Minnesota Department of Transportation

Memo

Bridge Office
Mail Stop 610
3485 Hadley Ave.
Oakdale, MN 55128

Office Tel: (651)366-4506
Fax: 366-4497

October 20, 2008

To: Bridge Design Engineers

From: Kevin Western
Bridge Design Engineer

Kevin Western

MEMO TO DESIGNERS (2008-02): Truss Bridge Gusset Plate Analysis

The collapse of the I35W bridge over the Mississippi River sparked a structural review of gusset plates in truss bridges throughout the state. In order to accomplish this task, a procedure for analyzing and rating the gusset plates was developed. This has resulted in the following Mn/DOT Bridge Office policy for analysis and rating of truss bridge gusset plates:

1) Mn/DOT Truss Bridge Gusset Plate Design Review Procedure (see attachment)
   This document details the gusset plate checks to be made for determination of inventory and operating ratings.
2) Mn/DOT Interpretation of Truss Bridge Gusset Plate Review Results (see attachment)
   This document describes how the gusset plate review results are to be interpreted and also details refined analysis methods for buckling and shear checks.

This Memo to Designers is being published now in order to make it official policy while structural review of the truss bridges on the local system is occurring. A comprehensive section on bridge rating is currently being developed for insertion in the LRFD Bridge Design Manual and will include the guidance contained in this memo when complete.

If you have any questions or concerns about the policy, please contact Dave Dahlberg at dave.dahlberg@dot.state.mn.us or by phone at 651-366-4491.

cc: D. Dorgan
D. Dahlberg
E. Wolhowe / Design Consultants
G. Peterson
T. Styrbicki
R. Garcia (FHWA)

[This Page Intentionally Left Blank]

Mn/DOT Truss Bridge Gusset Plate Design Review Procedure

1) Gather information and determine loads for gusset plate review.
   a. Obtain the original bridge plan, any subsequent repair plans, the shop drawings, and the most current inspection report.
   b. Verify (by approximate methods or frame analysis) the original dead load from the original plan truss load table (if available) and the live load where appropriate. The gusset plates will be rated for an HS20 loading. Note that original live load will likely not be HS20. Therefore, the live load will need to be increased by the ratio of HS20 to the original live load or be recalculated using an analysis program or BARS influence line data. Note that for bridges designed before 1931, the H15 loading used was not the same as H15 used today, so live load values for this case must be regenerated. Also note that the HS20 lane load concentrated load for moment (18 kips) is to be used for determination of top and bottom chord loads. The HS20 lane load concentrated load for shear (26 kips) is to be used for determination of diagonal and vertical loads. The original plan truss load tables typically include only the maximum member forces. Therefore for flexure and shear checks, coincident member live load forces must also be generated.
   c. Determine increased dead load in truss joint members due to additional loads (overlays, railings, etc) using one of the following methods:
      - Use influence lines from BARS or original truss design calculations (if available) to calculate truss member tension/compression due to additional loads.
      - Model truss using STAAD or another analysis program to determine truss member forces due to additional loads.
   d. Review the most current inspection report and identify gusset plates with appreciable section loss. If appreciable loss is reported, discuss with bridge inspector to determine the percentage of section loss. Otherwise, report ratings for the following scenarios:
      - For rivet/bolt shear and bearing check, report ratings for capacity reduction factors CRF = 1.00 and CRF = 0.95, both with 0% section loss
      - For all other checks, report ratings for capacity reduction factors CRF = 0.95 and CRF = 0.85, both with 0% section loss

      The range of results will be considered upon completion of the review.
   e. Confirm that gusset plates shown in the plans match those shown in the shop drawings in thickness and material.

