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Stiffened Elements with Multiple Intermediate Stiffeners and Edge Stiffened Elements with Intermediate Stiffeners

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Abstract

Section B5 of the AISI Specification, covering stiffened elements with multiple intermediate stiffeners and edge stiffened elements with intermediate stiffeners, has been entirely replaced in the latest edition of the Cold-Formed Steel Specification (NAS 2001). The new design rules are based primarily on the work of Schafer and Peköz (1998); however, subsequent to that work and prior to adoption by AISI, additional work was also completed. For elements with multiple intermediate stiffeners consideration of web/flange interaction was added. The resulting expressions are shown to agree well with both experimental and numerical data. New provisions for edge stiffened elements with intermediate stiffeners have also recently been adopted. The logic behind the development of these provisions is discussed herein. Compared with previously used procedures (AISI 1996) the new methods provide a more robust and reliable method for the design of these unique elements.

Introduction

AISI Specification section B5 has been completely replaced by new methods in the latest edition of the Cold-Formed Steel Specification (NAS 2001). This paper addresses certain changes in the development of the provisions for stiffened elements with multiple intermediate stiffeners that occurred over the course of adopting the new design procedure. The theoretical development of the expressions used in the design method are fully presented in Schafer and Peköz (1998), the focus in this paper is on the implementation of this method rather than its development. Traditionally, Section B5 has also covered edge stiffened elements with intermediate stiffeners, this practice is continued in the current edition of the Specification (NAS 2001), but the previous rules were completely abandoned. A new method, based on limited elastic buckling analyses, and a conservative implementation of the strength in the prevailing failure modes, has been developed. This method is a intuitive extrapolation of current knowledge and is explained herein.

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Stiffened Elements with Multiple Intermediate Stiffeners

Background

The compression flange of deck sections, as shown in Figure 1, are the most common uniformly compressed stiffened elements with multiple intermediate stiffeners. A full accounting of the available research, elastic buckling behavior, post-buckling behavior and improvements in design methods for these members is provided in Schafer and Peköz (1998). This work provides additions to that method and focuses on the design formula themselves, as opposed to their theoretical development.

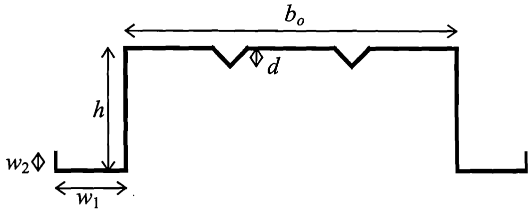


Figure 1 Deck with Multiple Longitudinal Intermediate Stiffeners

The new B5 design method is based on determining the plate buckling coefficient for the two competing modes of buckling: local buckling, in which the stiffener does not move; and distortional buckling in which the stiffener buckles with the entire plate – see Figure 2. Experimental and numerical research indicates that the distortional mode is far more prevalent for practical members with multiple intermediate stiffeners.

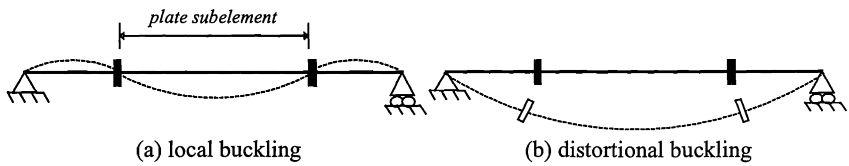


Figure 2 Buckling of a uniformly compressed element with multiple intermediate stiffeners

Design Method

The complete design method is provided in the Appendix. In the general case of multiple intermediate stiffeners of differing size and location, calculation of the effective width requires determining the following:

<u>for each stiffener</u>

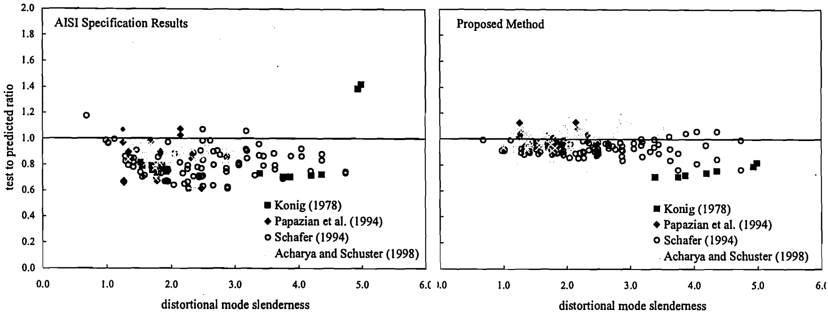
area of the stiffener (A_s) and its related non-dimensional variable δ (e.g., per B5.1.2-6)
location of the stiffener (c) and its related non-dimensional weight ω (e.g. per B5.1.2-5)
moment of inertia of the stiffener (I_{sp}) and its related variable γ (e.g. per B5.1.2-4)

