Design Considerations for W-Shape Flexural Members Built-Up from Plates

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INTRODUCTION

It is common practice in some areas of the world to build-up or fabricate W-shapes from plate as alternates to rolled W-shapes.

It is also possible that in order to meet project delivery schedules, a fabricator may request approval from the engineer-of-record to substitute a built-up W-shape for a temporarily unavailable rolled W-shape. In either case, it would be practicable if the engineer-of-record can select his W-shape members using the AISC *Manual* (AISC, 1994) and LRFD *Specification* (AISC, 1999) and companion design aids.

This paper addresses design and/or fabrication issues for the practice and attempts to arrive at "rules" to allow safe and timely application.

DESIGN ISSUES

Residual Stresses

Residual stresses occur in rolled sections as a result of the rolling and cooling process. Compressive and tensile stresses are "locked in" to the section as the rolled section cools. In built-up sections, residual compressive and tensile stresses are "locked in" as the weld metal and heat-affected zone cool. See Figure 1.

Compression residual stresses affect local stability and are accounted for in AISC's LRFD specification flexural design procedures. It is AISC's position that compressive residual stresses are higher in built-up sections than in rolled sections. As a result, the LRFD specification prescribes lower flexural strength for built-up shapes than rolled shapes for beams where the inelastic buckling limit state governs, typically medium span beams where L_b exceeds the compact section limit L_p.

Note that residual stresses are not directly accounted for in the AISC compression strength provisions because the design equations are a reasonable approximation of several different column design curves that consider buckling axis and residual stresses. See the SSRC *Guide* for additional discussion (SSRC, 1998).

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Compact Sections

Compact sections are able to develop the full plastic buckling capacity of the section. AISC specifications require that flanges must be continuously connected to the web(s) for a section to be considered to be compact.

Compact sections must have web slenderness ratios, h/t_w that are less than prescribed limits, λ_p. For rolled sections, h is defined as the distance between the web toe fillets. For built-up sections, h is defined as the distance between flanges.

Flexural Shear

By elastic theory, horizontal flexural shearing forces (F_v) are present across the cross-section, as determined by the equation $F_v = VQ/I$. For rolled sections, these forces are accommodated in the base metal. For built-up sections, AISC specifications require that the flange-to-web welds be proportioned to transfer these shear forces. AISC specifications require that all welds be in accordance with AWS D1.1 requirements (AWS, 2000). Neither AWS nor AISC specifications require a specific weld process or weld type for these welds.

Rolled W-shapes generally have excess flexural shear capacity. The decision or need to substitute built-up sections for rolled shapes offers the opportunity to reduce the thickness and weight of the W-shape web, yet still provide sufficient design shear strength. As presented, this study

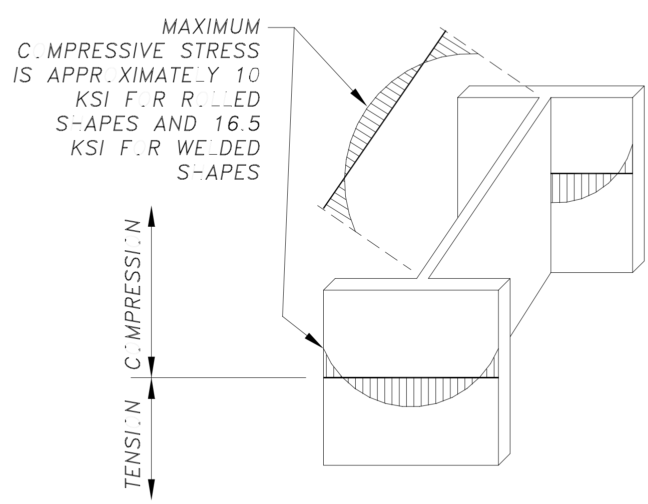


Fig. 1. Typical residual stress pattern in W-shape sections.

does not consider a reduction in web thickness because of the resulting reduction in design moment strength. However, the practicing Structural Engineer is encouraged to consider the possibility of reducing web thickness if the project schedule allows time for the investigation.