2) Check tension in gusset plates.
   a. Consider all truss joints with tension members. Use engineering judgement to eliminate checking of similar member connections.

b. Determine “Whitmore effective width” for each member. This is done by finding the first set of rivets in the member to gusset plate connection and drawing lines that start at the outside rivets radiating at 30 degrees outward from the direction of the member. The “Whitmore effective width” is equal to the distance between the 30 degree lines where they intersect a line through the last set of rivets. See Attachment 1, taken from the *AISC Steel Construction Manual 13th Edition.*
c. Determine factored resistance per LRFD 6.8.2.1 using “Whitmore effective width” for calculation of gusset plate gross and net area.
d. Calculate the inventory and operating rating factor (RF) as a function of HS20 live loading:

   $RF_{inv} = (\phi \cdot P_n - 1.3 \cdot P_{DL}) / 2.17 \cdot P_{HS20LL}$

   $RF_{op} = (\phi \cdot P_n - 1.3 \cdot P_{DL}) / 1.3 \cdot P_{HS20LL}$

   If pedestrian live load is present, include entire amount when calculating rating factors:

   $RF_{inv} = (\phi \cdot P_n - 1.3 \cdot P_{DL} - 2.17 \cdot P_{ped\ LL}) / 2.17 \cdot P_{HS20LL}$

   $RF_{op} = (\phi \cdot P_n - 1.3 \cdot P_{DL} - 1.3 \cdot P_{ped\ LL}) / 1.3 \cdot P_{HS20LL}$

3) Check flexural capacity of gusset plates.
a. Consider all truss joints. Use engineering judgement to eliminate checking of similar member connections.
b. Cut a section through the gusset plate at a line parallel to the chord that passes through the last line of rivets in diagonal/vertical members.
c. Determine gross section properties. Consider all plates that will resist bending at the joint being checked. This includes gusset plates as well as top, bottom, and side plates (if they exist).
d. Determine combined axial and bending stress ($f = P/A + My/I$) on the gross section due to eccentricity of max loading to neutral axis of plates for DL and LL. Use coincident LL forces determined by analysis. For cases where the coincident live load force is greater than the maximum force determined for the member (which may happen for top or bottom chords where max forces were determined with the 18 kip concentrated load, but coincident forces were determined using the 26 kip concentrated load), limit the coincident live load force to the maximum live load force.
e. Determine factored resistance based on a limiting stress of $\phi_f \cdot F_y$ per Guide Specs for Strength Design of Truss Bridges Article 1.11 and LRFD 6.14.2.8.
f. Determine rating factors:

   $RF_{inv} = (\phi_f \cdot F_y - 1.3 \cdot f_{DL}) / 2.17 \cdot f_{HS20LL}$

   $RF_{op} = (\phi_f \cdot F_y - 1.3 \cdot f_{DL}) / 1.3 \cdot f_{HS20LL}$

   If pedestrian live load is present, include entire amount when calculating rating factors:

   $RF_{inv} = (\phi_f \cdot F_y - 1.3 \cdot f_{DL} - 2.17 \cdot f_{ped\ LL}) / 2.17 \cdot f_{HS20LL}$

   $RF_{op} = (\phi_f \cdot F_y - 1.3 \cdot f_{DL} - 1.3 \cdot f_{ped\ LL}) / 1.3 \cdot f_{HS20LL}$
g. Cut a section through the gusset plate at a line normal to the chord that passes through the centerline of the joint and repeat steps above.

h. Consider cutting sections through the gusset plate at other locations in order to maximize the combined axial and bending stress and repeat steps above.

4) Check shear in gusset plates.

a. Consider all truss joints. Use engineering judgement to eliminate checking of similar member connections.
b. Cut a section through the gusset at a line parallel to the chord that passes through the line of rivets in the chord closest to the diagonal/vertical members.
c. Determine shear for DL and LL at the cut section. Use coincident LL forces determined by analysis.
d. Determine both gross area and net area of the plates at the cut section.
e. Determine factored yield resistance $\phi \cdot V_{ny} = \phi_{vy} \cdot \Omega \cdot (0.58 \cdot F_y) \cdot A_g$ and factored rupture resistance $\phi \cdot V_{nu} = \phi_{vu} \cdot (0.58 F_u) \cdot A_n$ per the FHWA Guidance for Load Rating Evaluation of Gusset Plates in Truss Bridges, LRFR Method. Determine the factored shear resistance $\phi \cdot V_n$, which is the smaller of $\phi \cdot V_{ny}$ and $\phi \cdot V_{nu}$. Use $\phi_{vy} = 0.95$, $\phi_{vu} = 0.80$, and $\Omega = 0.74$.
f. Determine rating factors:

