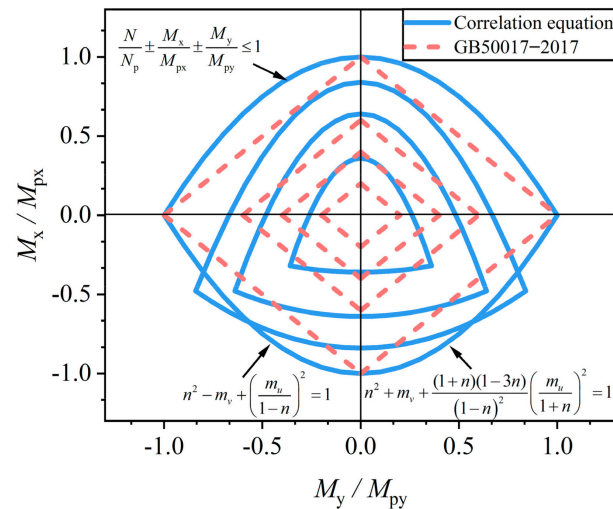


Figure 6. Comparison of full plasticity correlation equation and standard design formulas.

3. Plasticity Development Coefficient

3.1. Section Shape Coefficient

The plastic section modulus W_p divided by the elastic section modulus W_e is denoted by the form factor γ_F , which represents the full plastic capacity of the section. The section shape coefficients of the angle section strong axis γ_{Fu} and the weak axis γ_{Fv} for both regular size (limb width of 100 mm and 150 mm) and large-size (limb width of 220 mm and 250 mm), with different width-to-thickness ratios are calculated, as per the GBT706-2016 standard. The results are depicted in Figure 7.

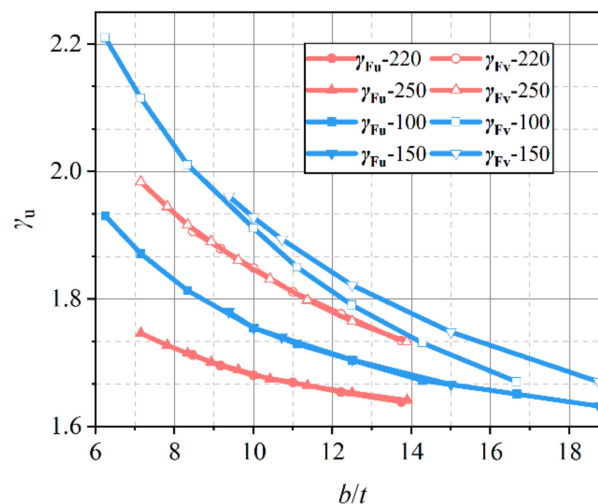


Figure 7. Comparison of section shape coefficient.

It can be observed that for a regular-size section angle with a limb width of 100 mm, the strong axis section shape coefficient γ_{Fu} ranges from 1.65 to 1.93, while the weak axis γ_{Fv} ranges from 1.67 to 2.21. For a limb width of 150 mm, the strong axis γ_{Fu} ranges from 1.63 to 1.78, and the weak axis γ_{Fv} ranges from 1.67 to 1.96. Large-size angle section with a limb width of 220 mm, the strong axis γ_{Fu} ranging from 1.64 to 1.71, and the weak axis γ_{Fv} ranging from 1.73 to 1.91. Similarly, in a large-size angle section with a limb width of 250 mm, the strong axis γ_{Fu} ranges from 1.64 to 1.75, and the weak axis γ_{Fv} ranges from 1.73 to 1.98. This reveals that for regular-size and large-size angles, the section shape coefficient of the weak axis is greater than that of the strong axis, which is consistent with the behavior of I-section biaxially symmetric sections. In general, the limb width exerts a relatively modest impact on the section shape coefficient of angle sections, especially notable for large-size angle sections, where the trends in section shape coefficient exhibit remarkable consistency across various limb widths. The section shape coefficients are inversely associated with their width-to-thickness ratio; an escalation in this ratio results in a gradual reduction in the section shape coefficients. This implies that angle sections possessing higher width-to-thickness ratios display diminished plasticity. Additionally, the section shape coefficients for large-size angle sections are smaller than those of regular-size sections, signifying that regular-size angle sections exhibit pronounced plasticity.