WELDING ISSUES

Weld Processes

Shielded Metal Arc Welding (SMAW) is the standard weld process for structural welds, especially in the field. Submerged Arc Welding (SAW) is a more common shop welding process. SAW yields a larger heat-affected zone, resulting in a higher strength fillet weld than the same size fillet weld made using SMAW. As a result, AWS and AISC prescribe larger effective throats (and design strengths) for fillet welds using SAW than those using SMAW. There is no design difference for groove welds.

AWS D1.1 Section 2—Design Provisions

Section 2.1.15 requires that "If two or more plates or rolled shapes are used to build up a member, sufficient welding (of the fillet, plug, or slot type) shall be provided to make the parts act in unison, but not less than that would be required to transfer calculated stress between the parts joined."

Sections 2.1.16, 2.1.17, and 2.1.18 give maximum spacing requirements for intermittent welds of built-up members.

AWS D1.1 Section 5—Fabrication Provisions

Section 5.21 requires control of distortion and shrinkage when welding built-up members. This section contains mostly "good practice" requirements to control and minimize distortion without locking in excessive residual stresses.

AISC DESIGN REQUIREMENTS

Chapter F and Appendix F of the LRFD *Specification* prescribes the flexural design requirements for W-shaped members. The design requirements reflect distinct flexural limit states, with each limit state bounded by a characteristic range of compression flange unbraced length, L_b. See Figure 2.

All notation is consistent with that defined in the LRFD *Specification*.

Limit State Bounding Ranges

The flexural limit state bounding ranges are defined as:

$$L_p = 1.76 r_y \sqrt{\frac{E}{F_{yf}}} \qquad \text{(LRFD Eq. F1-4)}$$

$$L_r = \frac{r_y X_1}{F_L}\sqrt{1+\sqrt{1+X_2 F_L^2}} \qquad \text{(LRFD Eq. F1-6)}$$

where:

$$X_1 = \frac{\pi}{S_x}\sqrt{\frac{EGJA}{2}} \qquad \text{(LRFD Eq. F1-8)}$$

$$X_2 = 4\frac{C_w}{I_y}\left(\frac{S_x}{GJ}\right)^2 \qquad \text{(LRFD Eq. F1-9)}$$

F_L = smaller of $(F_{yf} - F_r)$ or F_{yw} (LRFD Sec. F1.2)

F_r = compressive residual stress (LRFD Sec. F1.2)
= 10 ksi for rolled shapes
= 16.5 ksi for welded built-up shapes

Flexural Yielding Limit State

The compression flange is sufficiently braced to allow the full plastic moment, M_p, to be reached.

For compact sections with $L_b < L_p$:

$$M_n = M_p \qquad \text{(LRFD Eq. F1-1)}$$

where:

$$M_p = F_y Z \le 1.5 M_y \qquad \text{(LRFD Sec. F1.1)}$$

Inelastic Lateral-Torsional Buckling Limit State

The compression flange is not sufficiently braced to allow the full plastic moment, M_p, to be reached. The nominal moment capacity is limited by *inelastic* lateral-torsional buckling of the beam's compression flange.

For compact or noncompact sections with $L_p < L_b \le L_r$:

$$M_n = C_b\left[M_p - \left(M_p - M_r\right)\left(\frac{L_b - L_p}{L_r - L_p}\right)\right] \le M_p$$

(LRFD Eq. F1-2)