   $RF_{inv} = (\phi \cdot V_n - 1.3 \cdot V_{DL}) / 2.17 \cdot V_{HS20LL}$

   $RF_{op} = (\phi \cdot V_n - 1.3 \cdot V_{DL}) / 1.3 \cdot V_{HS20LL}$

   If pedestrian live load is present, include entire amount when calculating rating factors:

   $RF_{inv} = (\phi \cdot V_n - 1.3 \cdot V_{DL} - 2.17 \cdot V_{ped\ LL}) / 2.17 \cdot V_{HS20LL}$

   $RF_{op} = (\phi \cdot V_n - 1.3 \cdot V_{DL} - 1.3 \cdot V_{ped\ LL}) / 1.3 \cdot V_{HS20LL}$
g. Cut a section through the gusset plate at a line normal to the chord that passes through the centerline of the joint and repeat steps above.

5) Check block shear in gusset plates.

a. Consider all truss joints with tension members. Check block shear considering fracture line for each tension member connection. Use engineering judgement to eliminate checking of similar member connections.
b. Determine nominal and factored resistance using LRFD 6.13.4.
c. Determine rating factors:

   $RF_{inv} = (R_r - 1.3 \cdot P_{DL}) / 2.17 \cdot P_{HS20LL}$

   $RF_{op} = (R_r - 1.3 \cdot P_{DL}) / 1.3 \cdot P_{HS20LL}$

   If pedestrian live load is present, include entire amount when calculating rating factors:

   $RF_{inv} = (R_r - 1.3 \cdot P_{DL} - 2.17 \cdot P_{ped\ LL}) / 2.17 \cdot P_{HS20LL}$

   $RF_{op} = (R_r - 1.3 \cdot P_{DL} - 1.3 \cdot P_{ped\ LL}) / 1.3 \cdot P_{HS20LL}$

6) Check edge buckling of gusset plates.
   a. Consider all truss joints with compression members. Use engineering judgement to eliminate checking of similar member connections.
   b. Check Guide Specs for Strength Design of Truss Bridges Article 1.11 requirement for length of unsupported edge:
      $b/t \leq 11{,}000 / \sqrt{F_y}$.
   c. If requirement is not met, the edge may need stiffening with an angle.

7) Check gusset plate buckling at end of diagonals.
   a. Consider all truss joints with compression diagonals. Use engineering judgement to eliminate checking of similar member connections.
   b. Determine "Whitmore effective width" (w_{wh}) for diagonal member.
   c. Determine DL and LL compression on a 1 inch wide portion of one gusset plate equal to $P_{DL} / 2 \cdot w_{wh}$ and $P_{HS20LL} / 2 \cdot w_{wh}$.
   d. Determine unbraced length of gusset plate in compression beyond the end of diagonal equal to the distance along the centerline of the diagonal from the center of the last row of rivets in the diagonal to the centerline of the closest rivet line in the horizontal chord.
   e. Determine buckling capacity for a 1 inch wide column with unbraced length as determined above per Std Specs 10.54.1.1. Use K = 1.00.
   f. Determine rating factors:
      $RF_{inv} = (\phi P_u - 1.3 \cdot p_{DL}) / 2.17 \cdot p_{HS20LL}$
      $RF_{op} = (\phi P_u - 1.3 \cdot p_{DL}) / 1.3 \cdot p_{HS20LL}$
      If pedestrian live load is present, include entire amount when calculating rating factors:
      $RF_{inv} = (\phi P_u - 1.3 \cdot p_{DL} - 2.17 \cdot p_{ped\ LL}) / 2.17 \cdot p_{HS20LL}$
      $RF_{op} = (\phi P_u - 1.3 \cdot p_{DL} - 1.3 \cdot p_{ped\ LL}) / 1.3 \cdot p_{HS20LL}$
   g. Repeat steps above, but use a K = 0.75. The range of results for both values of K will be considered upon completion of the review.