3.2. Plastic Development Coefficient

The section's plastic development coefficient γ is closely linked to its section shape, plastic development depth μh , and stress state. In this section, we investigate the method for calculating the plastic development coefficient of angle sections, drawing inspiration from the derivation approach for the plastic development coefficient of H-section in GB50017. During the analysis, the stress state is categorized into four scenarios: stress state 1, where both the limb tip and limb back simultaneously experience plastic compressive stress and plastic tensile stress; stress state 2, where the limb tip undergoes plastic compressive stress; stress state 3, where the limb back undergoes plastic tensile stress; stress state 4, where both the limb tip and limb back simultaneously experience plastic tensile stress and plastic compressive stress. The stress distribution states were visualized in Figure 8, where σ_1 represents the tensile stress at the limb back in stress state 2, σ_2 represents the tensile stress at the limb tip in stress state 3, α represents the limb width ratio, defined as the ratio of the distance from the intersection point (between the weak axis and a single limb) to the limb back to the limb width. f_y signifies the yield stress, and σ_0 denotes the equivalent stress.

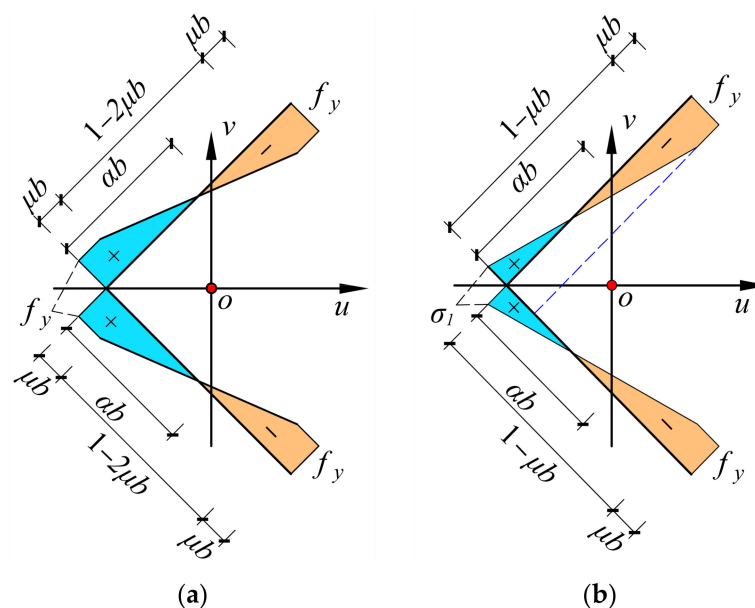


Figure 8. Cont.

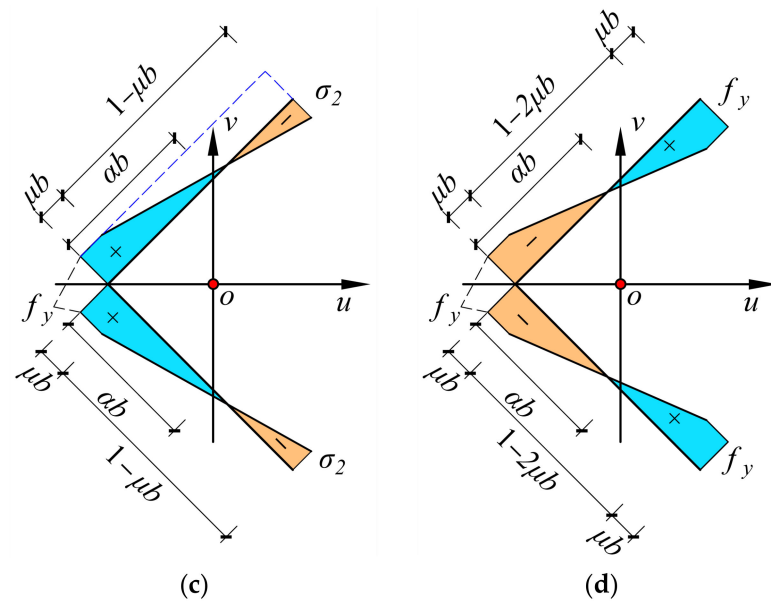


Figure 8. Different stress states: (a) stress state 1; (b) stress state 2; (c) stress state 3; (d) stress state 4.

