# Crippling of Webs with Partial-Depth Stiffeners under Patch Loading

RAGHUVIR SALKAR, ABHISHEK SALKAR and WILLIAM DAVIDS

## ABSTRACT

Chapter J of the 2010 AISC *Specification* recommends the use of either single- or double-sided minimum half-depth transverse web stiffeners where web crippling strength is less than design concentrated load; use of a doubler plate of minimum half-web depth is also suggested in the *Specification*. Commentary on the *Specification* mentions that because the web crippling phenomenon has been observed to occur in the web adjacent to the loaded flange, a half-depth stiffener (or stiffeners) or a half-depth doubler plate is needed to eliminate web crippling. Research conducted at the University of Maine, however, clearly showed that web crippling can occur even in webs having half-depth stiffeners. Further, the AISC *Specification* does not have a formula to predict crippling strength of webs with partial-depth stiffeners under local compressive loads. This paper presents a formula for evaluating crippling strength of webs with partial-depth stiffeners that considers the effect of depth of stiffener, width of load and eccentricity of loading.

**Keywords:** web crippling, stiffened webs, transverse stiffeners, nominal resistance or ultimate stiffened web capacity.

## INTRODUCTION

Rolled shapes and built-up beams and girders can be subjected to local concentrated compressive loads acting in the plane of the web. Such loads can occur either over supports or between supports of beams and girders. Chapter J of the 2010 AISC *Specification* (AISC, 2010) recommends the use of either single- or double-sided minimum half-depth transverse web stiffeners or web doubler plates where web crippling strength is less than design concentrated load.

Commentary on the AISC *Specification* mentions that because the web crippling phenomenon has been observed to occur in the web adjacent to the loaded flange, a half-depth stiffener (or stiffeners) or a half-depth doubler plate is needed to eliminate web crippling. Research conducted at the University of Maine (Salkar, 1992), however, clearly showed that web crippling can occur in webs having half-depth stiffeners. Therefore, it is important that formulas or procedures are made available for evaluating crippling strength of webs with partial-depth stiffeners.

Although Chapter J of the 2010 AISC *Specification* has formulas for predicting strength of unstiffened webs and stiffened webs with full-depth stiffeners under local compressive loads, it does not have any formula to predict crippling strength of webs with partial-depth stiffeners under local compressive loads. Research on the behavior and design rules of intermediate transverse stiffeners attached on web panels was summarized by Lee et al. (2002, 2003). Research on the requirements of transverse stiffeners in straight and horizontally curved steel I-girders was summarized by Kim et al. (2007). Research on unstiffened webs under compressive edge loads was summarized by Elgaaly (1983). Research on the same topic post-1983 was summarized by Salkar (1992) at the University of Maine.

This paper highlights part of the research at the University of Maine and gives recommendations based on the results of this research. This paper also presents a brief comparison of provisions of the 2010 AISC *Specification*, Canadian codes (CSA, 2006) and Australian (AS, 2012) codes with respect to crippling strength of stiffened webs under local compressive loads.

This paper addresses the strength of stiffened webs of rolled shapes under local compressive patch loads between supports. Three types of local compressive patch loading have been considered:

1. Loading through roller on top flange as shown in Figure 1.

2. Loading through patch plate on top flange as shown in Figure 2.

3. Loading through I-shaped beam on top flange as shown in Figure 3.

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Various parameters considered are depth of stiffener ($d_s$), thickness of stiffener ($t_s$), width of loading ($N$) and eccentricity of load ($e_1$) with respect to plane of stiffener. Stiffeners considered in this paper were welded to the web and the loaded flange, but likely transferred part of the load through bearing, similarly to fitted stiffeners with no weld between the stiffener and flange.

## RESEARCH AT UNIVERSITY OF MAINE

Research carried out at the University of Maine on the crippling strength of stiffened webs of rolled shapes was sponsored in part by AISC. Salkar (1992) conducted research on intermediate transverse load-bearing stiffeners for rolled shapes, which is summarized in this section. One of the main objectives of the research was to evaluate the then-current 1986 AISC *Specification* (AISC, 1986) design formulas and procedures that predict the strength of stiffened webs and, if necessary, derive new ones. The evaluation was done through experimental investigation as well as analytical work using finite element analysis.

**Experimental Investigation**

As a part of the experimental work, 27 rolled beams (W16×26 and W12×14) were tested in a Baldwin Testing Machine, and various values of stiffener thickness, $t_s$, depth of stiffener, $d_s$, eccentricity of load with respect to the plane of stiffeners, $e_1$, and width of patch load, $N$, were considered as test parameters. Small values of eccentricity up to 0.5 in., which can occur due to fabrication and construction tolerances, were considered. These 27 tests were divided into three groups, of which only group 3 tests were considered for analysis because the yield stress values of the stiffeners were not known for groups 1 and 2.