8) Check bearing and shear of rivets.
   a. Consider all truss joints. Use engineering judgement to eliminate checking of similar member connections.
   b. Determine number of rivets in single shear and in double shear based on the number and size of plates in the joint.
   c. Determine load per rivet due to maximum tension and compression loads for DL and LL.
   d. Determine the thickness of plates in bearing for the rivets in single shear and double shear.
   e. Determine factored bearing and shear capacity using Std Specs 10.56.1.3.
   f. Determine rating factors:
      $RF_{inv} = (\phi \cdot R - 1.3 \cdot p_{DL}) / 2.17 \cdot p_{HS20LL}$
      $RF_{op} = (\phi \cdot R - 1.3 \cdot p_{DL}) / 1.3 \cdot p_{HS20LL}$

If pedestrian live load is present, include entire amount when calculating rating factors:

$RF_{inv} = (\phi \cdot R - 1.3 \cdot p_{DL} - 2.17 \cdot p_{ped\ LL}) / 2.17 \cdot p_{HS20LL}$

$RF_{op} = (\phi \cdot R - 1.3 \cdot p_{DL} - 1.3 \cdot p_{ped\ LL}) / 1.3 \cdot p_{HS20LL}$

9) Checking fatigue stress in gusset plates due to riveted connections is deferred in accordance with Appendix F of the *Bridge Preservation, Improvement and Replacement Guidelines for Fiscal Year 2006 through 2008.* A fatigue analysis will be done when fatigue cracks are found or major work is planned for the bridge.

10) At the completion of each bridge review, provide the following documentation in the form of a printed report and electronic files:

a. This design review procedure document.
b. Copies of original plan sheets and shop drawings for the truss joints reviewed.
c. Copy of the latest inspection report.
d. A copy of the truss member load table sheet from the original plan (if available).
e. Sketches of the truss joints analyzed in flexure and shear showing the section cuts and dimensions used in the analysis.
f. The calculations for the truss joints reviewed, including the date and name of the engineers who did the review and check.
g. A summary table that reports all truss joints with an inventory and operating rating.

Attachment 1

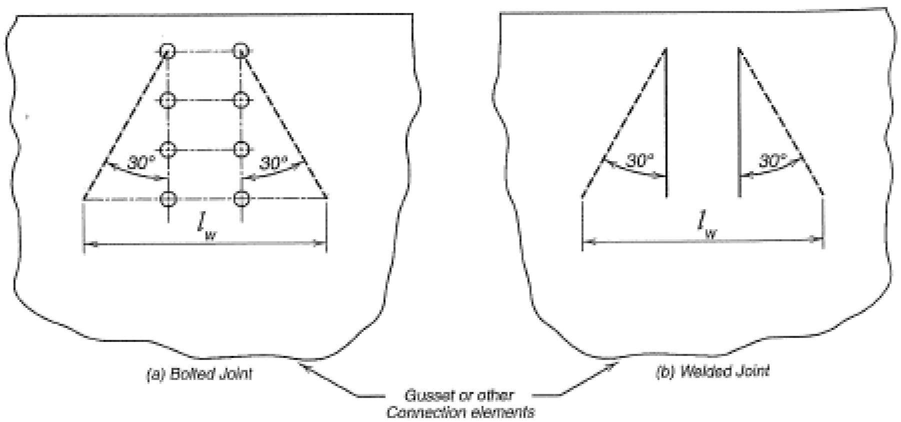


Figure 9–1. Illustration of the width of the Whitmore section.

AMERICAN INSTITUTE OF STEEL CONSTRUCTION, INC.