<u>elastic buckling for the element</u>
non-dimensional distortional buckling length β, buckling length is βb_o, (e.g. per B5.1.2-3)
plate buckling coefficient for distortional buckling k_d (e.g. per B5.1.2-2)
plate buckling coefficient for local buckling k_{loc} (e.g. per B5.1.2.-1)
web/flange interaction factor R (per B5.1-7 and 8)
minimum plate buckling coefficient $k=\min(Rk_d,k_{loc})$ (per B5.1-6)
<u>effective width</u>
slenderness of the element λ (per B5.1-4)
effectiveness of the element ρ (per B5.1-2 and 3)
effective width of the element b_e (per B5.1-1)

The reduction, ρ, is applied to the entire element (gross area of the element / thickness) instead of only the flat portions. Reducing the entire element to an effective width, which ignores the geometry of the stiffeners, for effective section property calculation allows distortional buckling to be treated consistent with the rest of the Specifcation, rather than as an "effective area" or other method. The resulting effective width must act at the centroid of the original element including the intermediate stiffeners. This insures that the neutral axis location for the member is unaffected by the use of the simple effective width, which replaces the more complicated geometry of the element with multiple intermediate stiffeners. One possible result of this approach is that the calculated effective width (b_e) may be greater than b_0. This may occur when ρ is near 1, and is due to the fact that b_e includes contributions from the stiffener area and b_0 does not. As long as the calculated b_e is placed at the centroid of the entire element, the use of $b_e>b_0$ is correct.

Performance of Design Method

A scatter plot of test-to-predicted ratios for the AISI (1996) Specification rules and the new method are presented in Figure 3 and a detailed summary of the investigated members is provided in Table 1. Test-to-predicted ratios less than 1 represent unconservative predictions. The data includes experimental research (König 1978, Papazian et al. 1994, Acharya and Schuster 1998) and finite element studies (Schafer 1994) on hat sections in bending with two to four longitudinal stiffeners in the compression flange.



(a) AISI (1996) (b) Proposed Method=NAS (2001)

Figure 3 Performance of Design Methods

Table 1 Detailed Breakdown of Test to Predicted Ratios*

		Current AISI Spec.		Proposed Method	
Research	**count**	**mean**	**stdev**	**mean**	**stdev**
Papazian et al. (1996)	18	0.85	0.19	1.02	0.05
Konig (1978)	12	0.86	0.30	0.84	0.14
Schafer (1995) - web h/t=100	47	0.84	0.13	0.92	0.06
- web h/t =50	47	0.77	0.14	0.93	0.05
Acharya and Schuster (1998)	91	1.04	0.33	1.02	0.10
All Data	215	0.99	0.27	1.00	0.10
		ϕ is 0.67		ϕ is 0.87	

* "Current AISI Spec." = AISI (1996) "Proposed Method" = NAS (2001)

Detailed comparison of the final approved method (as given in the Appendix) with that of Schafer and Peköz (1998) indicate some minor changes. The method of Schafer and Peköz (1998) uses a reduction factor R_d in place of R (i.e., B5.1-7 and 8). R_d was originally included to provide a reduction on the distortional buckling stress to reflect reduced capacity in this mode of failure. However, use of an isolated simply supported plate (which ignores web restraint) as is done in the AISI Specification (NAS 2001), provides enough reduction on distortional buckling, thus R_d was removed.

Removal of R_d without making other changes is not sufficient either, as Figure 4 shows, there is a trend in the data as a function of the flange width to web height ratio. This indicates that web/flange interaction needs to be considered in these members in order to get an accurate design method. An appropriate R factor was determined and implemented, resulting in the predictions summarized in Figure 3(b).