In all 17 tests of group 3, W16×26 rolled sections were used as test specimens, and the ratio of the length of the beam to its depth ($b/d$) was 2.3. Three methods of load application on the top flange were considered—namely, loading through a plate, an I-beam and a roller. It was noted that loading through a roller and an I-beam gave similar results. The details of the 17 tests conducted by Salkar (1992) during his experimental work are summarized in Table 1. In this table, $P_{tst}$ refers to the test failure load and $F_{yw}$ and $F_{ys}$
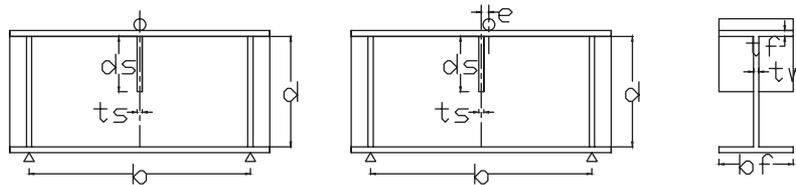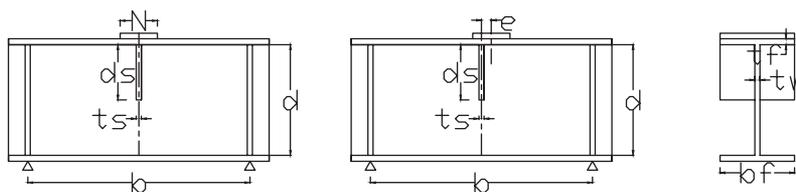


*Fig. 1.  Loading through roller on top flange.*
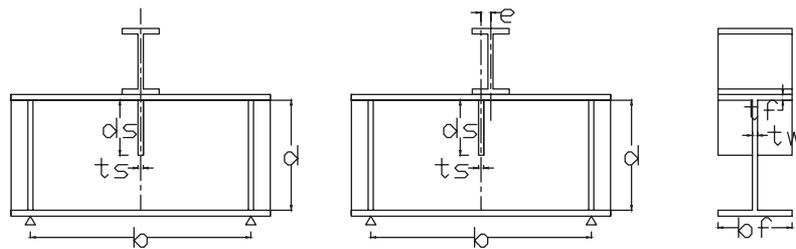


*Fig. 2.  Loading through patch plate on top flange.*



*Fig. 3.  Loading through I-shaped beam on top flange.*

| Test No. | $t_w$ in. | $t_f/t_w$ | $b_f/t_f$ | $d/t_w$ | $t_s/t_w$ | $d_s/d$ | $N/d$ | $e_1$ in. | $F_{yw}$ ksi | $F_{ys}$ ksi | $P_{tst}$ kips | Load Application Method |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.262 | 1.23 | 17.2 | 59.9 | 0.653 | 0.5 | 0.303 | 0 | 48 | 55 | 161.1 | Patch plate |
| 2 | 0.254 | 1.24 | 17.4 | 61.5 | 0.673 | | 0 | 0.5 | 49 | 55 | 107.0 | Roller |
| 3 | 0.262 | 1.22 | 17.2 | 59.9 | 0.653 | | 0.303 | | 46 | 55 | 161.6 | Patch plate |
| 4 | 0.249 | 1.29 | 17.2 | 62.8 | 0.695 | | 0 | 0 | 47 | 53 | 114.0 | Roller |
| 5 | 0.253 | 1.36 | 16.0 | 61.8 | 0.961 | | 0.304 | | 49 | 48 | 169.1 | Patch plate |
| 6 | 0.250 | 1.26 | 17.5 | 62.5 | 0.972 | | 0 | 0.5 | 52 | 48 | 120.0 | Roller |
| 7 | 0.260 | 1.31 | 16.2 | 60.3 | 0.935 | | 0.304 | | 48 | 48 | 161.0 | Patch plate |
| 8 | 0.255 | 1.27 | 17.0 | 61.3 | 0.949 | | 0 | 0 | 47 | 48 | 144.0 | Roller |
| 9 | 0.256 | 1.31 | 16.5 | 61.0 | 1.23 | | 0.303 | | 49 | 47 | 175.2 | Patch plate |
| 10 | 0.251 | 1.29 | 17.0 | 62.5 | 1.25 | | 0 | 0.5 | 49 | 47 | 127.5 | Roller |
| 11 | 0.258 | 1.27 | 16.8 | 60.8 | 1.22 | | | | 50 | 47 | 148.8 | Roller |
| 12 | 0.264 | 1.29 | 16.1 | 59.2 | 1.19 | | | | 44 | 49 | 150.0 | Roller |
| 13 | 0.253 | 1.34 | 16.2 | 61.8 | 0.676 | 0.75 | 0 | 0 | 47 | 45 | 126.0 | Roller |
| 14 | 0.263 | 1.29 | 16.1 | 59.4 | 0.932 | | | | 46 | 48 | 153.6 | Roller |
| 15 | 0.263 | 1.28 | 16.3 | 59.4 | 1.18 | | | | 46 | 48 | 164.0 | Roller |
| 16 | 0.262 | 1.26 | 16.7 | 59.6 | 0.920 | | | 0.5 | 46 | 48 | 132.1 | Roller |
| 17 | 0.255 | 1.29 | 16.7 | 61.3 | 0.945 | | 0.303 | 0 | 47 | 48 | 145.3 | I-section W4×13 |

Table 1. Tests on Webs with Intermediate Load-Bearing Stiffeners

refer to the yield stress of the web and stiffener material, respectively.

### *Modes of Failure*

Three modes of failure were observed in the preceding 17 tests: web crippling below the stiffener, local stiffener crippling and global stiffener crippling. In the following description of the failure modes, the photographs in Figures 4 through 9 were originally published by Elgaaly et al. (1992).

1. *Failure mode 1, web crippling below the stiffener:* Yielding in the web below the bottom of the stiffener with or without excessive yielding in the stiffener led to the web crippling failure mode and was seen in case of all half-depth stiffeners where the load was applied through a plate. It was also seen in the case of specimens with thick half-depth stiffeners subjected to concentric loading through a roller. Figures 4 and 5 show test specimens that failed in this mode.