Mn/DOT Interpretation of Truss Bridge Gusset Plate Review Results

For a given truss, the results of the Mn/DOT Truss Bridge Gusset Plate Design Review include a spreadsheet that calculates inventory and operating rating factors (RF_{inv} and RF_{op}) of the gusset plates and a rating factor summary table for each joint in the truss. Ratings are included for the following scenarios:

- For rivet/bolt shear and bearing check, report ratings for capacity reduction factors CRF = 1.00 and CRF = 0.95, both with 0% section loss
- For all other checks, report ratings for capacity reduction factors CRF = 0.95 and CRF = 0.85, both with 0% section loss

After the spreadsheet is complete, a field inspection of the gusset plates must be scheduled to look for corrosion, section loss, missing rivets, or other distress in the plates. All joints must receive a visual inspection. Of particular concern are truss joints located in the salt spray zone, below deck joints, and below deck drains with a calculated RF_{op} less than or close to 1.00 for a CRF = 0.85. Check these joints thoroughly to verify that corrosion does not exceed 15%. Other critical joints include those located outside of the salt spray zone (such as joints in the top chord of a high truss) with RF_{op} less than or close to 1.00 for a CRF = 0.95. These joints should be field inspected to verify that corrosion does not exceed 5%. For the critical joints where corrosion loss measurements are taken during the inspection, revise the spreadsheet such that CRF = 1.00 and input the actual percentage of section loss.

The long term goal for all truss bridge gusset plates is an adequate rating factor based on analysis using the Mn/DOT Truss Bridge Gusset Plate Design Review Procedure (Mn/DOT Procedure). If this cannot be achieved, the short term goal is an adequate rating factor based on refined analysis until strengthening can be done (within two years). If neither goal is achieved, critical joints must be strengthened immediately. Therefore, the completed rating factor summary table results are to be interpreted in light of the following:

1) Joints with an operating rating factor $RF_{op} \geq 1.00$ for HS20 determined using the Mn/DOT Procedure that meet the edge buckling stiffness requirements of AASHTO LRFD Article 6.14.2.8 are considered adequate. However, all joints with an $RF_{op} < 1.30$ must also be evaluated for load posting.
2) For joints that do not meet the edge buckling stiffness requirements, if the HS20 operating rating factor $RF_{op} \geq 1.50$ with K = 1.00 for the interior plate buckling check, the joint is considered adequate. If $RF_{op} < 1.50$, a refined analysis based on the Dowswell paper and Salmon & Johnson (see below) must be completed. If the joint is shown to be adequate by the refined analysis, the bridge should be scheduled within two years for strengthening of the joint by adding edge stiffeners.

3) For joints that meet the edge buckling stiffness requirements, if the HS20 operating rating factor $RF_{op} \geq 1.00$ with $K = 0.75$ for the interior plate buckling check, the joint is considered adequate. If $RF_{op} < 1.00$, a refined analysis based on the Dowswell paper and Salmon & Johnson (see below) must be completed. If the joint is shown to be adequate using refined analysis, the bridge should be scheduled within two years for strengthening of the joint by adding angles to the compression area of the gusset plate. If it is decided not to strengthen the joint, load posting of the bridge is recommended based on the Mn/DOT Procedure rating.
4) For joints with an HS20 operating rating factor $RF_{op} < 1.00$ for shear governed by the gross section yield criterion, a refined analysis based on the paper by Drucker (see below) must be completed. If the joint is shown to be adequate using refined analysis, the bridge should be scheduled within two years for strengthening of the joint. For joints with RF_{op} values between 1.00 and 1.10 by the Mn/DOT Procedure, inspect the joint and perform any needed maintenance to guard against further deterioration. If it is decided not to strengthen the joint, load posting of the bridge is recommended based on the Mn/DOT Procedure rating.
5) For joints with an HS20 operating rating factor $RF_{op} < 1.00$ for the rivet bearing/shear check, reanalyze considering the rivet diameter to be equal to the size of the hole. If the joint is shown to be adequate using the hole diameter, the bridge should be scheduled within two years for strengthening of the joint.
6) For bridges subject to pedestrian loads that do not result in an acceptable operating rating factor based on the criteria above, consideration should be given to reducing the pedestrian load for calculation of the operating rating factor.

The refined analysis procedures for buckling and shear evaluation are given below. Refined analysis examples are available from the Bridge Office.