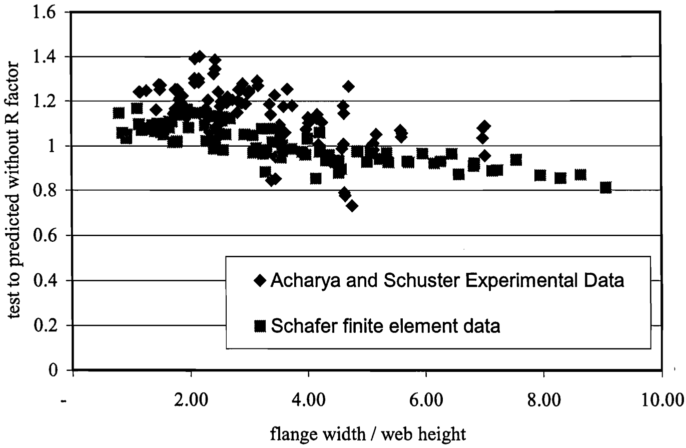


Figure 4 Test to Predicted Ratio if R (i.e. Eq.'s B5.1-7 and 8) are removed or set = 1

Industry Impact:

The new design method is significantly different than the previous methods and this obviously has an impact on profile shapes and strength predictions. In AISI (1996), members with stiffeners less that I_{min} must be neglected. These members see a significant benefit from the new design rules (e.g., note the members with AISI test to predicted ratios above 1.6 in Figure 3(a)). Members with unusual stiffener configurations (e.g. two small stiffeners near the corners and no other stiffeners) now will have reliable, applicable design rules. In the AISI (1996) method if many small stiffeners were used a smeared thickness t_s was employed in the method, the new design rules will provide more conservative strength prediction in these cases, though experiments show it to be more correct as well.

Edge Stiffened Elements with Intermediate Stiffeners

Adoption of the new provisions for multiple longitudinal intermediate stiffeners in section B5 of the AISI Specification was delayed because the method did not provide a means to design edge stiffened elements with intermediate stiffeners. Since edge stiffened elements with intermediate stiffeners were covered in the AISI (1996) Specification any method that did not cover all the existing cases for B5 was considered incomplete. Continued use of the AISI (1996) Specification method for edge stiffened elements with intermediate stiffeners was considered unadvisable due to shortcomings in the method, particularly the use of I_{min} in AISI (1996) which is incorrect and unrealistic. Further, distortional buckling of the edge stiffened element will likely control the failure mode and this is largely unaccounted for in the existing procedure.

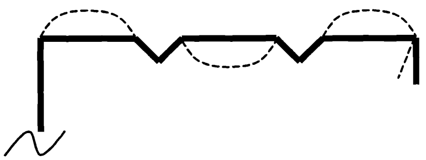
Finite strip analyses of isolated edge stiffened elements with an intermediate stiffener were conducted using CUFSM (Schafer 2001) in order to gain better insight on the behavior of these elements. Analyses included overall element slenderness (w/t) of 30, 60, 90, and 120, where 120 is greater than the Specification currently allows. Simple lip edge stiffeners at 90 degrees from the flange, with I_s = ½ I_a and 1.0 I_a, where I_a is from Case III of section B4.2 (AISI 1996) were employed. Finally, intermediate stiffeners with I_{st} = ½ I_{min} and 1.0 I_{min} from the AISI (1996) B5 section (where $I_{st} < I_{min}$ is currently ignored) were also included in the parametric study. This work lead to the following conclusions:

- I_{min} in B5 (AISI 1996) ignores nearly all practical intermediate stiffener sizes
- even small intermediate stiffeners (e.g., $I_{int\_stiffener}$=½I_{min}) increase the local buckling stress significantly in these elements
- increases in the local buckling stress may be estimated using the proposed methods for multiple intermediate stiffeners (NAS 2001), but R < 1

With regard to distortional buckling of edge stiffened elements:

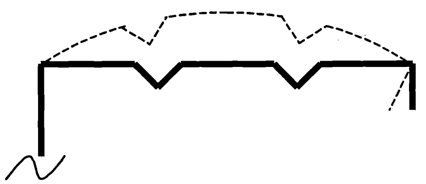
- intermediate stiffeners increase the distortional buckling stress if the edge stiffener is small (e.g., $I_{edge\_stiffener}$=½I_a from case III section B4.2 AISI 1996)
- but intermediate stiffeners decrease the distortional buckling stress if the edge stiffener is large (e.g. $I_{edge\_stiffener}$=1.0I_a from case III section B4.2 AISI 1996)
- The effect of intermediate stiffeners on the distortional buckling stress is less than 10% for practical intermediate stiffener sizes - regardless of whether the stiffener is beneficial or detrimental

Therefore, for practical intermediate stiffener sizes it is assumed that the intermediate stiffener may be ignored in determining the distortional buckling of the edge stiffened element.