2. *Failure mode 2, local stiffener crippling:* This occurred in beams with thin to moderately thick half-depth stiffener under concentric loading through a roller. It was also noted in all specimens subjected to eccentric roller loads. In this failure mode, one of the stiffeners crippled with either some or no crippling in adjacent

web. Figures 6 and 7 show test specimens that failed in this mode.

3. *Failure mode 3, global stiffener crippling:* This was found to occur in all specimens with deep stiffeners, subjected to concentric loads through a roller or an I-beam. In this failure mode, a cross-section comprised of both stiffeners and part of the web on each side of the stiffeners crippled together. Figures 8 and 9 show test specimens that failed in this mode.

It is worth noting that web crippling below the stiffeners (failure mode 1) occurred where webs had half-depth stiffeners. This type of failure, however, was not seen in webs with three-quarters-depth stiffeners. This observation led to one of the important conclusions and recommendations of this paper.

### Finite Element Analysis (FEA)

A nonlinear finite elemental analysis was carried out using the modified version of the program NONSAP. The original version was developed by Bathe et al. (1974) at the University of California, Berkeley, and modifications were made by Du (1991) at the University of Maine. The main objectives of the analysis were to obtain a better picture of the stiffened web behavior and to conduct a parametric study to

determine the effect of various parameters $t_s$, $d_s$, $e_1$ and $N$ on the stiffened web strength.

A three-dimensional isoparametric shell element was used to discretize the specimens. The eight-node isoparametric doubly curved shell element had six degrees of freedom per node—namely, the displacements along and the rotations about the $x$, $y$ and $z$ axes. It was the degeneration of the well-known quadratic isoparametric hexahedron. The Updated Lagrangian formulation was employed for considering large displacements. For materially nonlinear analysis, an elastic plastic material model was employed. The nonlinear material model employed the von Mises yield criterion, the Prandtl-Reuss flow rule and isotropic hardening. Hardening

was used because an elastic perfectly plastic material model would have slowed or prevented convergence; the hardening modulus was selected to be 1,000 ksi (about 3.5% of the elastic modulus).

Finite element analyses were conducted to study the web behavior and strength for the following cases. This paper, however, deals only with the fourth case of stiffened stocky webs.

1. Slender and stocky webs under loads in the plane of the web and acting between the supports at the beam mid-span—in-plane interior loading.

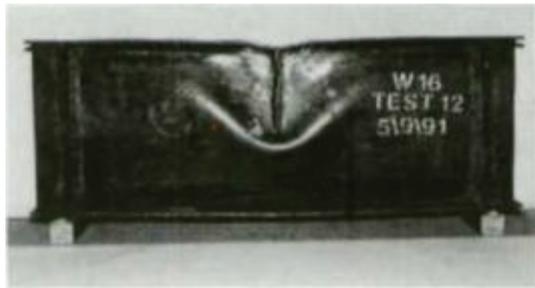2. Slender and stocky webs under interior loads at an



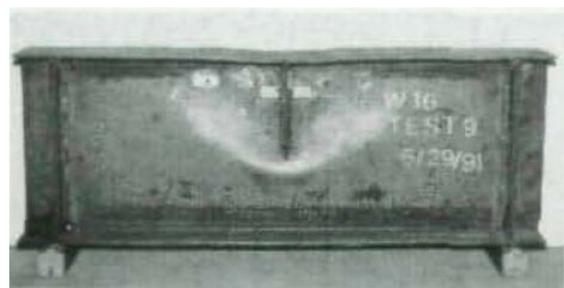*Fig. 4. Failure mode 1—web crippling below stiffeners (test 12).*



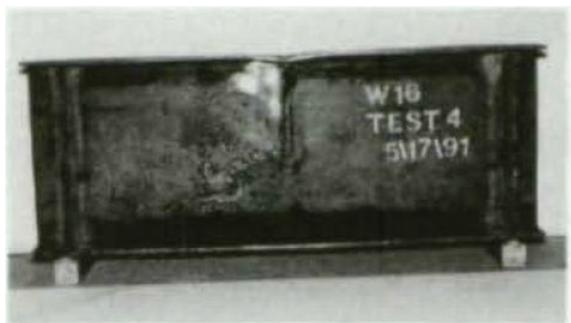*Fig. 5. Failure mode 1—web crippling below stiffeners (test 9).*



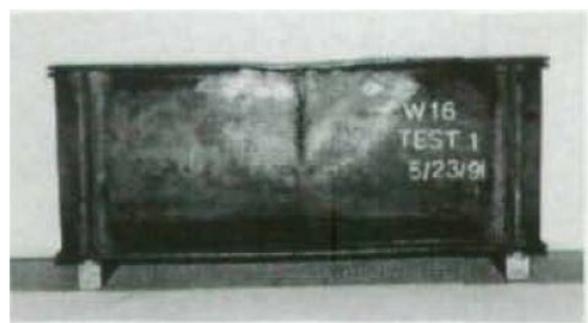*Fig. 6. Failure mode 2—local stiffener crippling (test 4).*



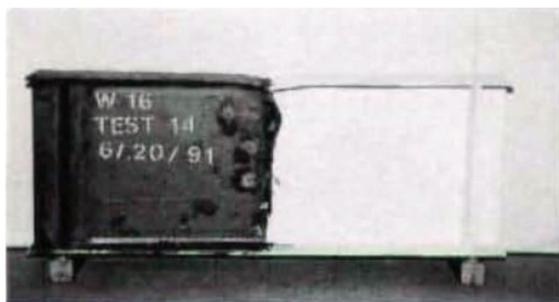*Fig. 7. Failure mode 2—local stiffener crippling (test 1).*