Based on the guidance given above, provide a summary report of the final HS20 inventory and operating rating for each truss joint. This will become a page of the final rating form package. Other forms required for the rating form package can be found at:

http://www.dot.state.mn.us/bridge/DocumentsFormsLinks/discDOCS.html

Refined Plate Buckling Check Per Dowswell Paper and Salmon & Johnson Book

This method is based on:

Bo Dowswell, *Effective Length Factors for Gusset Plate Buckling*, AISC Engineering Journal, 2nd Quarter, 2006

Salmon & Johnson, *Steel Structures: Design and Behavior*, 3rd Edition, Harper Collins Publishers Inc., 1990

Procedure:

1) Check whether section is compact (whether section can reach yield stress before sidesway buckling occurs) using Dowswell method.

   The section is compact for Dowswell method if:

   $t_{gp} \geq t_{\beta}$

   where t_{gp} = gusset plate thickness

   $t_{\beta} = 1.5 \cdot \sqrt{[F_y \cdot c^3/(E \cdot l_1)]}$

   F_y = yield stress

   c = minimum clear distance between last line of rivets in diagonal and rivet line in chord/vertical

   E = elastic modulus

   l_1 = clear distance between last line of rivets in diagonal and rivet line in chord/vertical measured along diagonal centerline

2) Check whether section is compact (whether section can reach yield stress before sidesway buckling occurs) using Salmon & Johnson method.

   Plates under uniform compression are governed by:

   $F_{cr} = k \cdot \{\pi^2 \cdot E / [12 \cdot (1-\mu^2) \cdot (b/t)^2]\}$

   where F_{cr} = elastic critical buckling stress for plates, ksi

   k = buckling coefficient

   E = elastic modulus, ksi

   μ = Poisson's ratio

   b = width of rectangular plate

   t = thickness of plate

   Determine F_{cr} for gusset plate assuming an equivalent rectangular plate with the following characteristics:

   E = 29000 ksi

   μ = 0.3

b = width of equivalent rectangular plate
a = length of equivalent rectangular plate
k = value from attached Figure 6.15.2 from Salmon & Johnson for fixed-fixed supports along unloaded edges and loaded edges fixed (dashed Curve A)

The section is compact for the Salmon & Johnson method if $F_{cr} > F_y$

3) Determine the capacity of the section in compression.

The section is considered compact for buckling only if it satisfies both of the compactness criteria found in 1) and 2).

If section is compact:

$\phi P_u = \phi \cdot F_y \cdot W_{wh} \cdot t$

where $\phi = 0.9$

F_y = yield stress

W_{wh} = Whitmore effective width

t = thickness of plate

If section is noncompact:

Determine ϕP_{uD} based on AASHTO Std. Specs. 10.54.1.1, using $\phi = 1.0$, K = 1.0, and a buckling length L_c equal to the average L_1, L_2, and L_3 per Dowswell paper.

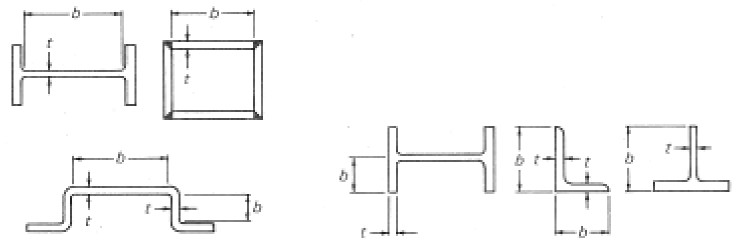
Determine ϕP_{uSJ} based on AASHTO Std. Specs. 10.54.1.1, using F_{cr} (if $F_{cr} > F_y$, take $F_{cr} = F_y$) calculated per Salmon & Johnson method.

Take ϕP_u as equal to the smallest of the values ϕP_{uD} and ϕP_{uSJ} calculated by the two above methods.

4) Determine HS20 operating rating factor RF_{op} based on ϕP_u calculated previously in 3).

Figure 6.15.2 taken from:

Salmon & Johnson, *Steel Structures: Design and Behavior,*
3rd Edition, Harper Collins Publishers Inc., 1990



(a) Elements supported along two edges (stiffened elements)

(b) Elements supported along one edge (unstiffened elements)

Fig. 6.15.1 Stiffened and unstiffened compression elements.