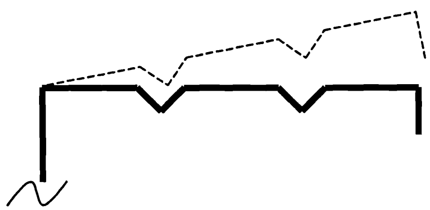
(a) Local sub-element buckling

This mode is similar to local buckling in a stiffened element with multiple intermediate stiffeners. It may be estimated using the same rules for k_{loc} as in the proposed methods for section B5.



(b) Distortional buckling of the intermediate stiffeners

This mode is similar to distortional buckling in a stiffened element with multiple intermediate stiffeners, except for the web restraint. It is conservative to ignore all beneficial effects of web restraint (R) and calculate k_d the same as in the new B5, i.e., always keep R<1.



(c) Distortional buckling of the edge stiffened element

This mode is similar to distortional buckling in an edge stiffened element without intermediate stiffeners. It is proposed to ignore the effect of the intermediate stiffener, which is small in the majority of cases, and calculate k using existing B4.2 rules.

Figure 5 Buckling Modes for an Edge Stiffened Element with Intermediate Stiffeners

Four remedies were considered for the 1996 Specification method:

- remove AISI (1996) rules for edge stiffened elements with intermediate stiffeners
- keep the AISI (1996) rules for edge stiffened elements w/ intermediate stiffeners
- use current knowledge to create a new approach
- perform new research to develop and verify a new detailed method

Although performing additional research would provide the most robust procedure it was determined that neither money nor time was available for such an approach. Therefore, a largely intuitive, yet conservative procedure was adopted for the strength prediction. The new method provides a viable solution until such time as new research can be conducted. At the same time, we can use what we know today to replace the old, impractical and incorrect rules. Consider the three buckling modes for an edge stiffened elements with intermediate stiffeners discussed in Figure 5.

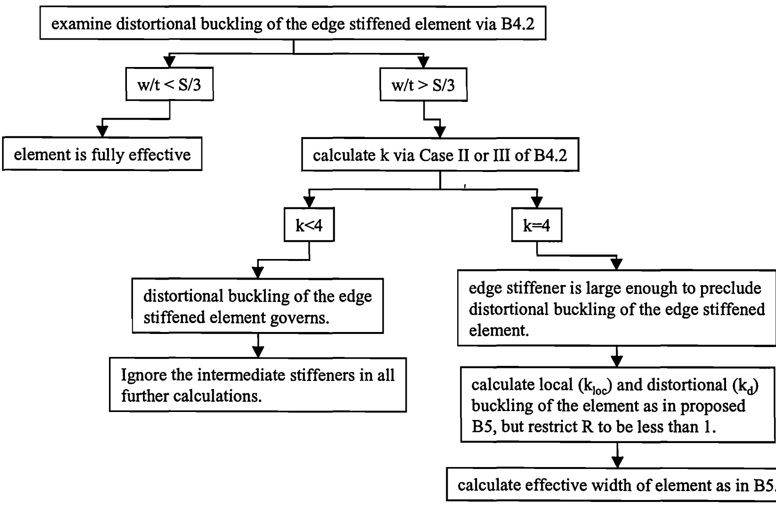


Figure 6 Flow Chart for Design of Edge Stiffened Elements with Intermediate Stiffeners

A flow chart of the new design procedure is given in Figure 6. The procedure first checks the slenderness of the flange, if it is stocky ($w/t < S/3$ and $w = b_0$) then intermediate stiffeners are not needed and the element may simply be considered fully effective. If the flange is slender, then the size of the edge stiffener must be considered. If the edge stiffener is inadequate then k for the flange is less than 4 – in this case it is decided to conservatively ignore any contribution the intermediate stiffener may make to the strength – and proceed as if the stiffener is not in place. If the edge stiffener is fully adequate then the flange may be treated per the new provisions of B5.1, with one proviso. The empirical local web/flange interaction factor, R, is intended for stiffened elements (e.g. compression flange of a deck) and the web restraint is not as beneficial for flanges made up of edge stiffened elements; therefore R must be restricted to be less than 1 in this case. The procedure is outline in the flow chart of Figure 6, and detailed in the Appendix.