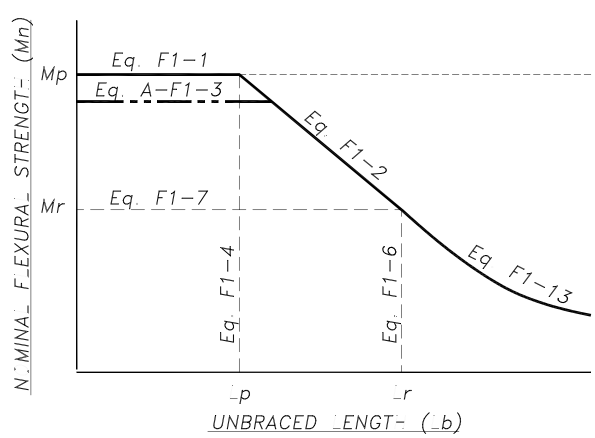


Fig. 2. Nominal flexural strength as a function of unbraced compression flange length and moment gradient (C_b *= 1.00).*

where:

$$M_r = F_L S_x \quad \text{(LRFD Eq. F1-7)}$$

Elastic Lateral-Torsional Buckling Limit State

The compression flange is not sufficiently braced to allow the full plastic moment, M_p, to be reached. The nominal moment capacity is limited by *elastic* lateral-torsional buckling of the beam's compression flange.

For compact or noncompact sections with $L_r < L_b$:

$$M_n = M_{cr} \le M_p \quad \text{(LRFD Eq. F1-12)}$$

where:

$$M_{cr} = C_b \frac{\pi}{L_b}\sqrt{EI_y GJ + \left(\frac{\pi E}{L_b}\right)^2 I_y C_w} \quad \text{(LRFD Eq. F1-13)}$$

$$= \frac{C_b S_x X_1 \sqrt{2}}{L_b / r_y}\sqrt{1 + \frac{X_1^2 X_2}{2\left(L_b / r_y\right)^2}} \quad \text{(LRFD Sec. F1.2)}$$

Flange And Web Buckling Limit States

Noncompact sections are capable of developing the material yield stress across some, but not all, of the beam cross-section before compression buckling. The nominal moment capacity is limited by local buckling of either the beam flange or web.

For noncompact sections:

$$M_n = M_p - \left(M_p - M_r\right)\left(\frac{\lambda - \lambda_p}{\lambda_r - \lambda_p}\right) \quad \text{(LRFD Eq. A-F1-3)}$$

where λ, λ_r, and λ_p are the limiting width-thickness ratios for compression elements defined in LRFD *Specification* Table B5.1.

Effect Of Compressive Residual Stresses

Note that compressive residual stresses, F_r, are defined different for rolled shapes and welded built-up shapes. As a result all equations that include the effects of F_r will be different for rolled shapes and welded built-up shapes. The effect of the residual stresses is to reduce the design strengths of a welded built-up shape from the rolled shape with the same flange and web plate dimensions. This reduced strength can be compensated for by selecting plates for the welded built-up shape that are larger than the comparable rolled shape.

STUDY METHODOLOGY

In order to compare AISC rolled shapes to built-up shapes, a spreadsheet was developed using MathCAD software (MathCAD, 1998) that calculated all of the required design variables. The study addressed 50 ksi steel only, and the use of metric plates to fabricate the built-up sections.

Spreadsheet Input

Study input variables were:

- Yield Strength, F_y = 50 ksi
- Modulus of Elasticity, E = 29000 ksi
- Shear Modulus, G = 11200 ksi
- Resistance factor, ϕ_b = 0.90
- Bending coefficient, C_b = 1.00
- Available metric plate thicknesses

It is recognized that plates are typically produced in discrete plate thicknesses. The metric plate thicknesses considered in this study were selected based on a study of metric plate availability for South American projects: 6, 8, 10, 12, 16, 19, 25, 31, 37, 43 and 50 mm.