The different stress states are analyzed to determine the calculation method for the plastic development coefficient. For the strong axis of stress state 1, based on the stress equilibrium conditions, we can obtain:

$$N = 0 \quad (38)$$

$$M_{1u} = \left[\mu b \left(b - \frac{\mu b}{2} \right) - \mu b \frac{\mu b}{2} \right] \frac{1}{\sqrt{2}} b t f_y \cdot 2 + \left\{ \frac{(1-2\mu)b}{2} \left[b - \mu b - \frac{(1-2\mu)b}{3} \right] \frac{1}{\sqrt{2}} - \frac{(1-2\mu)b}{2} \left[\mu b + \frac{(1-2\mu)b}{3} \right] \frac{1}{\sqrt{2}} \right\} b t f_y \cdot 2 \quad (39)$$

Collating the above equation obtains:

$$M_{1u} = \frac{1 + 2\mu(1 - \mu)}{3\sqrt{2}} b^2 t f \quad (40)$$

When $\mu = 0$, obtains:

$$M_{1ue} = \frac{1}{3\sqrt{2}} b^2 t f \quad (41)$$

Therefore,

$$\gamma_{1u} = \frac{M_{1u}}{M_{1ue}} = 1 + 2\mu(1 - \mu) \quad (42)$$

For the weak axis, according to the stress equilibrium conditions, it can be obtained that:

$$N = 0 \quad (43)$$

$$M_{1v} = \left\{ \mu b \left[(1 - \alpha)b - \frac{\mu b}{2} \right] \frac{1}{\sqrt{2}} + \mu b \left[\alpha b - \frac{\mu b}{2} \right] \frac{1}{\sqrt{2}} \right\} b t f_y \cdot 2 + \left\{ \frac{(1-2\mu)b}{2} \left[(1 - \alpha)b - \mu b - \frac{(1-2\mu)b}{3} - \left(\alpha b - \frac{b}{2} \right) \right] \frac{1}{\sqrt{2}} + \frac{(1-2\mu)b}{2} \left[\alpha b - \mu b - \frac{(1-2\mu)b}{3} \right] \frac{1}{\sqrt{2}} \right\} b t f_y \cdot 2 \quad (44)$$

Collating the above equation obtains:

$$M_{1v} = \frac{2[1 + 2\mu(1 - \mu)] - 3(1 - 2\mu)(2\alpha - 1)}{6\sqrt{2}} b^2 t f_y \quad (45)$$

When $\mu = 0$, obtains:

$$M_{1ve} = \frac{2 - 3(2\alpha - 1)}{6\sqrt{2}} b^2 t f_y \quad (46)$$

Therefore,

$$\gamma_{1v} = \frac{M_{1v}}{M_{1ve}} = \frac{2[1 + 2\mu(1 - \mu)] - 3[(1 - 2\mu)(2\alpha - 1)]}{2 + 3(2\alpha - 1)} \quad (47)$$

For the strong axis of stress state 2, we can obtain that:

$$N = 2bt\sigma_0 = 2bt f_y - \frac{(1 - \mu)b}{2} t (f_y + \sigma_1) \cdot 2 \quad (48)$$

$$M_{2u} = \frac{(1 - \mu)b}{2} t \left[b - \frac{(1 - \mu)b}{3} \right] \frac{1}{\sqrt{2}} (f_y + \sigma_1) \cdot 2 \quad (49)$$

Then:

$$(f_y + \sigma_1) = \left(\frac{2}{1 - \mu} \right) (f_y - \sigma_0) \quad (50)$$

$$\begin{aligned} M_{2u} &= \left(\frac{1 - \mu}{2} \cdot \frac{2 + \mu}{3\sqrt{2}} \right) \left(\frac{2}{1 - \mu} \right) b^2 t (f_y + \sigma_1) \cdot 2 \\ &= \frac{2(2 + \mu)}{3\sqrt{2}} b^2 t (f_y - \sigma_0) \end{aligned} \quad (51)$$

When $\mu = 0$, obtains:

$$M_{2ue} = \frac{4}{3\sqrt{2}} b^2 t (f_y - \sigma_0) \quad (52)$$

Therefore:

$$\gamma_{2u} = \frac{M_{2u}}{M_{2ue}} = \frac{2 + \mu}{2} \quad (53)$$

For the weak axis:

$$N = 2bt\sigma_0 = 2bt f_y - \frac{(1 - \mu)b}{2} t (f_y + \sigma_1) \cdot 2 \quad (54)$$

$$M_{2v} = \frac{(1 - \mu)b}{2} t \left[\alpha b - \frac{(1 - \mu)b}{3} \right] \frac{1}{\sqrt{2}} (f_y + \sigma_1) \cdot 2 \quad (55)$$

