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Design of cold-formed steel structural members and connections for cyclic loading (fatigue)

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Final Report

DESIGN OF COLD-FORMED STEEL STRUCTURAL MEMBERS AND CONNECTIONS FOR CYCLIC LOADING (FATIGUE)

by

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PREFACE

Fatigue in a structural steel member or connection is the process of initiation and subsequent growth of a crack under the action of a cyclic or repetitive load. The fatigue process commonly occurs at a stress level less than the static failure condition.

Although fatigue design guidelines have existed for hot-rolled steel structural members and connection, there have been no generally accepted design guidelines in the AISI Specification for addressing fatigue in a cold-formed steel member or connection. Therefore, the intent of the research reported herein was to develop general design rules for design of cold-formed steel members and connections subject to fatigue loading. The fatigue design recommendations developed and reported herein are based on a review of available test data. No additional experimental studies were performed to support the suggested design recommendations.

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Introduction

Fatigue in a structural steel member or connection is the process of initiation and subsequent growth of a crack under the action of a cyclic or repetitive load. The fatigue process commonly occurs at a stress level less than the static failure condition.

When fatigue is a design consideration, its' severity is determined primarily by three factors: (1) the number of cycles of loading, (2) the type of member and connection detail, and (3) the stress range at the detail under consideration (Fisher et al. 1998: Load 1999).

Although fatigue design guidelines have existed for hot-rolled steel structural members and connections there have been no generally accepted design guidelines in the AISI Specification for addressing fatigue in a cold-formed steel member or connection. Therefore, the intent of the research reported herein was to develop general design rules for design of cold-formed steel members and connections subject to fatigue loading.

The fatigue design recommendations developed and reported herein are based on a review of available test data. No additional experimental studies were performed to support the suggested design recommendations. In addition to design recommendations and supporting commentary, a design example for the AISI Manual is contained in Appendix C. Future research needs are also contained herein.

Literature Review

Based on a survey of current fatigue-design procedures and available fatigue test data, Barsom (1980) developed recommendations for future research. It was concluded that although extensive data and knowledge existed about strain-life behavior of steels, it was difficult to use this information for predicting the strain-life behavior of formed and/or fabricated components, especially welded components. Thus, Klippstein (1980, 1981, 1985, 1988) performed an extensive, multi-year research project aimed at assessing the fatigue behavior of cold-formed steel members and connections. This research focused on the application of cold-formed steel members and connections in the ground-transportation and agricultural-equipment industries.

A discussion of the stress-range fatigue-design concept, including the results of 77 welded cold-formed steel sheet specimens exposed to constant amplitude stress cycles were reported by Klippstein (1981). The test specimens were fabricated from steel sheet with yield strengths ranging from 30 to 80 ksi. The steel sheet conformed to ASTM grades, A715 Grade 80 (F_u/F_y = 1.13) A607 Grade 60, and SAE 1008 (F_y = 30 ksi). Several types of beam details were studied such as as-rolled surfaces, slit and sheared edges, cold-formed corners, rolled sheet steel surfaces, and drilled holes with and without screws. Welded details included flange-to-web welds, plate attachments with transverse welds, and plate attachments with short or long longitudinal welds.

Klippstein, in 1985, reported on further studies of fabricated steel sheet details. Based on a compilation of 163 tests, it was reported that the results indicated that the stress-range fatigue-design concept adopted by bridge and crane girder design specifications provided a reliable method for fatigue analysis of fabricated sheet steel details. Klippstein's experimental studies consisted of constant amplitude fatigue tests with stress ratios of > 0 through -1.

In the 1985 report, Klippstein summarized his multi-year studies and recommended an appropriate design methodology based on mean fatigue life curves (S-N curves). A significant conclusion reported by Klippstein was that spot welded or screwed-on attachments fall under the same fatigue design category as welded attachments to a plate or a beam, transverse fillet welds, and continuous longitudinal fillet welds that are less than and equal to 2 inches in length. Klippstein (1985) also reported that intermittent welds parallel to the direction of the applied load may be considered in the same fatigue category as fillet welded attachments greater than 2 inches in length parallel to the direction of the applied force.

The fatigue resistance S-N curve has been expressed as an exponential relationship between stress range and life cycle (Fisher, 1970). The general relationship is often plotted as a linear log-log function, Eq. 1.

$$\log N = C_f - m \log F_{SR} \qquad (1)$$

$$C_f = b - (n * s) \qquad (2)$$

where N = number of full stress cycles
m = slope of the mean fatigue analysis curve
F_{SR} = effective stress range
b = intercept of the mean fatigue analysis curve
n = number of standard deviations to obtain a desired confidence level
s = approximate standard deviation of the fatigue data.