Input variables for the rolled shapes were:

- AISC rolled shape name, generally selected from the top and bottom of section lists in the AISC *Manual*
- Flange width, from AISC *Manual*
- Flange thickness, from AISC *Manual*
- Section depth, from AISC *Manual*
- Web thickness, from AISC *Manual*
- Compressive flange residual stress, F_r = 10 ksi

Input variables for the built-up shapes were:

- Compressive flange residual stress, F_r = 16.5 ksi

Spreadsheet Calculations

Calculated variables for the built-up shapes were:

- Flange width, match rolled shape
- Flange thickness, from available metric plate thicknesses
- Section depth, match rolled shape
- Web thickness, from available metric plate thicknesses
- Compressive flange residual stress, F_r = 16.5 ksi

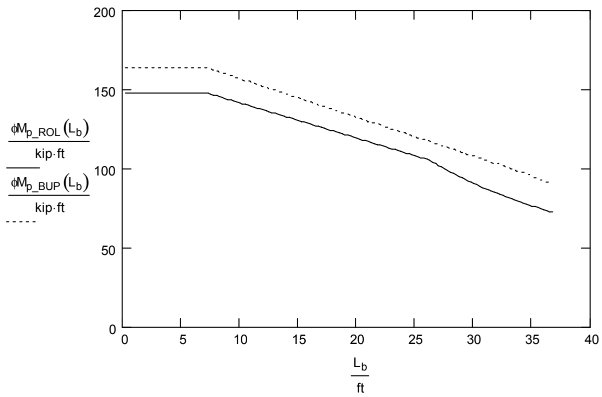
Calculated variables for both the rolled shapes and built-up shapes were:

- Cross-section area, A
- Weak-axis moment of inertia, I_y
- Weak-axis radius of gyration, r_y
- Elastic section modulus, S_x
- Plastic section modulus, Z_x

Table 1. W8×40 Comparison

COMPARISON SHEET

$F_y = 50\,\text{ksi}$
Size = "W8x40"
Rolled_Section = "Compact"
Builtup_Section = "Compact"

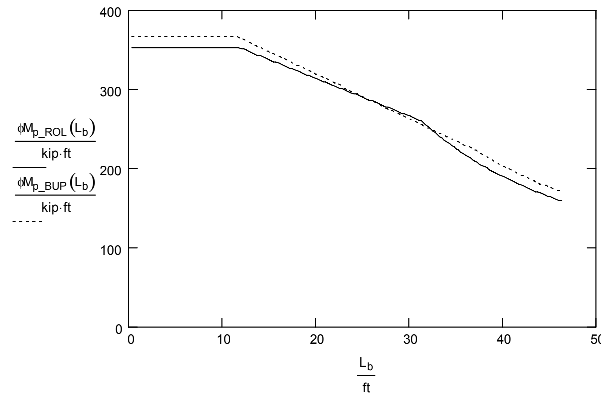


Variable	Rolled Section	Built-Up Section
Flange Width	$b_f = 8.07\,in$	$b_f = 8.07\,in$
Flange Thickness	$t_{f\_ROL} = 14.224\,mm$	$t_{f\_BUP} = 16\,mm$
Section Depth	$d = 8.25\,in$	$d = 8.25\,in$
Web Thickness	$t_{w\_ROL} = 9.144\,mm$	$t_{w\_BUP} = 10\,mm$
Plastic Length (Lp)	$L_{p\_ROL} = 7.271\,ft$	$L_{p\_BUP} = 7.309\,ft$
Moment Lb < Lp	$\phi M_{p\_ROL}(0.1 \cdot ft) = 147.5\,kip \cdot ft$	$\phi M_{p\_BUP}(0.1 \cdot ft) = 163.3\,kip \cdot ft$
Elastic Length (Lr)	$L_{r\_ROL} = 26.252\,ft$	$L_{r\_BUP} = 34.391\,ft$
Moment @ Lr	$\phi bM_{r\_ROL} = 105.261\,kip \cdot ft$	$\phi bM_{r\_BUP} = 96.924\,kip \cdot ft$
Weight	$Weight_{ROL} = 39.49\,plf$	$Weight_{BUP} = 43.96\,plf$
Weight Increase		$\Delta = 11.32\,\%$