Then:

$$(f_y + \sigma_1) = \left(\frac{2}{1 - \mu} \right) (f_y - \sigma_0) \quad (56)$$

$$\begin{aligned} M_{2v} &= \left(\frac{1 - \mu}{2} \cdot \frac{3\alpha - 1 + \mu}{3\sqrt{2}} \right) \left(\frac{2}{1 - \mu} \right) b^2 t (f_y + \sigma_1) \cdot 2 \\ &= \frac{2(3\alpha - 1 + \mu)}{3\sqrt{2}} b^2 t (f_y - \sigma_0) \end{aligned} \quad (57)$$

When $\mu = 0$, obtains:

$$M_{2ve} = \frac{2(3\alpha - 1)}{3\sqrt{2}} b^2 t (f_y - \sigma_0) \quad (58)$$

Therefore,

$$\gamma_{2v} = \frac{M_{2v}}{M_{2ve}} = \frac{3\alpha - 1 + \mu}{3\alpha - 1} \quad (59)$$

For the strong axis of stress state 3, we can obtain that:

$$N = 2bt\sigma_0 = \frac{(1 - \mu)b}{2} t (f_y + \sigma_2) \cdot 2 - 2bt f_y \quad (60)$$

$$M_{3u} = \frac{(1 - \mu)b}{2} t \left[b - \frac{(1 - \mu)b}{3} \right] \frac{1}{\sqrt{2}} (f_y + \sigma_2) \cdot 2 \quad (61)$$

Then:

$$(f_y + \sigma_2) = \left(\frac{2}{1 - \mu} \right) (f_y - \sigma_0) \quad (62)$$

$$\begin{aligned} M_{3u} &= \left(\frac{1 - \mu}{2} \cdot \frac{2 + \mu}{3\sqrt{2}} \right) \left(\frac{2}{1 - \mu} \right) b^2 t (f_y - \sigma_0) \cdot 2 \\ &= \frac{2(2 + \mu)}{3\sqrt{2}} b^2 t (f_y - \sigma_0) \end{aligned} \quad (63)$$

When $\mu = 0$, one obtains:

$$M_{3ue} = \frac{4}{3\sqrt{2}} b^2 t (f_y - \sigma_0) \quad (64)$$

Therefore,

$$\gamma_{3u} = \frac{M_{3u}}{M_{3ue}} = \frac{2 + \mu}{2} \quad (65)$$

For the weak axis:

$$N = 2bt\sigma_0 = \frac{(1 - \mu)b}{2} t (f_y + \sigma_2) \cdot 2 - 2bt f_y \quad (66)$$

$$M_{3v} = \frac{(1 - \mu)b}{2} t \left[(1 - \alpha)b - \frac{(1 - \mu)b}{3} \right] \frac{1}{\sqrt{2}} (f_y + \sigma_2) \cdot 2 \quad (67)$$

Then:

$$(f_y + \sigma_2) = \left(\frac{2}{1 - \mu} \right) (f_y - \sigma_0) \quad (68)$$

$$\begin{aligned} M_{3v} &= \left(\frac{1 - \mu}{2} \cdot \frac{2 + \mu - 3\alpha}{3\sqrt{2}} \right) \left(\frac{2}{1 - \mu} \right) b^2 t (f_y + \sigma_2) \cdot 2 \\ &= \frac{2(2 + \mu - 3\alpha)}{3\sqrt{2}} b^2 t (f_y - \sigma_0) \end{aligned} \quad (69)$$

When $\mu = 0$, one obtains:

$$M_{3ve} = \frac{2(2 - 3\alpha)}{3\sqrt{2}} b^2 t (f_y - \sigma_0) \quad (70)$$

Therefore,

$$\gamma_{3v} = \frac{M_{3v}}{M_{3ve}} = \frac{2 + \mu - 3\alpha}{2 - 3\alpha} \quad (71)$$