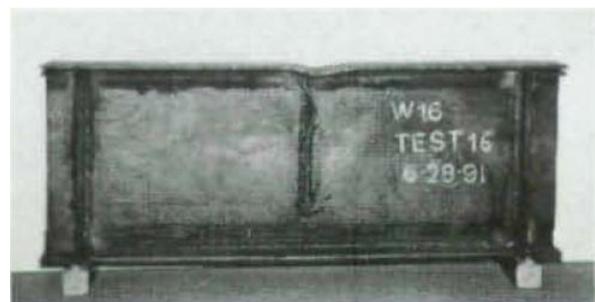*Fig. 8. Failure mode 3—global stiffener crippling (test 14).*



*Fig. 9. Failure mode 3—global stiffener crippling (test 16).*

| Table 2.  Boundary Conditions (Refer to Figure 4) | | | | | | |
|---|---|---|---|---|---|---|
| | Displacements In | | | Rotations About | | |
| Location | X | Y | Z | X | Y | Z |
| Lines ABC and DEF | 1 | 1 | 1 | 1 | 1 | 0 |
| Lines GHI and JKL | 0 | 1 | 1 | 1 | 1 | 0 |
| Lines BH and EK, excluding B, H, E, K | 0 | 1 | 1 | 1 | 0 | 0 |

1 = degree of freedom is restrained
0 = degree of freedom is not restrained

| Table 3.  Comparison of Test Results with FEA Results | | | | | | |
|---|---|---|---|---|---|---|
| Test No. | $t_s$ in. | $d_s/d$ | Test Results kips | Test/ Predicted | FEA Predicted Failure Mode | Experimentally Observed Failure Mode |
| 4 | 0.172 | 0.5 | 114.0 | 1.12 | Failure mode 2 | Failure mode 2 |
| 6 | 0.243 | | 120.0 | 0.914 | Failure mode 2 | Failure mode 2 |
| 8 | 0.243 | | 144.0 | 1.03 | Failure mode 2 | Failure mode 2 |
| 11 | 0.313 | | 148.8 | 1.02 | Failure mode 1 | Failure mode 1 |
| 13 | 0.172 | 0.75 | 126.0 | 1.06 | Failure mode 3 | Failure mode 3 |
| 14 | 0.243 | | 153.6 | 0.96 | Failure mode 3 | Failure mode 3 |

eccentricity with respect to the web plane—eccentric interior loading.

3. In-plane loads on stocky webs acting at the supports—in-plane exterior loads.

4. In-plane interior loads on transversely stiffened stocky webs, acting concentric or eccentric with respect to the vertical axis of the stiffener.

Figure 10 shows a typical finite element mesh that was used to study transversely stiffened webs under in-plane interior loads. The load was either concentric or eccentric with respect to the vertical axis of the stiffener. The mesh was made up of 216 shell elements and 705 nodes. The effect of the end stiffener was considered by imposing certain boundary conditions on the corresponding nodes as shown in Table 2.

The finite element model performed satisfactorily when used to predict failure loads for tests with in-plane interior loading. Table 3 shows a comparison between the test and the predicted failure loads. All six tests listed in the table were conducted on W16×26 rolled sections and were a part of the 17 tests of Table 1. In these tests, the ratio of the stiffener to web depth was 0.5 or 0.75, and the load eccentricity with respect to the vertical axis of the stiffener was 0 or 0.5 in. The values of other parameters, such as $t_w$, $t_f/t_w$, $b_f/t_f$, $d/t_w$, $F_{yw}$ and $F_{ys}$, were taken as the average values of the 17 tests of Table 1. The average value of the ratio of the test to the finite element analysis failure load was 1.017. Thus, the finite element analysis was able to predict the test results to a very good degree of accuracy.

Note: In all tests, $N/d$ was 0, and the load eccentricity with respect to the stiffener center line ($e_1$) was 0, except in test 6, where it was 0.5 in. As described earlier, three modes of failure—web crippling below the stiffener, local stiffener crippling and global stiffener crippling—were observed in the FEA results. As may be noted from Table 3 and Figures 11, 12 and 13, the finite element analysis was able to predict these failure modes accurately.

Because the finite element model was found to accurately predict failure loads and failure modes, it was used to conduct a parametric study to determine the effect of parameters $t_s$, $d_s$, $e_1$ and $N$ on the stiffened web strengths. The parametric study was conducted using W16×26 and W12×14 rolled beam sections. The $t_s/t_w$ values varied from 0.625 to 1.22, $d_s/d$ was 0.5 or 0.75, $N/d$ was varied from 0 to 0.4, and $e_1$ was 0 or 0.5 in.

Results of the parametric study are given in Table 4. One of the important observations of the parametric study is presented in Figure 11. It shows a graph of web crippling strength, $P_{fea}$, versus ratio of stiffener to web thickness,

$(t_s/t_w)$, for half-depth and three-quarters-depth stiffeners, indicating that few gains in capacity are observed as stiffener thickness, $t_s$, is increased beyond $t_w$.

**Summary of Experimental and FEA Investigations**

Experimental as well as finite-element based analytical research at the University of Maine led to the following conclusions, which are applicable for rolled beams, and for the parameters $N/d$ up to 0.3, $e_1$ up to 0.5 in., and $d_s/d$ value up to 0.75.