The selected methodology takes advantage of our existing knowledge as well as the newly proposed method for elements with intermediate stiffeners. It is a conservative implementation, but at the same time allows the beneficial effects of intermediate stiffeners to be considered where they are appropriate.

Conclusions

The development of new design provisions for the effective width of uniformly compressed elements with multiple intermediate stiffeners and uniformly compressed edge stiffened elements with intermediate stiffeners significantly improves a portion of the AISI Specification that had become badly outdated and could provide markedly conservative or unconservative strength predictions (as evidenced by comparisons to tested sections and numerical analysis). Consideration of web/flange interaction for members with multiple intermediate stiffeners is shown to remove systematic error and improve the reliability of the new design method. The development of the new design procedure for edge stiffened elements with intermediate stiffeners is fully presented for the first time.

Appendix – References

Acharya, V.V., Schuster, R.M. (1998). "Bending tests of Hat Section with Multiple Longitudinal Stiffeners." *Proceedings of the Fourteenth International Specialty Conference on Cold-Formed Steel Structures*, University of Missouri-Rolla.

König, J. (1978). "Transversally Loaded Thin-Walled C-Shaped Panels With Intermediate Stiffeners." *Swedish Council for Building Research*, Stockholm, Sweden, D7:1978.

Papazian, R.P., Schuster, R.M., Sommerstein, M. (1994). "Multiple Stiffened Deck Profiles." *Proceedings of the Twelfth International Specialty Conference on Cold-Formed Steel Structures*, University of Missouri-Rolla, 217-228.

Schafer, B.W. (2001) CUFSM: Elastic Buckling Analysis of Thin-Walled Members Using the Classical Finite Strip Method, version 2.0, distributed freely at www.ce.jhu.edu/bschafer

Schafer, B.W., Peköz, T. (1998). "Cold-Formed Steel Members with Multiple Longitudinal Intermediate Stiffeners." *Journal of Structural Engineering*, ASCE, 124 (10) 1175-1181.

Appendix: North American Specification Provisions (2001)

B5 Effective Widths of Stiffened Elements with More Than One Intermediate Stiffeners or Edge Stiffened Elements with Intermediate Stiffeners

B5.1 Effective Widths of Uniformly Compressed Stiffened Elements with Multiple Intermediate Stiffeners

The following notation is used in this section.

A_g = Gross area of the element including stiffeners
A_s = Gross area of a stiffener
b_e = Effective width of the element, located at centroid of the element including stiffeners, Fig. B5-2.
b_p = Largest sub-element flat width, see Figure B5-1.
b_0 = Total flat width of the stiffened element, see Figure B5-1.
c_i = Horizontal distance from the edge of the element to centerline(s) of the stiffener(s), Fig. B5-1.
f_1 = Uniform compressive stress acting on the flat element
h = Width of elements adjoining the stiffened element (e.g., the depth of the web in a hat section with multiple intermediate stiffeners in the compression flange is equal to h; if adjoining elements have different widths, use the smallest one.)
I_{sp} = Moment of inertia of a stiffener about the centerline of the flat portion of the element, the radii which connect the stiffener to the flat may be included.
k = Plate buckling coefficient of the element
k_d = Plate buckling coefficient for distortional buckling.
k_{loc} = Plate buckling coefficient for local sub-element buckling.
L_{br} = Unsupported length between brace points or other restraint which restricts distortional buckling of the element.
R = Modification factor for the distortional plate buckling coefficient
n = Number of stiffeners in the element
t = Element thickness
λ = Slenderness of the element
i = index for stiffener "i"