For the strong axis of stress state 4, we can obtain that:

$$N = 0 \quad (72)$$

$$\begin{aligned} M_{4u} &= \left[\mu b \left(b - \frac{\mu b}{2} \right) - \mu b \frac{\mu b}{2} \right] \frac{1}{\sqrt{2}} b t f_y \cdot 2 \\ &+ \left\{ \frac{(1 - 2\mu)b}{2} \left[b - \mu b - \frac{(1 - 2\mu)b}{3} \right] \frac{1}{\sqrt{2}} \right. \\ &\left. - \frac{(1 - 2\mu)b}{2} \left[\mu b + \frac{(1 - 2\mu)b}{3} \right] \frac{1}{\sqrt{2}} \right\} b t f_y \cdot 2 \end{aligned} \quad (73)$$

Collating the above equation obtains:

$$M_{4u} = \frac{1 + 2\mu(1 - \mu)}{3\sqrt{2}} b^2 t f \quad (74)$$

When $\mu = 0$, one obtains:

$$M_{4ue} = \frac{1}{3\sqrt{2}} b^2 t f \quad (75)$$

Therefore,

$$\gamma_{4u} = \frac{M_{4u}}{M_{4ue}} = 1 + 2\mu(1 - \mu) \quad (76)$$

For the weak axis:

$$N = 0 \quad (77)$$

$$M_{4v} = \left\{ \mu b \left[(1 - \alpha)b - \frac{\mu b}{2} \right] \frac{1}{\sqrt{2}} + \mu b \left[\alpha b - \frac{\mu b}{2} \right] \frac{1}{\sqrt{2}} \right\} b t f_y \cdot 2 \\ + \left\{ \frac{(1 - 2\mu)b}{2} \left[(1 - \alpha)b - \mu b - \frac{(1 - 2\mu)b}{3} \right] \frac{1}{\sqrt{2}} \right. \\ \left. + \frac{(1 - 2\mu)b}{2} \left[\alpha b - \mu b - \frac{(1 - 2\mu)b}{3} - \left(\alpha b - \frac{\mu b}{2} \right) \right] \frac{1}{\sqrt{2}} \right\} b t f_y \cdot 2 \quad (78)$$

Collating the above equation obtains:

$$M_{4v} = \left\{ \frac{2[1 + 2\mu(1 - 2\mu)] - 3[(1 - 2\mu)(2\alpha - 1)]}{6\sqrt{2}} \right\} b^2 t f_y \quad (79)$$

When $\mu = 0$, one obtains:

$$M_{4ve} = \frac{2 - 3(2\alpha - 1)}{6\sqrt{2}} b^2 t f_y \quad (80)$$

Therefore,

$$\gamma_{4v} = \frac{M_{4v}}{M_{4ve}} = \frac{2[1 + 2\mu(1 - 2\mu)] - 3[(1 - 2\mu)(2\alpha - 1)]}{2 - 3(2\alpha - 1)} \quad (81)$$

Based on the preceding analysis, it can be inferred that the plastic development coefficients γ_u and γ_v of angle sections in various stress states for the strong and weak axis are dependent on μ and α . Consequently, Tables 1 and 2 present the values of γ_u and γ_v for angle sections with varying μ values (0.125, 0.15, 0.20, 0.25) and different α values. The α values in Table 1 are obtained from regular-size angle sections L150 $\times$ 8, L150 $\times$ 12, and L150 $\times$ 16, with respective α values of 0.532, 0.553, and 0.575. The α values in Table 2 are derived from large-size angle sections L250 $\times$ 18, L250 $\times$ 26, and L250 $\times$ 35, yielding α values of 0.547, 0.572, and 0.598, respectively.

Table 1. Plastic development coefficient for regular-size angle sections.

Stress State	μ α	0.125			0.15			0.20			0.25		
		0.532	0.553	0.575	0.532	0.553	0.575	0.532	0.553	0.575	0.532	0.553	0.575
1	γ_{1u}		1.219			1.255			1.320			1.375	
	γ_{1v}	1.269	1.308	1.354	1.314	1.361	1.415	1.396	1.457	1.528	1.468	1.542	1.628
2	γ_{2u}		1.063			1.075			1.100			1.125	
	γ_{2v}	1.210	1.189	1.173	1.252	1.227	1.207	1.336	1.303	1.276	1.419	1.379	1.345
3	γ_{3u}		1.063			1.075			1.100			1.125	
	γ_{3v}	1.309	1.368	1.453	1.371	1.441	1.543	1.495	1.588	1.725	1.619	1.735	1.906
4	γ_{4u}		1.219			1.255			1.320			1.375	
	γ_{4v}	1.269	1.308	1.354	1.314	1.361	1.415	1.396	1.457	1.528	1.468	1.542	1.628

Table 2. Plastic development coefficient for large-size angle sections.