1. As may be noted from Figure 14, web strength increases with $t_s$ up to a certain optimum value of $t_s$, beyond which the increase in strength is not significant. This optimum value was found to be approximately the thickness of the web (valid only for rolled shapes) for all rolled shapes considered in this study.
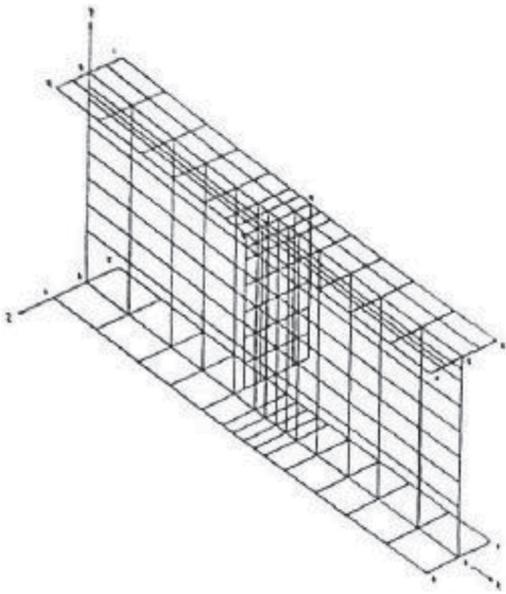


Fig. 10. Finite element mesh for stiffened stocky webs under in-plane (concentric and eccentric) interior loads.
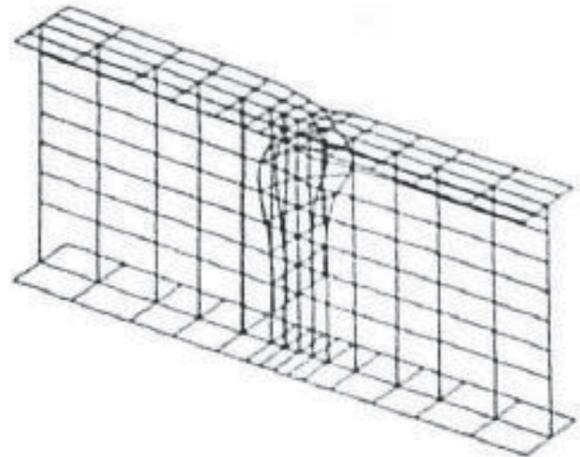


Fig. 11. Three-dimensional view of the deformed beam near failure ($t_s = \frac{1}{4}$, $d_s/d = \frac{3}{4}$, $N/d = 0$, $e_1 = 0$). Failure mode 3.
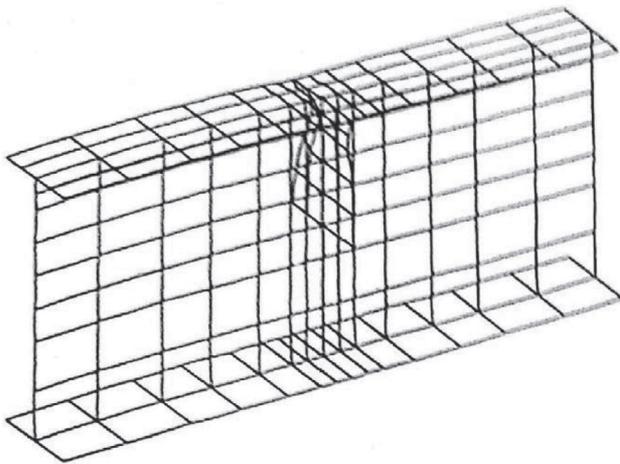


Fig. 12. Three-dimensional view of the deformed beam near failure ($t_s = \frac{3}{16}$, $d_s/d = \frac{1}{2}$, $N/d = 0$, $e_1 = 0$). Failure mode 2.
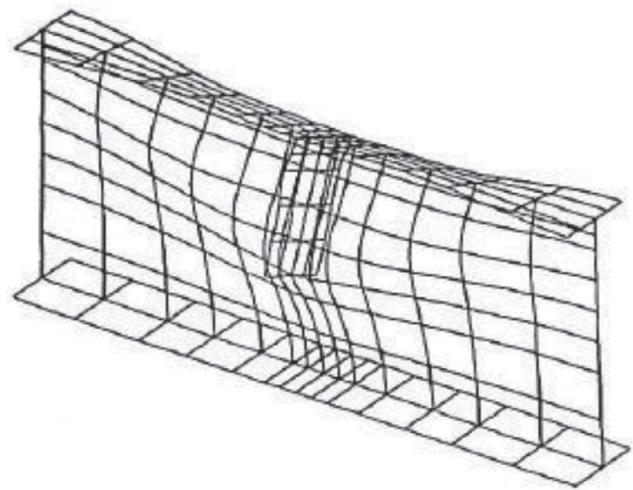


Fig. 13. Three-dimensional view of the deformed beam near failure ($t_s = \frac{5}{16}$, $d_s/d = \frac{1}{2}$, $N/d = 0$, $e_1 = 0$). Failure mode 1.