The exponential form of Eq. 1 is as follows:

$$F_{SR} = (C_f/N)^{1/m} \qquad (3)$$

Equation 3 represents the adopted format for fatigue analysis of both the AASHTO (Fisher,1970) and AISC (Load 1999) design specifications.

Using the format of Eq. 3 with m = 3, Klippstein (1988) proposed a classification system for the various stress ranges. Table 1 summarizes the categories along with the corresponding values for C_f. For the computation of C_f, Klippstein recommended that n and s, in Eq. 2, be taken as 2 and 0.25, respectively. The intercept for the mean fatigue analysis curves, b, are summarized in Table 2.

Analysis of Klippstein Data

Although Klippstein (1988) recommended that bolt and screw connections and spot welds be classified as Category F, data presented by Klippstein (1985) showed that Category C provided an appropriate classification. Therefore, the recommendation of this research is to use Category C for bolt and screw connections and spot welds.

Data (Klippstein 1985) also demonstrated that intermittent welds parallel to the direction of the applied force may be classified in Category D. Thus, this research recommends that Category D be used for intermittent welds parallel to the direction of the applied force.

The proposed fatigue categories are summarized in Table 3. To avoid confusion with fatigue categories contained in other design specifications the categories in Table 3 use Roman Numerals.

Fluctuation in stress below a defined threshold will not cause a fatigue crack. However, Klippstein's research was focused on the application of cold-formed steel members and connections in the ground-transportation and agricultural-equipment industries. These applications experience constant amplitude stress range, and therefore are not exposed to a threshold stress. Therefore, Klippstein made no attempt to define a threshold stress. To provide a threshold stress for design, F_{TH} was computed using Klippstein's mean fatigue life curves and the number of cycles that define the threshold stress in the AISC Specification (1999). Figure 1 summarizes the AISC mean fatigue life curves and corresponding number of cycles, N, at the threshold stress. The computed threshold stress for each category is listed in Table 3.

Table 3 presents a summary of the recommended fatigue categories and the corresponding design parameters. Also presented in Table 3 are the AISC design parameters for each category. In all cases, good correlation is shown between the recommended design parameters and AISC's design parameters.

Using Eq. 3, with m = 3 and N = 1,000,000, values of F_{SR} were determined using both the AISI and AISC design parameters (Table 3). Summarized in Table 4 are the resulting F_{SR} values, as well as the ratio of AISI to AISC F_{SR} values. For the four proposed fatigue categories, the ratio of AISI to AISC F_{SR} values ranged from 0.896 to 1.085. Variation in the number of cycles, N, will not alter the resulting ratios. These ratios demonstrate the good correlation between the proposed AISI design formulation and the AISC design method.

Appendix A contains a draft design specification for cold-formed steel structural members and connections for cyclic loading (fatigue). Appendix B contains a draft commentary to support the draft specification.

Future Research Needs

Although the proposed design recommendations are based on an extensive collection of data, future research is recommended to broaden the applicability of the fatigue design for cold-formed steel members and connections. Particular emphasis should be placed on future research to study additional fabrication details, effect of holes, and a broader array of screw sizes.

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Table 1
Klippstein's Fatigue Design Categories

Description	Stress Category	Constant C_f
Base metal and components with as received surfaces, including sheared edges and cold-formed corners.	A	$3.16x10^{10}$
Base metal and weld metal in members connected by continuous longitudinal fillet welds.	B	$1.0x10^{10}$
Continuously welded attachments to a plate or a beam, transverse web stiffeners, transverse fillet welds, weld washers with outside diameter less than 2 inches, and continuous longitudinal welds in regions of cold-forming and subsequent welding.	C	$3.16x10^{9}$
Weld washers with diameter ranging from 2 to 4 inches. Any welded attachment with a length of 2 to 4 inches parallel to the direction of the applied stress. Transverse welds in regions of cold-forming.	D	$1.0x10^{9}$
Attachments longer than 4 inches parallel to the direction of the applied stress, and intermittent welds parallel to the direction of the applied stress.	E	$3.16x10^{8}$
Bolt and screw holes in connections and other punched and drilled holes, spot welds, and shear connectors.	F	$1.0x10^{10}$