The effective width shall be determined as follows:

$$b_e = \rho\left(\frac{A_g}{t}\right) \qquad (Eq.\ B5.1\text{-}1)$$

$$\rho = 1 \qquad \text{when } \lambda \le 0.673 \qquad (Eq.\ B5.1\text{-}2)$$

$$\rho = (1-0.22/\lambda)/\lambda \qquad \text{when } \lambda > 0.673 \qquad (Eq.\ B5.1\text{-}3)$$

$$\lambda = \sqrt{\frac{f_1}{f_{cr}}} \qquad (Eq.\ B5.1\text{-}4)$$

$$f_{cr} = k\frac{\pi^2 E}{12(1-\mu^2)}\left(\frac{t}{b_0}\right)^2 \qquad (Eq.\ B5.1\text{-}5)$$

The plate buckling coefficient, k, shall be determined from the minimum of Rk_d and k_{loc}, as determined from section B5.1.1 or B5.1.2, as appropriate.

k = the minimum of Rk_d and k_{loc} (*Eq.* B5.1-6)

$R = 2$ when $b_0/h < 1$ (*Eq.* B5.1-7)

$$R = \frac{11 - b_0/h}{5} \geq \tfrac{1}{2} \quad \text{when } b_0/h \geq 1 \qquad (Eq.\ B5.1\text{-}8)$$

B5.1.1 Specific Case: 'n' Identical Stiffeners, Equally Spaced

(a) Strength Determination

$$k_{loc} = 4(n+1)^2 \qquad (Eq.\ B5.1.1\text{-}1)$$

$$k_d = \frac{(1+\beta^2)^2 + \gamma(1+n)}{\beta^2(1+\delta(n+1))} \qquad (Eq.\ B5.1.1\text{-}2)$$

$\beta = (1+\gamma(n+1))^{1/4}$ if $L_{br} < \beta b_0$ then L_{br}/b_0 may be substituted for β (*Eq.* B5.1.1-3) to account for increased capacity due to bracing.

$$\gamma = \frac{10.92 I_{sp}}{b_0 t^3} \qquad (Eq.\ B5.1.1\text{-}4)$$

$$\delta = \frac{A_s}{b_0 t} \qquad (Eq.\ B5.1.1\text{-}5)$$

(b) Deflection Determination

The effective width, b_d, used in computing deflection shall be determined as in Section B5.1.1(a), except that f_d shall be substituted for f_1, where f_d is the computed compressive stress in the element being considered based on the effective section at the load for which deflections are determined.

B5.1.2 General Case: Arbitrary Stiffener Size, Location and Number

(a) Strength Determination

$$k_{loc} = 4(b_0/b_p)^2 \qquad (Eq.\ B5.1.2\text{-}1)$$

$$k_d = \frac{(1+\beta^2)^2 + 2\sum_{i=1}^{n}\gamma_i\omega_i}{\beta^2\left(1+2\sum_{i=1}^{n}\delta_i\omega_i\right)} \qquad (Eq.\ B5.1.2\text{-}2)$$

$\beta = \left(2\sum_{i=1}^{n}\gamma_i\omega_i + 1\right)^{1/4}$ if $L_{br} < \beta b_0$ then L_{br}/b_0 may be substituted for β (*Eq.* B5.1.2-3)

to account for increased capacity due to bracing.

$$\gamma_i = \frac{10.92(I_{sp})_i}{b_0 t^3} \qquad (Eq.\ B5.1.2\text{-}4)$$

$$\omega_i = \sin^2\left(\pi \frac{c_i}{b_0}\right) \qquad (Eq.\ B5.1.2\text{-}5)$$

$$\delta_i = \frac{(A_s)_i}{b_0 t} \qquad (Eq.\ B5.1.2\text{-}6)$$

(b) Deflection Determination

[same as B5.1.1(b) – removed here for brevity]

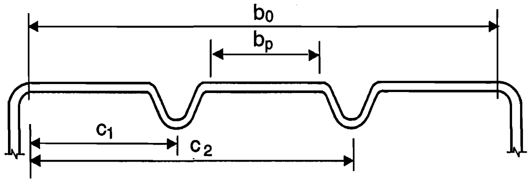


Figure B5-1 Plate Widths and Stiffener Location

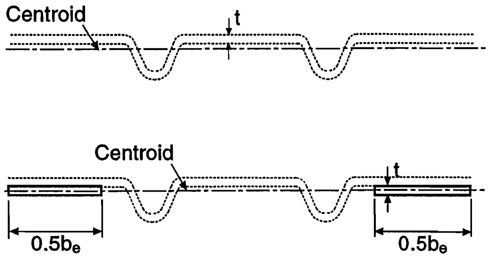


Figure B5-2 Effective Width Determination

B5.2 Edge Stiffened Elements with Intermediate Stiffeners

(a) *Strength Determination*

The effective width, b_e, shall be determined as follows:

If $b_0/t \leq S/3$ then the element is fully effective and no local buckling reductions are required.