| No. | Section | $t_s/t_w$ | $d_s/d$ | $N/d$ | $e_1$ in. | $F_{yw}$ ksi | $F_{ys}$ ksi | $P_{fea}$ kips |
|---|---|---|---|---|---|---|---|---|
| 1 | W16×26 | 0.669 | 0.5 | 0 | 0 | 48 | 53 | 102 |
| 2 | | 0.944 | 0.5 | 0.3 | 0 | 48 | 48 | 159 |
| 3 | | 0.944 | 0.5 | 0 | 0.5 | 48 | 48 | 131 |
| 4 | | 0.944 | 0.5 | 0 | 0 | 48 | 48 | 141 |
| 5 | | 1.22 | 0.5 | 0 | 0 | 48 | 48 | 147 |
| 6 | | 0.699 | 0.75 | 0 | 0 | 48 | 53 | 119 |
| 7 | | 0.944 | 0.75 | 0 | 0 | 48 | 48 | 160 |
| 8 | W12×14 | 0.625 | 0.5 | 0 | 0 | 36 | 36 | 36 |
| 9 | | 0.780 | 0.5 | 0 | 0 | 36 | 36 | 51 |
| 10 | | 0.940 | 0.5 | 0 | 0 | 36 | 36 | 63 |
| 11 | | 1.00 | 0.5 | 0 | 0 | 36 | 36 | 65 |
| 12 | | 1.125 | 0.5 | 0 | 0 | 36 | 36 | 66 |
| 13 | | 0.940 | 0.5 | 0.2 | 0 | 36 | 36 | 70 |
| 14 | | 0.940 | 0.5 | 0.4 | 0 | 36 | 36 | 77 |
| 15 | | 0.940 | 0.5 | 0 | 0.5 | 36 | 36 | 50 |

Table 4. Results of FEA Parametric Study

2. As may be noted from Table 4, increase in $d_s$ from $0.5d$ to $0.75d$ increased stiffened web crippling strength by about 15%. Web strength increased linearly with $N$. The values of $N/d$ were limited to 0.3, and this is the limit in most practical cases.

3. It was noted that eccentric loading through a plate had negligible effect on the stiffened web crippling strength, while eccentric loading through a roller or an I-beam reduced the stiffened web strength considerably.

4. The extent to which the eccentricities of load reduce the stiffened web crippling depends directly upon the magnitude of $e_1$, and also factors $t_f/t_w$ and $t_f/t_s$.
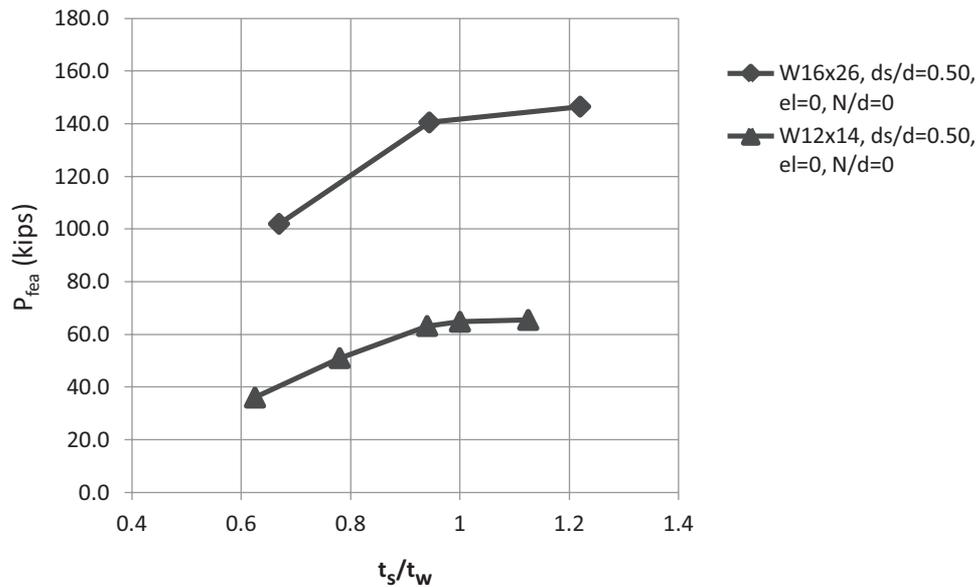


Fig. 14. Effect of stiffener thickness on stiffened web crippling strength.

5. It was noted that relatively thick stiffeners as well as sufficiently wide load patches could cause crippling in the web below the stiffener when it is 0.5*d* deep. This was not found to occur when the stiffener extended 0.75*d*. This observation does not support AISC *Specification* recommendation that stiffener of 0.5*d* depth is sufficient to eliminate the limit state of web crippling. This observation also suggests that it is not desirable to have stiffener thickness higher than web thickness, and this led to one of the conclusions and recommendations of this paper.

## DEVELOPMENT OF DESIGN EQUATION

The results of the parametric study were used with the test results to develop a formula to predict the stiffened web capacity, $P_u$, given by:

$$P_u = K + F_{ys}t_s b_s (R)(2d_s/d)^X \qquad (1)$$

where $K$ is defined as:

$$K = 0.80t_w^2 \left\{ 1 + 3\left(N/d\right)\left(t_w/t_f\right)^{1.5} \right\} \left(EF_{yw}t_f/t_w\right)^{0.5} \qquad (2)$$

$$R = 2e_1 \left\{ \left(t_f/t_w\right)^{0.5}\left(t_f/t_s\right)^{0.5}/1.55 - 1 \right\} + 1 \qquad (3)$$

$$X = 0.50\left(d/d_s\right) \qquad (4)$$

$b_s$ = twice the width of the front or back stiffener

Equation 1 is valid only if the stiffener satisfied the width-to-thickness compactness criteria; that is, the ratio of the width of stiffener (front to back) to its thickness should not exceed $0.56\left(E/F_{ys}\right)^{0.5}$. The effectiveness of this formula is discussed later in this paper when the test results are compared with the predictions of several design codes.