Table 2
Intercept for Mean Fatigue Curves

Stress Category	b
A	11.0
B	10.5
C	10.0
D	9.5
E	9.0
F	10.5

Table 3
Recommended Fatigue Design Parameters for Cold-Formed Steel Structures

Description	Stress Category	Constant C_f	Threshold F_{TH} (ksi)	Illustrative Example
As received base metal and components with as rolled surfaces, including sheared edges and cold-formed corners.	I	3.2×10^{10} (2.5×10^{10})	25 (24)	Fig. 2
As received base metal and weld metal in members connected by continuous longitudinal welds.	II	1.0×10^{10} (1.2×10^{10})	15 (16)	Fig. 3
Welded attachments to a plate or a beam, transverse fillet welds, and continuous longitudinal fillet welds less than and equal to 2 inches. Bolt and screw connections and spot welds.	III	3.2×10^{9} (4.4×10^{9})	16 (10)	Fig. 4, 5
Longitudinal fillet welded attachments greater than 2 inches parallel to the direction of the applied stress, and intermittent welds parallel to the direction of the applied force.	IV	1.0×10^{9} (1.0×10^{9})	9 (7)	Fig. 4

The numbers in ( ) are the corresponding AISC values for information only.

Table 4
Comparison of Recommended Fatigue Design Parameters

Category	C_f AISI	C_f AISC	F_{SR} AISI (ksi)	F_{SR} AISC (ksi)	$(F_{SR})_{AISI}/(F_{SR})_{AISC}$
I	3.2×10^{10}	2.5×10^{10}	3.17	2.92	1.085
II	1.0×10^{10}	1.2×10^{10}	2.15	2.29	0.939
III	3.2×10^{9}	4.4×10^{9}	1.47	1.64	0.896
IV	1.0×10^{9}	1.1×10^{9}	1.00	1.03	0.971

F_{SR} calculations used Eq. 3 with m = 3 and N = 1,000,000 cycles.

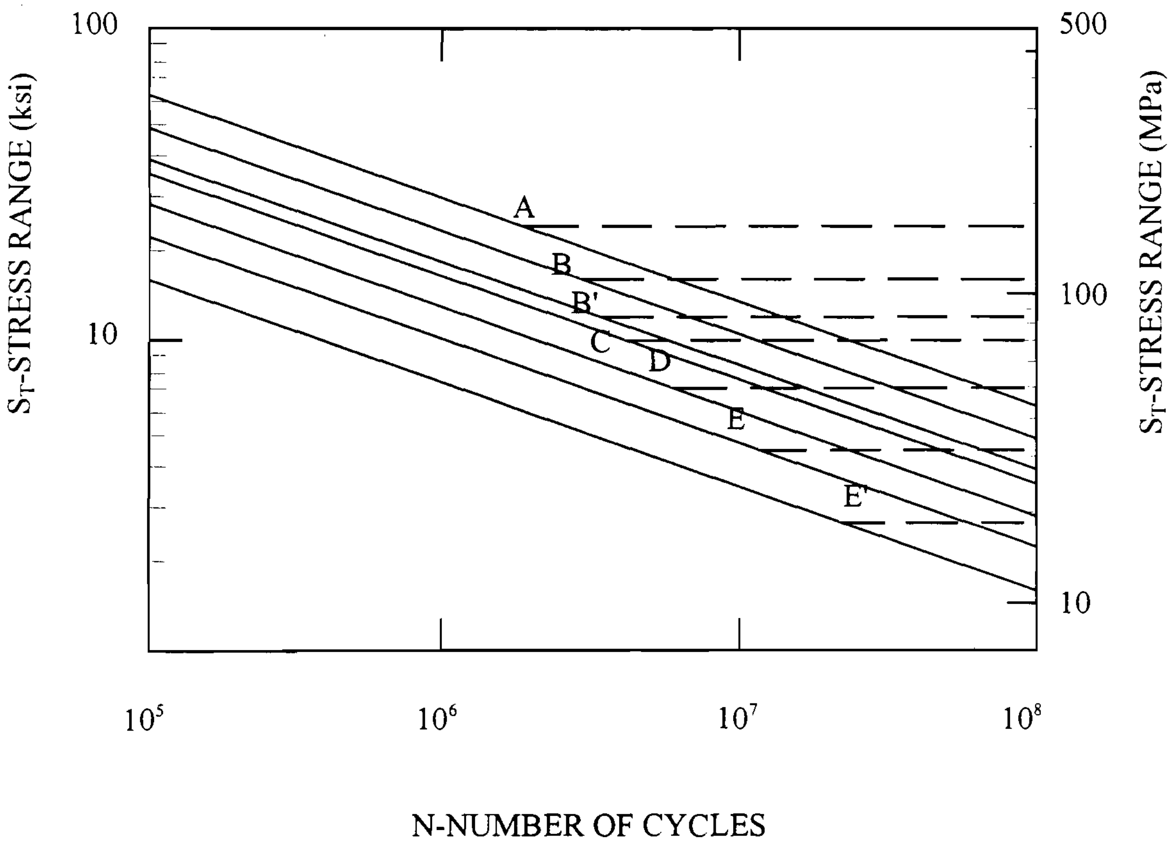


Figure 1 S-N Curves for the Various Detail Categories (Load 1999)