Stress State	μ α	0.125			0.15			0.20			0.25		
		0.547	0.572	0.598	0.547	0.572	0.598	0.547	0.572	0.598	0.547	0.572	0.598
1	γ_{1u}		1.219			1.255			1.320			1.375	
	γ_{1v}	1.296	1.348	1.415	1.347	1.408	1.487	1.439	1.518	1.622	1.519	1.616	1.741
2	γ_{2u}		1.063			1.075			1.100			1.125	
	γ_{2v}	1.195	1.175	1.157	1.234	1.209	1.189	1.312	1.279	1.252	1.390	1.349	1.314
3	γ_{3u}		1.063			1.075			1.100			1.125	
	γ_{3v}	1.349	1.440	1.610	1.419	1.528	1.732	1.558	1.704	1.977	1.698	1.880	2.221
4	γ_{4u}		1.219			1.255			1.320			1.375	
	γ_{4v}	1.296	1.348	1.415	1.347	1.296	1.348	1.415	1.347	1.296	1.348	1.415	1.347

The results demonstrate that as the section's plastic development depth increases, both γ_u and γ_v values also rise. Furthermore, the weak axis value γ_v surpasses the strong axis γ_u , signifying superior plastic development capability along the weak axis, thereby affirming the earlier findings presented in this paper. The strong axis γ_u values for large-size angle sections are the same as those for regular-size angle sections. However, when considering various plastic development depths, the weak axis γ_v values for large-size angle sections exhibit average deviations of 3.94% ($\mu = 0.125$), -1.72% ($\mu = 0.15$), 7.32% ($\mu = 0.20$), and 3.94% ($\mu = 0.25$) in comparison to regular-size angle sections. This suggests no substantial disparity in the plastic development coefficients between regular-size and large-size angle sections by the analysis method presented in this paper. For ease of design and safety margin considerations, the plastic development coefficients for the strong and weak axis of the angle section are adopted as $\gamma_u = 1.05$ and $\gamma_v = 1.15$, respectively. This choice aligns with the Chinese steel structure design codes stipulating that the plastic development depth should not exceed 1/8 of the section height. Notably, these selected values are smaller than the minimum calculated values in Tables 1 and 2.

Substituting the plastic development coefficients of the angle section into the strength design formula for biaxial bending specimens in the GB50017 and comparing it with the H-section and box-section, as shown in Figure 9. It can be observed that the strength design formula for the angle section follows a similar form to that of the H-section and box-section, and the plastic development capability of the angle section falls between that of the H-section and box-section.

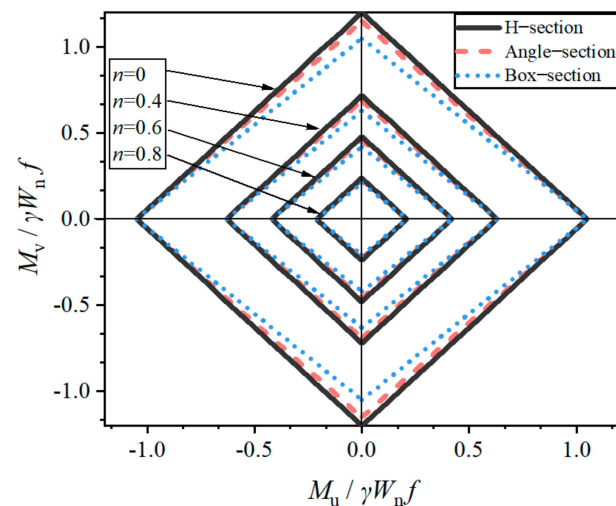


Figure 9. Comparison of strength design formulas for different section forms.