## PROVISIONS FOR TRANSVERSE STIFFENERS IN VARIOUS CODES

This section presents design specifications and formulas of various international codes to calculate the strength of webs with full-depth stiffeners under patch compressive loads. The Canadian code (CSA S16-01, 2006), the Australian code (AS, 2012) and the 2010 AISC *Specification for Structural Steel Buildings* (AISC, 2010) have been selected for comparison. None of these codes contains formulas to predict crippling strength of webs with partial-depth stiffeners. In the absence of such a formula for partial-depth stiffeners, strength of webs with full-depth stiffeners as predicted by formulas from these three codes have been compared with the test results conducted at the University of Maine.

## Design Specifications of Canadian Code CSA S16-01 2006

Canadian code CSA S16-01 2006 (CSA, 2006) provides formulas to evaluate bearing strength of web with full-depth stiffeners under compressive load on flanges, as given in Equation 5. According to Section 14.4 of CSA S-16-01, the ultimate stiffened web capacity is given by:

$$P_u = AF_y\left(1 + \lambda^{2n}\right)^{-1/n} \qquad (5)$$

where
  $n$ = 1.34
  $F$ = yield stress value
  $A$ = area of cross-section consisting of the pair of stiffeners and a centrally located strip of the web equal to not more than 25 times its thickness

$$\lambda = \left(KL/r\right)\left(F_y/\pi^2 E\right)^{0.5} \qquad (6)$$

Here, $E$ is the elastic modulus of steel, $KL$ shall be taken as not less than three-fourths of the length of the stiffeners and $r$ is the radius of gyration about the minor axis.

## Design Specifications of Australian Code AS 4100 2012

Australian code AS 4100 2012 (AS, 2012) provides formulas to evaluate bearing strength of web with full-depth stiffeners under compressive load on flanges, as given in Equations 8 and 11. Section 5.14 of AS 4100 deals with the design of load-bearing stiffeners. It states that when a load-bearing stiffener is required, the following two conditions should be satisfied:

### 1. Yield Capacity

$$P_x \leq R_{sy} \qquad (7)$$

where
  $P_x$  = the design bearing force
  $R_{sy}$ = the nominal yield capacity of the stiffened web and
  $$R_{sy} = 1.25\, b_{bf}t_w f_y + A_s f_y \qquad (8)$$
  $A_s$  = area of the stiffener in contact with the flange
  $f_y$   = maximum yield stress value of steel
  $$b_{bf} = N + 5t_f \qquad (9)$$

### 2. Buckling Capacity

This section is applicable for slender webs and not for rolled sections that have stocky webs. For the sake of completeness, however, procedure and formulas for calculating buckling capacity has been given here:

$$P_x \leq R_{sb} \qquad (10)$$

where $R_{sb}$ is the nominal buckling capacity of the stiffened web and is determined by the following procedure according to Section 6 of AS 4100:

$$R_{sb} = \alpha_c N_s \leq N_s \qquad (11)$$

where

$$\alpha_c = \xi\left\{1 - \left[1 - (90/\xi\lambda)^2\right]^{0.5}\right\} \qquad (12)$$

$$\xi = \left\{(\lambda/90)^2 + 1 + \eta\right\}/2(\lambda/90)^2 \qquad (13)$$

$$\eta = 0.00326(\lambda - 13.5) \geq 0 \qquad (14)$$

$$\lambda = \lambda_n + \alpha_a\alpha_b \qquad (15)$$

$$\lambda_n = (L_e/r)(k_f)^{0.5}(f_y/250)^{0.5} \qquad (16)$$

$$\alpha_a = \left\{2100(\lambda_n - 13.5)\right\}/\left(\lambda_n^2 - 15.3\,\lambda_n + 2050\right) \qquad (17)$$

$\alpha_b = 0.5$, the appropriate member section constant given in Table 6.3.3 of the Code

$k_f = 1$, as determined in Section 6.2.2 of the Code

$L_e = 0.7d_1$ where $d_1$ = clear depth between flanges ignoring fillets and welds

$r$ = radius of gyration about the minor axis

$$N_s = k_f A_n f_y \qquad (18)$$

$A_n$ = net area of cross-section consisting of the pair of stiffeners and a centrally located strip of the web of width not greater than the lesser of $17.5t_w/\sqrt{(f_y/250)}$ and $s/2$, where $s$ = spacing of stiffeners

### AISC *Specification for Structural Steel Buildings* 2010

Section J10.8 of the AISC *Specification* (AISC, 2010) provides a procedure to evaluate the strength of webs with full-depth stiffeners under compressive load on flanges, as given in Equation 19. As per Section J10.8, transverse full-depth bearing stiffeners for compressive forces applied to a beam or plate girder flange(s) shall be designed as axially compressed members (columns) in accordance with the requirements of Sections E6.2 and J4.4. The member properties shall be determined using an effective length of $0.75h$, a cross-section composed of two stiffeners, and a strip of the web having a width of $25t_w$ at interior stiffeners and $12t_w$ at the ends of members.

As mentioned earlier, Section J10.8 requires that provisions of Section J4.4 be used to evaluate strength of full-length bearing stiffeners under concentrated loads. Section J4.4 states that the available strength of connecting elements in compression for the limit states of yielding and buckling can be determined as follows:

(a) When $KL/r \leq 25$ (yielding)

$$P_n = F_y A_g \qquad (19)$$

with

$\phi = 0.90$

$F_y$ = specified minimum yield stress

$A_g$ = gross area of a cross-section composed of two stiffeners and a strip of the web having a width of 25 times the thickness of the web

$r$ = radius of gyration about the minor axis

$KL = 0.75h$, where $h$ is the clear distance between the flanges less the fillet or corner radius

(b) When $KL/r > 25$ (buckling), the provisions of Chapter E apply.