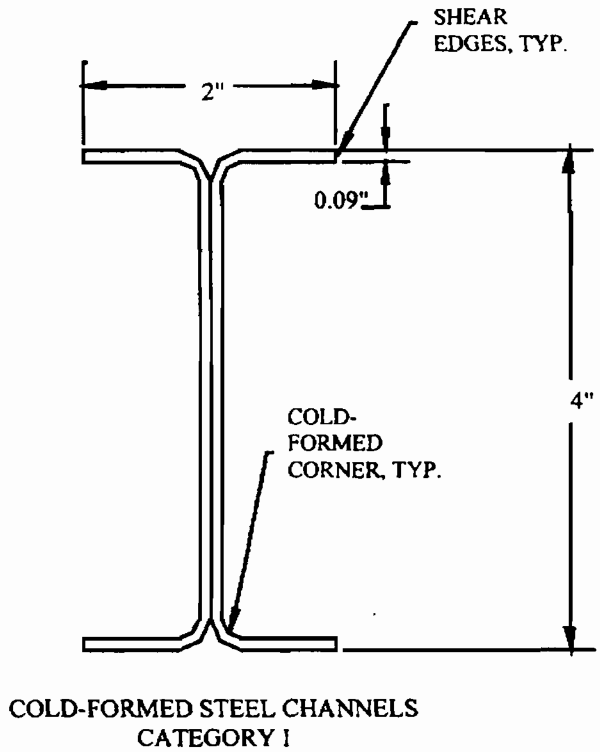


Figure 2 Typical Test Beam for Category I

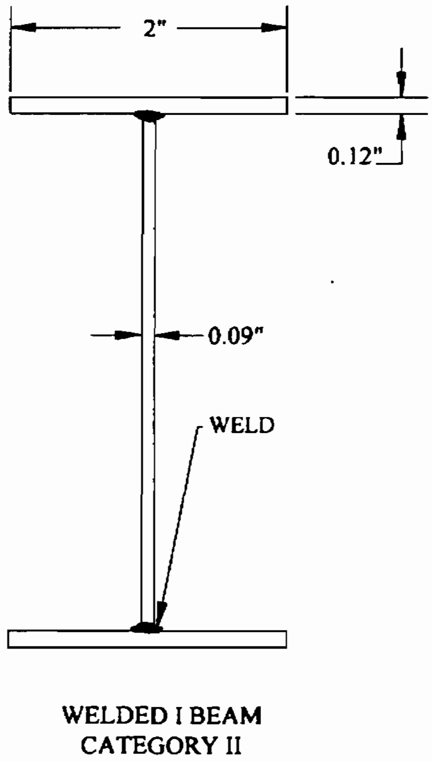


Figure 3 Typical Test Beam for Category II

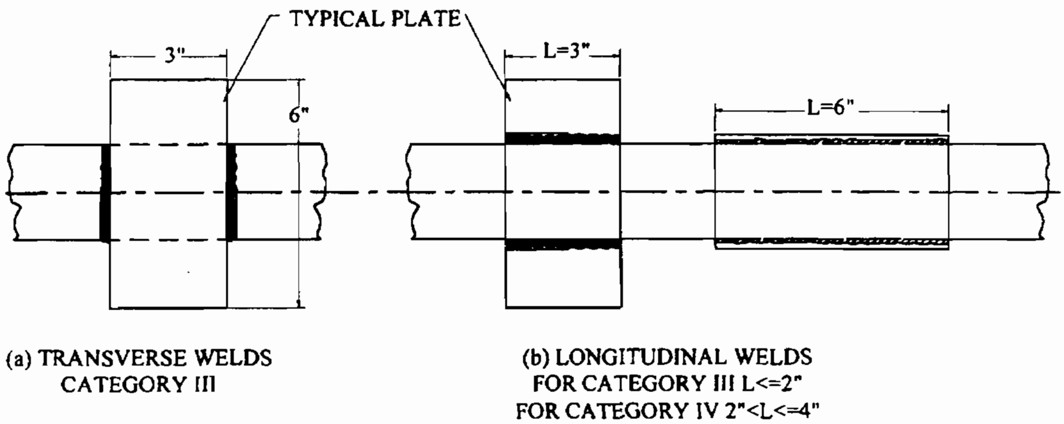


Figure 4 Typical Test Weld Attachments for Categories III and IV

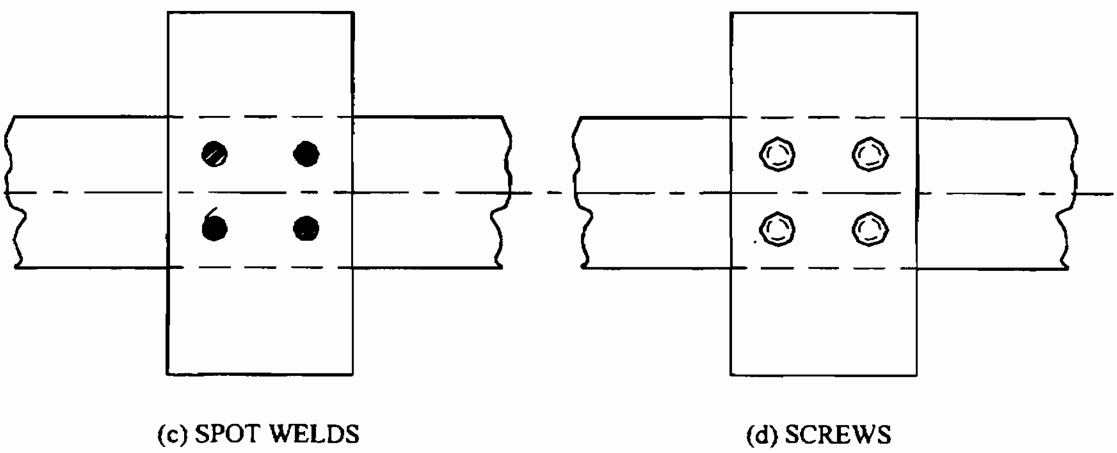


Figure 5 Typical Test Spot Weld and Screw Attachments for Category III

Appendix A

Proposed Specification

DESIGN OF COLD-FORMED STEEL STRUCTURAL MEMBERS AND CONNECTIONS FOR CYCLIC LOADING (FATIGUE)

This design procedure shall apply to cold-formed steel members and connections subject to cyclic loading within the elastic range of stresses of frequency and magnitude sufficient to initiate cracking and progressive failure (fatigue).

1. General

The provisions of this section apply to stresses calculated on the basis of unfactored loads. The maximum permitted tensile stress due to unfactored loads is 0.6 F_y.

Stress range is defined as the magnitude of the change in stress due to the application or removal of the unfactored live load. In the case of a stress reversal, the stress range shall be computed as the numerical sum of maximum repeated tensile and compressive stresses or the numerical sum of maximum shearing stresses of opposite direction at the point of probable crack initiation.

Evaluation of fatigue resistance is not required if the live load stress range is less than the threshold stress range, F_{TH}, given in Table A1.

Evaluation of fatigue resistance is not required if the number of cycles of application of live load is less than 20,000.

The cyclic load resistance determined by the provisions of this section are applicable to structures with suitable corrosion protection or subject only to non-agressive atmospheres.