4. Angle Section Classification Discussion

In this study, we found that the plastic development capacity of the angle section is intimately connected with the component plates' width-to-thickness ratio and its plastic development depth, which is consistent with the conclusions of the references [3,4,39–41]. Moreover, Trahair believes that in comparison with flat bar sections, the plastic moment for angle sections is 1.5 times the first yield moment. However, in the standard GB50017, the plastic development depth of steel components is limited, not exceeding 1/8 of the section height, to ensure the plastic design's safety margin. Therefore, based on the calculation method of the plastic development coefficient in this paper, the value of the plastic development coefficient for angle sections is discussed. The GB50017 and Eurocode 3 establish distinct grades for various section types when designing flexural and beam-column members, delineating them according to their width-to-thickness ratio to represent the member's plastic development capacity. Nonetheless, it is noteworthy that these codes do not explicitly address angle sections. Trahair [49], based on the corresponding design standards, discussed the section grades classification for the angle section using

local buckling coefficients. They considered the single-leg plates of the angle section as the extensions of the hot-rolled I-section flange. The Eurocode 3 also adopted a similar approach and classified the angle section into four categories based on the slenderness ratio λ_T of the constituent plates, which include plastic ($\lambda_T < \lambda_p$), compact ($\lambda_p < \lambda_T \leq \lambda_c$), semi-compact ($\lambda_c < \lambda_T \leq \lambda_y$), and slender ($\lambda_y < \lambda_T$).

Furthermore, the slenderness ratio λ_T for the strong and weak axes differ because of variations in local buckling coefficients. In the context of angle section classification, the plastic and compact types can be subject to plastic design, while the semi-compact type can attain the first-order yield moment. However, the slender type, constrained by local stability limitations, necessitates elastic design, and the section's area must be determined based on the effective area. Following the classification method outlined in this reference, angle sections with Q420 strength grades, encompassing both regular-size (with limb widths of 100 mm and 150 mm) and large-size (with limb widths of 220 mm and 250 mm), are categorized and presented in Tables 3 and 4. Tables 3 and 4 reveal that, for regular-size angle sections, when assessed along the strong axis, all sections, with the exception of L100 × 7, L100 × 6, L150 × 10, and L100 × 8, are eligible for plastic design. When considering the weak axis, in addition to adhering to the criteria for the strong axis, sections L100 × 8 and L150 × 12 are also ineligible for plastic design. Concerning large-size angle sections, when assessed along the strong axis, all sections, with the exception of L220 × 16 and L250 × 18, meet the criteria for plastic design. In contrast, when evaluated along the weak axis, similar to the strong axis criteria, sections L220 × 18 and L250 × 20 are also ineligible for plastic design. This observation highlights that, when appraised along the strong axis, a larger number of angle sections qualify for plastic design in comparison to the weak axis. Furthermore, no angle sections are assigned to this category within the classification of slender sections, indicating that this classification method may be somewhat stringent.

Table 3. Section classification of regular-size angle section.

Axis	Plastic λ_p	Compact λ_c	Semi-Compact λ_y	Slender
Strong	12 L100 × 16, L100 × 14 L100 × 12, L100 × 10 L150 × 16, L150 × 15	16 L100 × 9, L100 × 8 L150 × 14, L150 × 12	26 L100 × 7, L100 × 6 L150 × 10, L100 × 8	>26 /
	10 L100 × 16, L100 × 14 L100 × 12	14 L100 × 10, L100 × 9 L150 × 16, L150 × 15 L150 × 14	23 L100 × 8, L100 × 7 L100 × 6, L150 × 12 L150 × 10, L100 × 8	>23 /

Table 4. Section classification of large-size angle.

Axis	Plastic λ_p	Compact λ_c	Semi-Compact λ_y	Slender
Strong	12 L220 × 26, L220 × 24 L220 × 22, L250 × 35 L250 × 32, L250 × 30 L250 × 28, L250 × 26	16 L220 × 20, L220 × 18 L250 × 24, L250 × 22 L250 × 20	26 L220 × 16 L250 × 18	>26 /
	10 L220 × 26, L250 × 35 L250 × 32, L250 × 30	14 L220 × 24, L220 × 22 L220 × 20, L250 × 28 L250 × 26, L250 × 24 L250 × 22	23 L220 × 16 L220 × 18 L250 × 18 L250 × 20	>23 /

For the sake of design convenience, this paper treats the single-leg plates of angle sections as extensions of hot-rolled I-section flanges and adopts the section classification method outlined in GB50017. Both regular-size and large-size angle sections are classified

into five grades, as presented in Tables 5 and 6. According to the standard, plastic design is appropriate when the width-to-thickness ratio grade of the section plates falls within S1, S2, or S3. Conversely, elastic design should be employed when the width-to-thickness ratio grade is S4 or S5. These guidelines are equally applicable to angle sections, aligning with the stipulations in the standard.