Because $KL/r \leq 25$ for all tests reported here, provisions of Section J4.4 (b) are not applicable.

### Comparison of Test Results with Nominal Capacity Values and Predictive Equation

A comparison between the test results conducted at the University of Maine and the stiffened web strengths predicted by the AISC, CSA and AS design codes as well as the proposed formula are presented in Table 5.

The average ratios of test results to the predicted failure loads were found to be 1.03 for both AISC and CSA, 1.36 for AS and 0.98 for the proposed formula. The coefficients of variation were found to be 0.13 for both AISC and CSA, 0.22 for AS and 0.05 for the proposed formula. Hence, it may be said that the proposed formula is more consistently able to predict stiffened web strength. Further, the proposed formula is able to evaluate the crippling strength of webs with partial-depth stiffeners and eccentric loading, unlike the design codes.

## CONCLUSIONS AND RECOMMENDATIONS

The provisions given in the 2010 AISC *Specification* (AISC, 2010) for calculating the stiffened web strength may be reexamined in the light of the information provided here:

1. Presently, the AISC *Specification* recommends half-depth stiffeners or doubler plates for eliminating web crippling limit state. This, however, is not correct for web crippling under patch loading; failure mode 1, which is web crippling failure below the stiffener, occurs when stiffeners are half depth. Based on the research at the University of Maine, it is recommended that webs shall be provided with minimum three-quarters-depth web stiffeners for eliminating web crippling limit state.

2. Presently, the AISC *Specification* does not recommend any specific optimum thickness for the stiffener. As may be noted from the test results shown in Table 1 and the FEA parametric study (in particular, Table 4 and Figure 14), web strength increased with increase

| Test No. | Test Results kips | AISC Results (AISC) kips | Canadian Results (CSA) kips | Australian Results (AS) kips | Proposed Formula (Eq. 1) kips | Test/AISC | Test/CSA | Test/AS | Test/ Proposed Formula |
|---|---|---|---|---|---|---|---|---|---|
| | | | | **Table 5: Comparison of Test Results with Design Codes and Proposed Formula** | | | | | |
| 1 | 161 | 135 | 135 | 154 | 169 | 1.20 | 1.20 | 1.05 | 0.95 |
| 2 | 107 | 130 | 130 | 72 | 116 | 0.82 | 0.82 | 1.48 | 0.92 |
| 3 | 162 | 132 | 132 | 150 | 165 | 1.23 | 1.23 | 1.08 | 0.98 |
| 4 | 114 | 123 | 123 | 70 | 114 | 0.93 | 0.93 | 1.62 | 1.00 |
| 5 | 169 | 139 | 139 | 161 | 173 | 1.21 | 1.21 | 1.05 | 0.98 |
| 6 | 120 | 142 | 142 | 89 | 120 | 0.84 | 0.84 | 1.36 | 1.00 |
| 7 | 161 | 142 | 142 | 162 | 171 | 1.13 | 1.13 | 0.99 | 0.94 |
| 8 | 144 | 138 | 138 | 85 | 129 | 1.05 | 1.05 | 1.69 | 1.12 |
| 9 | 175 | 158 | 158 | 178 | 193 | 1.11 | 1.11 | 0.98 | 0.91 |
| 10 | 128 | 154 | 154 | 103 | 126 | 0.83 | 0.83 | 1.23 | 1.02 |
| 11 | 149 | 161 | 161 | 106 | 150 | 0.93 | 0.93 | 1.41 | 0.99 |
| 12 | 150 | 157 | 157 | 102 | 152 | 0.96 | 0.96 | 1.47 | 0.99 |
| 13 | 126 | 115 | 115 | 66 | 122 | 1.10 | 1.10 | 1.92 | 1.03 |
| 14 | 154 | 141 | 141 | 86 | 153 | 1.09 | 1.09 | 1.79 | 1.01 |
| 15 | 164 | 157 | 157 | 102 | 174 | 1.04 | 1.04 | 1.61 | 0.94 |
| 16 | 132 | 140 | 140 | 85 | 139 | 0.94 | 0.94 | 1.56 | 0.95 |
| 17 | 145 | 137 | 137 | 157 | 148 | 1.06 | 1.06 | 0.92 | 0.98 |

in stiffener thickness and is maximum when stiffener thickness is almost equal to web thickness. Further, it was noted from tests on half-depth stiffeners that when stiffener thickness exceeded web thickness, web crippling occurred under the stiffeners. Therefore, it is recommended that the stiffener thickness be approximately the thickness of the web.

3. Presently, the AISC *Specification* recommends the use of half-depth stiffener to eliminate the web crippling limit state. It, however, does not provide any direct formula to evaluate enhanced web strength due to addition of a half-depth stiffener. Equation 1 provides a means for evaluating stiffened web crippling strength because it considers the effect of all the parameters—namely, depth of stiffener, thickness of stiffener, eccentricity of loading and width of loading—and compares well with the test results, as illustrated in Table 5.

4. Equation 1 could be useful for evaluating the remaining strength of webs with full-depth stiffeners where the bottom portion of the stiffener has been badly corroded. Such an evaluation may be necessary in older structures requiring retrofit and also in structures that are anticipated to be overloaded in specific areas.

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