The cyclic load resistance determined by the provisions of this section is applicable only to structures subject to temperatures not exceeding 300°F.

The contract documents shall provide, either complete details including weld sizes, or shall specify the planned cycle life and the maximum range of moments, shears, and reactions for the connections.

2. Calculation of Maximum Stresses and Stress Ranges

Calculated stresses shall be based upon elastic analysis. Stresses shall not be amplified by stress concentration factors for geometrical discontinuities.

For bolts and threaded rods subject to axial tension, the calculated stresses shall include the effects of prying action, if applicable.

In the case of axial stress combined with bending, the maximum stresses, of each kind, shall be those determined for concurrent arrangements of applied load.

For members having symmetric cross sections, the fasteners and welds shall be arranged symmetrically about the axis of the member, or the total stresses including those due to eccentricity shall be included in the calculation of the stress range.

For axially stressed angle members where the center of gravity of the connecting welds lies between the line of the center of gravity of the angle cross section and the center of the connected leg, the effects of eccentricity shall be ignored. If the center of gravity of the connecting welds lies outside this zone, the total stresses, including those due to joint eccentricity, shall be included in the calculation of stress range.

3. Design Stress Range

If the stress range is less than the fatigue threshold stress range, F_{TH}, fatigue is not a limit state. Otherwise, the range of stress at service loads shall not exceed the design stress range computed using Equation A1, but F_{SR} shall not be less than the fatigue threshold, F_{TH}.