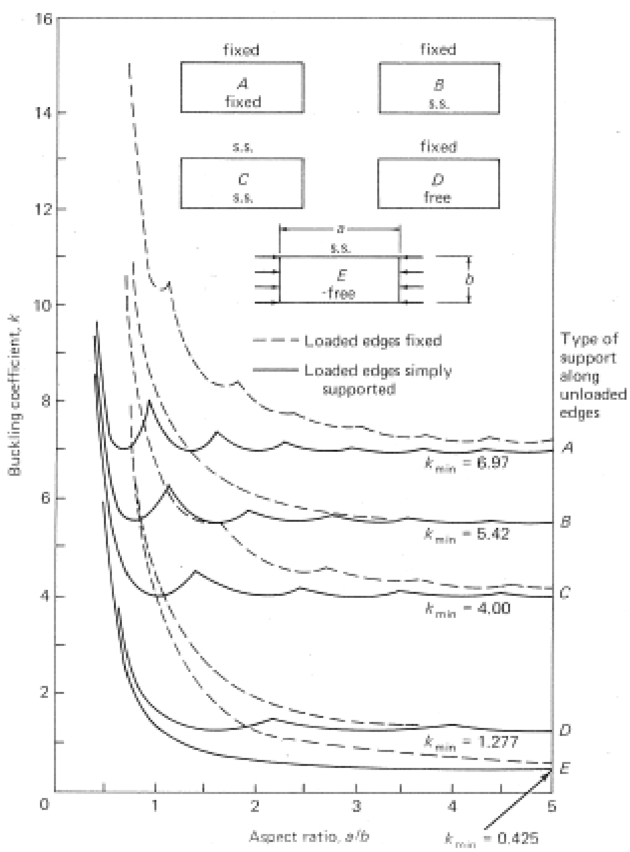


Fig. 6.15.2 Elastic buckling coefficients for compression in flat rectangular plates. (Adapted from Gerard and Becker [43])

Refined Shear Check Per Drucker Paper

This method is based on:
D. C. Drucker, *The Effect of Shear on the Plastic Bending of Beams*, National Applied Mechanics Division Conference, Urbana, IL, 1956, ASME

The paper considers the effects of normal stress acting in conjunction with shear at the critical section of a stable plate. Drucker recommends the following interaction equation:

$$M_u / M_0 \leq 0.98 \cdot [1-(V_u / V_0)^4]$$

where M_u = factored applied moment
M_0 = plastic moment capacity
V_u = factored applied shear
V_0 = plastic shear capacity = $0.58 \cdot F_y \cdot A$

Solve for V_u and add a resistance factor ϕ:

$$V_u \leq \phi \cdot [1-(M_u / 0.98 \cdot M_0)]^{1/4} \cdot (0.58 \cdot F_y \cdot A)$$

or

$$V_u \leq \phi \cdot \Omega \cdot (0.58 \cdot F_y \cdot A)$$

where $\Omega = [1-(M_u / 0.98 \cdot M_0)]^{1/4}$ (similar to equation found in FHWA guidance)

Note that for $M_u = M_y$, $V_u = 0.75V_0$ which is ≈ AASHTO value of $0.74V_0$

Procedure:

1) Determine factored applied shear V_u and moment M_u.

2) Determine plastic moment capacity M_0 :
$$M_0 = 1.5 \cdot M_y = 1.5\, F_y \cdot S$$

3) Determine shear/moment interaction reduction factor Ω :
$$\Omega = [1-(M_u / 0.98 \cdot M_0)]^{1/4}$$

4) Determine factored shear capacity $\phi \cdot V_n$, which is the smaller of:
$$\phi \cdot V_{ny} = \phi_{vy} \cdot \Omega \cdot (0.58 \cdot F_y \cdot A_g)$$
$$\phi \cdot V_{nu} = \phi_{vu} \cdot (0.58 \cdot F_u \cdot A_n)$$

5) Determine HS20 operating rating factor RF_{op} based on $\phi \cdot V_n$ calculated previously in 4).