If $b_0/t > S/3$ then the plate buckling coefficient, k shall be determined from the provisions of section B4.2, but with b_0 replacing w in all expressions.

If k calculated from section B4.2 is less than 4.0 ($k < 4$) then the intermediate stiffeners shall be ignored. Follow the provisions of section B4.2 for calculation of the effective width.

If k calculated from section B4.2 is equal to 4.0 ($k = 4$) then the effective width of the element shall be calculated from the provisions of section B5.1, with the following exception:

R calculated from equations B5.1-7 and B5.1-8 must be less than or equal to 1.

(b) *Deflection Determination*

The effective width, b_d, used in computing deflection shall be determined as in Section B5.2, except that f_d shall be substituted for f_1, where f_d is the computed compressive stress in the element being considered.

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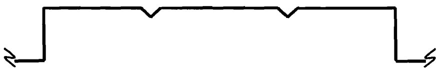
Example of section B5
effective width of an element with multiple intermediate stiffeners

Consider an element with 2 evenly placed intermediate stiffeners attached to a 2 in. tall web



material properties

$E := 295000 \cdot ksi$ $\mu := 0.3$ $f_y := 50 \cdot ksi$

element properties

element flat width $b_0 := 12 \cdot in$

element thickness $t := 0.03 \cdot in$

plate rigidity $D := \frac{E \cdot t^3}{12 \cdot (1 - \mu^2)}$

stiffener properties

area $A_s := 0.036 \cdot in^2$

moment of inertia $I_{sp} := 1.581 \cdot 10^{-3} \cdot in^4$

number of stiffeners $n := 2$

Find the plate buckling coefficient k, per B5.1.1 $k := \min([k_{loc} \;\; R \cdot k_d])$

local plate buckling: $k_{loc} := 4 \cdot (n + 1)^2$ $k_{loc} = 36$

distortional plate buckling

$\delta := \frac{(A_s)}{b_0 \cdot t}$ $\delta = 0.1$ $\gamma := \frac{E \cdot (I_{sp})}{b_0 \cdot D}$ $\gamma = 53.286$ $\beta := (1 + \gamma \cdot (n + 1))^{\frac{1}{4}}$ $\beta = 3.561$

$k_d := \frac{(1 + \beta^2)^2 + \gamma \cdot (n + 1)}{\beta^2 \cdot (1 + \delta \cdot (n + 1))}$ $k_d = 21.051$

modification factor as a function of the web height $h := 2 \cdot in$

$$R := \begin{cases} 2 & \text{if } \frac{b_0}{h} < 1 \\ \max\left(\left[\frac{11 - \frac{b_0}{h}}{5} \;\; \frac{1}{2}\right]\right) & \text{otherwise} \end{cases}$$

$R = 1$

The governing plate buckling coefficient: $k := \min([k_{loc} \;\; R \cdot k_d])$ $k = 21.051$

Now find the effective width

assume applied stress is equal to the yield stress $f_1 := f_y$

$f_{cr} := k \cdot \frac{\pi^2 \cdot E}{12 \cdot (1 - \mu^2)} \cdot \left(\frac{t}{b_0}\right)^2$ $f_{cr} = 35.079 \cdot ksi$ $\lambda := \sqrt{\frac{f_1}{f_{cr}}}$ $\lambda = 1.194$

$$\rho := \begin{cases} 1 & \text{if } \lambda \le 0.673 \\ \frac{\left(1 - \frac{0.22}{\lambda}\right)}{\lambda} & \text{otherwise} \end{cases}$$

$\rho = 0.683$

gross area of the flange is approximately $A_g := b_0 \cdot t + n \cdot A_s$ $A_g = 0.432 \cdot in^2$

$b_e := \rho \cdot \left(\frac{A_g}{t}\right)$ $b_e = 9.839 \cdot in$