For all stress categories,

$$F_{SR} = (C_f/N)^{0.333} \qquad \text{(A1)}$$

where:

F_{SR} = Design stress range
C_f = Constant from Table A1
N = Number of stress range fluctuations in design life,
= Number of stress range fluctuations per day x 365 x years of design life.
F_{TH} = Threshold fatigue stress range, maximum stress range for indefinite design life from Table A1

4. Bolts and Threaded Parts

For mechanically fastened connections loaded in shear, the maximum range of stress in the connected material at service loads shall not exceed the design stress range computed using Equation A1. The factor C_f shall be taken as 22×10^8. The threshold stress, F_{TH}, shall be taken as 7 ksi.

For not-fully-tightened high-strength bolts, common bolts, and threaded anchor rods with cut, ground or rolled threads, the maximum range of tensile stress on the net tensile area from applied axial load and moment plus load due to prying action shall not exceed the design stress range computed using Equation A1. The factor C_f shall be taken as 3.9×10^8. The threshold stress, F_{TH}, shall be taken as 7 ksi. The net tensile area is given by Equation A2.

$$A_t = (\pi/4)\,[d_b - (0.9743/n)]^2 \qquad \text{(A2)}$$

d_b = nominal diameter (body or shank diameter)
n = number of threads per inch

5. Special Fabrication Requirements

Backing bars that are parallel to the stress field are permitted to remain in place, and if used, shall be continuous.

In transverse joints subject to tension, backing bars, if used, shall be removed and the joint back gouged and welded.

Flame cut edges subject to cyclic stress ranges shall have a surface smoothness not more than ANSI 1000.

Re-entrant corners at cuts, copes and weld access holes shall form a radius of not less than 3/8 in., by pre-drilling or sub-punching and reaming a hole, or by thermal cutting to form the radius of the cut. If the radius portion is formed by thermal cutting, the cut surface shall be ground to a bright metal contour to provide a radiused transition, free of notches, with a surface smoothness not more that ANSI 1000.

For transverse butt joints in regions of high tensile stress, weld tabs shall be used to provide for cascading the weld termination outside the finished joint. End dams shall not be used. Weld tabs shall be removed and the end of the weld finished flush with the edge of the member.

Table A1
Fatigue Design Parameters for Cold-Formed Steel Structures

Description	Stress Category	Constant C_f	Threshold F_{TH} (ksi)	Illustrative Example
As received base metal and components with as rolled surfaces, including sheared edges and cold-formed corners.	I	3.2×10^{10}	25	A1
As received base metal and weld metal in members connected by continuous longitudinal welds.	II	1.0×10^{10}	15	A2
Welded attachments to a plate or a beam, transverse fillet welds, and continuous longitudinal fillet welds less than and equal to 2 inches. Bolt and screw connections and spot welds.	III	3.2×10^{9}	16	A3, A4
Longitudinal fillet welded attachments greater than 2 inches parallel to the direction of the applied stress, and intermittent welds parallel to the direction of the applied force.	IV	1.0×10^{9}	9	A4