Table 5. Slenderness ratio limit for classification of regular-size angle section.

Section Class	S1	S2	S3	S4	S5
b/t	$9\epsilon_k$	$11\epsilon_k$	$13\epsilon_k$	$15\epsilon_k$	20
Angle section	L100 × 16	L150 × 16	L100 × 10	L100 × 9	L100 × 6
	L100 × 14	L100 × 12	L150 × 15	L100 × 8	L100 × 7
			L150 × 14	L150 × 12	L150 × 10
					L150 × 8

Table 6. Slenderness ratio limit for classification of large-size angle section.

Section Class	Class S1	Class S2	Class S3	Class S4	Class S5
b/t	$9\epsilon_k$	$11\epsilon_k$	$13\epsilon_k$	$15\epsilon_k$	20
Angle section			L220 × 24		
	L250 × 35	L220 × 26	L220 × 22	L220 × 18	L220 × 16
	L250 × 32	L250 × 30	L220 × 20	L250 × 22	L250 × 18
		L250 × 28	L250 × 26	L250 × 20	
			L250 × 24		

ϵ_k is the correction coefficient of the steel grade. $\epsilon_k = \sqrt{\frac{235}{f_y}}$.

In the process of classification, the method used did not distinguish angle sections based on their different principal axis but directly categorized them based on the width-to-thickness ratio. A comparison between Tables 3 and 4, and Tables 5 and 6 reveals that, with the exception of the inclusion of regular-size angle section L100 × 9 and large-size angle section L250 × 22, which require elastic design, all other section classifications correspond to plastic design. In contrast, the classification method in reference [49] divides angle sections into four grades, whether regular-size or large-size, with no sections allocated to the slender section grades. However, following the classification method outlined in the GB50017 standard, angle sections are classified into five grades, encompassing both regular-size and large-size angle sections in all five grades. This suggests that the section grade classification for the angle section in this paper is relatively cautious compared with the reference [49]. This implies that, for the angle section, adopting the GB50017 standard's classification method is a more prudent approach, offering increased safety margins for design and ensuring a safer and more reliable design. Therefore, when performing plastic design for angle sections, for section width-to-thickness ratio grades S1, S2, and S3, the section plastic development coefficients γ_u and γ_v should be taken as 1.05 and 1.15, respectively, i.e., the plastic development depth of the angle section is taken as 1/8 of the section height. When the section width-to-thickness ratio grade is S4 or S5, a value of 1.0 should be used.

5. Conclusions

This paper explored the plastic behavior of angle sections under the combined action of axial force and biaxial bending, derived the correlation equations for axial force and moment, analyzed the affecting factors of the angle sections' plastic development capacity, introduced a method for computing the plastic development coefficients of angle sections, and summarized the key findings as follows:

1. The axial force and moment full plasticity equation results are nonlinear, whereas the specification design formula follows a linear relationship. Furthermore, the specification design formula is relatively conservative compared with the full plasticity equation. This conservative arises from the fact that the standard employs a linear

- simplified formula, utilizing the section plastic development coefficient to restrict the section plastic development depth.
2. The section shape coefficients are inversely associated with their width-to-thickness ratio; an escalation in this ratio results in a gradual reduction in the section shape coefficients. This implies that angle sections possessing higher width-to-thickness ratios display diminished plasticity. Additionally, the section shape coefficients for large-size angle sections are smaller than those of regular-size sections, signifying that regular-size angle sections exhibit pronounced plasticity.
 3. The angle sections' plastic development coefficients are related to plastic development depth. Higher values of development depths are associated with larger values of γ_u and γ_v . The plastic development capability of angle sections is also between that of H-sections and box-sections, and they exhibit better plastic development capacity along the weak axis than the strong axis.
 4. For regular-size and large-size angle sections, the plastic development coefficients for plastic design can be set to the same values. This choice aligns with the steel structure design code GB50017, stipulating that the plastic development depth should be taken as 1/8 of the section height, with strong and weak axes taken as $\gamma_u = 1.05$ and $\gamma_v = 1.15$, respectively.

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