Table 2. W12×65 Comparison

COMPARISON SHEET

$F_y = 50\,\text{ksi}$
Size = "W12x65"
Rolled_Section = "Non-Compact"
Builtup_Section = "Non-Compact"



Variable	Rolled Section	Built-Up Section
Flange Width	$b_f = 12\,in$	$b_f = 12\,in$
Flange Thickness	$t_{f\_ROL} = 15.367\,mm$	$t_{f\_BUP} = 16\,mm$
Section Depth	$d = 12.12\,in$	$d = 12.12\,in$
Web Thickness	$t_{w\_ROL} = 9.906\,mm$	$t_{w\_BUP} = 10\,mm$
Plastic Length (Lp)	$L_{p\_ROL} = 10.772\,ft$	$L_{p\_BUP} = 10.815\,ft$
Moment Lb < Lp	$\phi M_{p\_ROL}(0.1 \cdot ft) = 351.6\,kip \cdot ft$	$\phi M_{p\_BUP}(0.1 \cdot ft) = 365.9\,kip \cdot ft$
Elastic Length (Lr)	$L_{r\_ROL} = 31.351\,ft$	$L_{r\_BUP} = 36.807\,ft$
Moment @ Lr	$\phi bM_{r\_ROL} = 259.39\,kip \cdot ft$	$\phi bM_{r\_BUP} = 224.51\,kip \cdot ft$
Weight	$Weight_{ROL} = 63.887\,plf$	$Weight_{BUP} = 65.993\,plf$
Weight Increase		$\Delta = 3.296\,\%$

- Torsional moment of inertia, J
- Warping constant, C_w
- Torsional parameters, X_1, X_2
- Slenderness parameters, λ
- Compact element limiting parameter, λ_p
- Noncompact element limiting parameter, λ_r
- Plastic length, L_p
- Elastic Length, L_r
- Yield moment, M_y
- Design moment at L_p, $\phi_b M_p$
- Design moment at L_r, $\phi_b M_r$
- Design moment at all L_b, $\phi_b M_n$
- Section weight

The calculated section properties for rolled shapes do not agree exactly with those published by AISC because they were calculated based on rectangular dimensions with no consideration of web fillets. Any differences are small and do not noticeably affect the study results.

Spreadsheet Output

After the necessary variables were calculated, summary sheets were developed for each selected shape that included $\phi_b M_n$ vs. L_b plots for the rolled section and the built-up section on the same graph at the same scale. The summary sheets also list selected variables of the built-up section properties compared side-by-side to the rolled section properties, and a weight comparison.

Three representative comparisons were selected and are presented as Tables 1, 2, and 3 to illustrate typical results and to support the authors' conclusions. The three selected comparisons are representative of the 86 sections analyzed.

DATA INTERPRETATION

A total of 86 sections were analyzed and compared in the study. The following general observations can be made:

1. For compact sections, the built-up section yielding limit state strength is always greater than or equal to that of the rolled section.
2. For noncompact sections, the built-up section flange and web buckling limit state strengths are always greater than or equal to that of the rolled section.
3. For all sections, the limiting unbraced length L_r for the built-up section is always greater than or equal to that of the rolled section.

Table 3. W24×162 Comparison

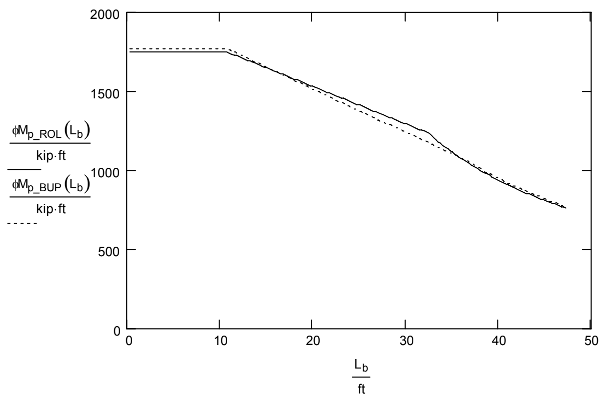
COMPARISON SHEET

$F_y = 50\,ksi$

Size = "W24x162"