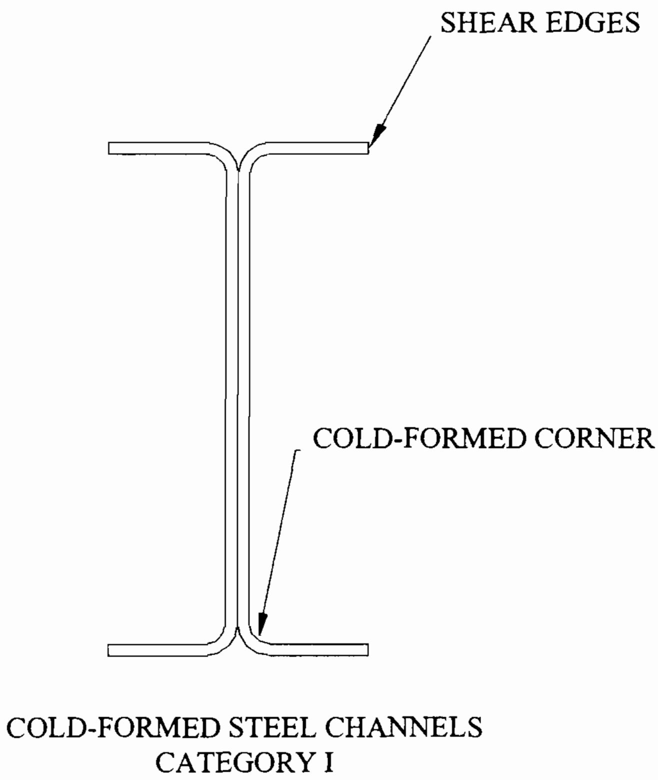


Figure A1 Typical Test Beam for Category I

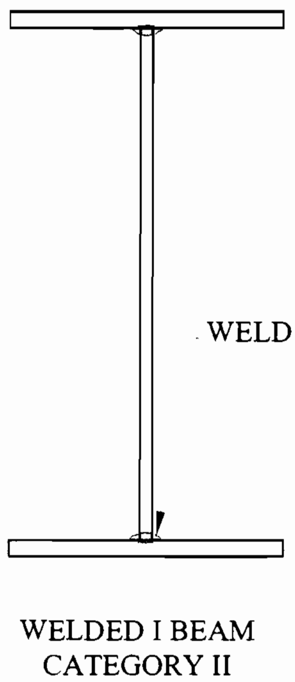
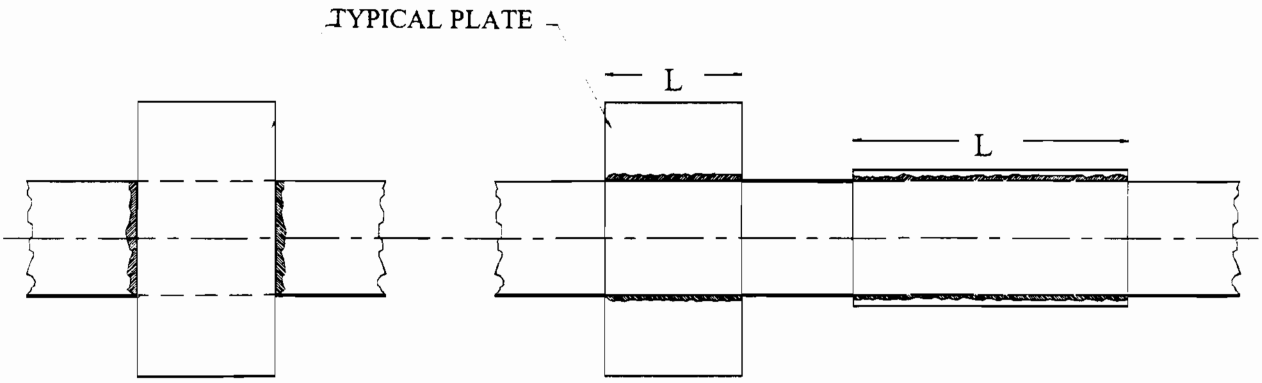


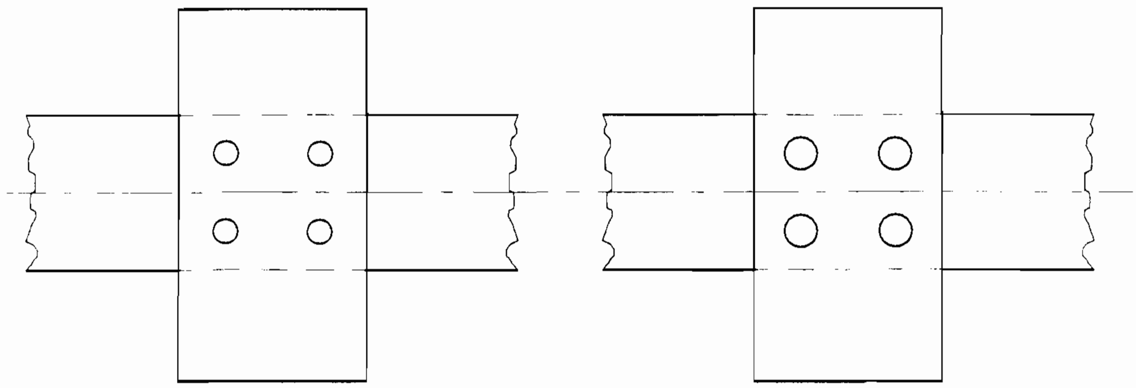
Figure A2 Typical Test Beam for Category II



(a) TRANSVERSE WELDS
CATEGORY III

(b) LONGITUDINAL WELDS
FOR CATEGORY III L ≤ 2"
FOR CATEGORY IV 2" < L ≤4"

Figure A3 Typical Test Weld Attachments for Categories III and IV



(c) SPOT WELDS

(d) SCREWS

Figure A4 Typical Test Spot Weld and Screw Attachments for Category III

Appendix B

Commentary for Proposed Specification

COMMENTARY ON DESIGN OF COLD-FORMED STEEL STRUCTURAL MEMBERS AND CONNECTIONS FOR CYCLIC LOADING (FATIGUE)

Fatigue in a cold-formed steel member or connection is the process of initiation and subsequent growth of a crack under the action of a cyclic or repetitive load. The fatigue process commonly occurs at a stress level less than the static failure condition.

When fatigue is a design consideration, its severity is determined primarily by three factors: (1) the number of cycles of loading, (2) the type of member and connection detail, and (3) the stress range at the detail under consideration (Fisher et al. 1998).

Fluctuation in stress which does not involve tensile stress does not cause crack propagation and is not considered to be a fatigue situation.

When fabrication details involving more than one category occur at the same location in a member, the design stress range at the location must be limited to that of the most restrictive category. By locating notch-producing fabrication details in regions subject to a small range of stress, the need for a member larger than required by static loading will often be eliminated.

Research by Barsom (1980) and Klippstein (1988, 1985, 1981, 1980) developed fatigue information on the behavior of sheet and plate steel weldments and mechanical connections. Using regression analysis, mean fatigue life curves (S-N curves) with the corresponding standard deviation were developed. The fatigue resistance S-N curve has been expressed as an exponential relationship between stress range and life cycle (Fisher, 1970). The general relationship is often plotted as a linear log-log function, Eq. C1.

$$\log N = C_f - m \log F_{SR} \qquad \text{(C1)}$$

$$C_f = b - (n * s) \qquad \text{(C2)}$$

where N = number of full stress cycles
- m = slope of the mean fatigue analysis curve
- F_{SR} = effective stress range
- b = intercept of the mean fatigue analysis curve from Table C1
- n = number of standard deviations to obtain a desired confidence level = 2 for C_f given in the Specification
- s = approximate standard deviation of the fatigue data = 0.25 (Klippstein, 1988)

The data base for these design provisions are based upon cyclic testing of real joints; therefore, stress concentrations have been accounted for by the category in Table A1 of the Specification. It is not intended that the allowable stress ranges should be compared to "hot-spot" stresses determined by finite element analysis. Also, calculated stresses computed by ordinary analysis need not be amplified by stress concentration factors at geometrical discontinuities and changes of cross section. All categories were found to have a common slope with m = -3. Equation 1 of the Specification is to be used to calculate the design stress range for the chosen design life, N. Table A1 of the Specification provides a classification system for the various stress categories. This also provides the constant C_f that is applicable to the stress category that is required for calculating the design stress range F_{SR}.

Table C1
Intercept for Mean Fatigue Curves

Stress Category	b
I	11.0
II	10.5
III	10.0
IV	9.5

The provisions for bolts and threaded parts were taken from the AISC Specification (Load 1999).

References

Barsom, J. M., Klippstein, K. H., and Shoemaker, A. K. (1980), "Fatigue Behavior of Sheet Steels for Automotive Applications," Research Report SG 80-2, American Iron and Steel Institute.

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Appendix C

Design Example

Given:

(1) Cold-formed steel flexural member with sheeting attached to its compression flange.
(2) The flexural member is C-shaped in geometry, 9CS3x075
(3) ASTM A653 Grade 50 steel was used to roll the C-shape.
(4) Sheeting is attached using self-drilling screws which are spaced 12 in. center-to-center.
(5) A 20 year life expectancy is stipulated for the design.

If the C-shape is subjected to a loading rate of 2 cycles per hour, determine the design stress range for the C-shape.

Solution:

The number of cycles is,

$$N = 2 \text{ cycles/hour} \times 24 \text{ hrs/day} \times 365 \text{ days/year} \times 20 \text{ year life} = 350{,}400 \text{ cycles}$$

(A) Between the fasteners:

The C-shape has rolled corners, therefore stress category I applies, $C_f = 3.2x10^{10}$ and $F_{TH} = 25$ ksi.

The maximum stress range is 0.6 x 50 ksi = 30 ksi. Because F_{TH} is less that 30 ksi, fatigue must be considered.

The fatigue design stress range for the C-shaped member is,

$$F_{SR} = (C_f/N)^{0.333}$$

$$= (\ 3.2x10^{10} / 350{,}400)^{0.333}$$

$$= 44.86 \text{ ksi}$$

Because F_{SR} is greater than 30 ksi, fatigue will not control the design of the C-shaped flexural member between the fastener locations.

(B) At the location of the attachment:

The attachment of the sheet to the C-shape uses self-drilling screws, thus the design of the C-shape is governed by stress category III, $C_f = 3.2x10^9$ and $F_{TH} = 16$ ksi.

Because F_{TH} is less than 30 ksi, fatigue must be considered.

The fatigue design stress range for the attachment is,

$F_{SR} = (C_f/N)^{0.333}$

$= (\ 3.2x10^9 \ / \ 350{,}400)^{0.333}$

$= 20.84$ ksi

Because F_{SR} is less than 30 ksi, fatigue will control the design of the C-shape at the sheeting attachment locations.