Rolled_Section = "Compact"

Builtup_Section = "Compact"



Variable	Rolled Section	Built-Up Section
Flange Width	$b_f = 12.955\,in$	$b_f = 12.955\,in$
Flange Thickness	$t_{f\_ROL} = 30.988\,mm$	$t_{f\_BUP} = 31\,mm$
Section Depth	$d = 25\,in$	$d = 25\,in$
Web Thickness	$t_{w\_ROL} = 17.907\,mm$	$t_{w\_BUP} = 19\,mm$
Plastic Length (Lp)	$L_{p\_ROL} = 10.793\,ft$	$L_{p\_BUP} = 10.686\,ft$
Moment Lb < Lp	$\phi M_{p\_ROL}(0.1\cdot ft) = 1745.8\,k\cdot ft$	$\phi M_{p\_BUP}(0.1\cdot ft) = 1.8\times 10^3\,k\cdot ft$
Elastic Length (Lr)	$L_{r\_ROL} = 32.395\,ft$	$L_{r\_BUP} = 37.054\,ft$
Moment @ Lr	$\phi bM_{r\_ROL} = 1.235\times 10^3\,kip\cdot ft$	$\phi bM_{r\_BUP} = 1.043\times 10^3\,kip\cdot ft$
Weight	$Weight_{ROL} = 161.683\,plf$	$Weight_{BUP} = 165.026\,plf$
Weight Increase		$\Delta = 2.067\,\%$

4. For all sections, the limiting buckling moment M_r for the built-up section is always less than or equal to that of the rolled section.
5. For all sections, the slope of the nominal strength Equation F1-2 is steeper for the built-up section than that of the rolled section. The start point for the equation (L_p, M_p) for the built-up section is always at an M_n value greater than or equal to that of the rolled section. Any understrength in the built-up section relative to the rolled section occurs near the other end of the curves (L_r, M_r).
6. For all sections, any understrength in the built-up section relative to the rolled section occurs at large values of L_b where the compressive flange strength will be limited by either inelastic or elastic lateral-torsional buckling. This implies that closer study may be warranted for industrial structures where flexural members seldom have the continuous compression flange support of a concrete slab.

CONCLUSIONS

Although some of the data indicates some built-up shapes falling below the design strength of the rolled shape, the margins are very small, and are confined to a small range of unbraced lengths near the transition between compression flange elastic and inelastic lateral-torsional buckling. The margins are well within the accuracy of the loads normally applied to structures.

An examination of the data supports the conclusion that the built-up W-shapes can be safely substituted for rolled W-shapes provided that *all* of the following occur:

1. Flange and web plate thicknesses (t_f and t_w) are equal to or larger than the rolled shape thicknesses;
2. Flange and web plate widths (b_f and h) are equal to or larger than the rolled shape thicknesses;
3. Plate material strengths (F_y and F_u) are equal to or larger than the rolled shape strengths; and
4. All welding is in accordance with AWS D1.1, and
5. Fabrication shop inspection efforts are increased to account for the greater quantity of shop welding.

This study addressed only 50 ksi yield strength steel and metric plate thickness increments. It is the author's opinion that studies of steels with higher yield strengths and different plate thickness increments would yield the same results.

Studies of steels with lower yield strengths are less likely to yield similar results because the residual stress values in the AISC *Specification* will be a larger percentage of the yield stress, reducing the values of the built-up section nominal moment strengths relative to those of the comparable rolled section.

In addition, the practicing Structural Engineer is encouraged to consider the possibility of reducing web thickness if the project schedule allows time for the investigation.

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