APPENDIX D

COMPARISON OF
CURVED STEEL I-GIRDER BRIDGE
DESIGN SPECIFICATIONS

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APPENDIX D

COMPARISON OF CURVED STEEL I-GIRDER BRIDGE DESIGN SPECIFICATIONS

D1 OBJECTIVE

The purpose of this study was to perform a comparison between the three most-recent curved girder design specifications; the load factor design protocols in the 1993 AASHTO Guide Specifications for Horizontally Curved Girders (*D1*), hereafter referred to as "LFD"; the 2003 Guide Specifications for Horizontally Curved Steel Highway Bridges (*D2*), hereafter referred to as "12-38" having been codified as a direct result of the NCHRP 12-38 project; and the 2005 Interims to the LRFD Bridge Design Specifications (*D3*), hereafter referred to as "12-52" since the adopted changes are a direct result of this NCHRP project.

D2 METHODOLOGY

A sample of 32 bridges was collected from various agencies and compiled by Modjeski and Masters, Inc. Bridge numbers 1 through 21 were submitted by state DOTs and/or design agencies and represent real, in-service bridges utilizing typical modern-day construction. Bridge numbers 22 through 32, hereafter referred to as simulated bridges, are examples that have been modified from existing structures for analysis purposes; these modifications included simplifying the span lengths, making skewed supports radial and limiting the structure to single curvature.

When a reference to an equation number is made in this appendix, the equation number is that used for the equation in the specifications. As will be explained in further detail later in the report, this collection of bridges was further supplemented by modifying specific parameters slightly such that all logical design paths through the specifications could be exercised.

Basic geometric information (e.g., span length, radius of curvature) about the bridges in the sample is included in Table D-1. Several of the key aspects of the bridges in this sample are as follows:

- Most of the bridges are multi-span continuous girder bridges with four of the 32 bridges being single-span structures.
- For the greatest portion of the bridges, the critical positive moment section occurred in an end span and the critical negative moment section occurred over the first interior pier.
- The critical shear section generally occurred at or near a pier.
- The vast majority of the bridges used 50-ksi steel exclusively; only two had hybrid sections, both occurring in the negative moment region. Four bridges used 36-ksi steel throughout.
- Two of the bridges had haunched girders.
- Twenty of the 32 bridges in the sample were transversely-stiffened and none had longitudinal stiffeners.
- The longest span of the bridges in the sample was 190 feet and the minimum radius among the existing bridges was 239 feet, while among the simulated bridges the minimum radius was approximately 120 feet.

- The deepest webs in the sample were 95 inches with the shallowest webs at 32 inches.
- Lateral bending stresses were not submitted for some of the bridges in the study; for one of these the original design ignored the lateral stresses, another consisted of straight girders with a curved deck, and the V-load method was utilized to estimate the lateral stresses for the other bridges.

For each bridge the critical positive flexure, critical negative flexure and critical shear locations were either submitted by the agency or determined by Modjeski and Masters, Inc. from the documentation submitted. When slab details (e.g., thickness, compressive strength) were not provided by the submitting agency they were assumed based on the properties of the other bridges in the sample.

Two load cases were considered for this study. The shear and flexural critical stress and applied stress of the sections were determined for the LRFD Strength I load case and the flexural critical stress and applied stress were determined for the LRFD Service II load case.

For the Strength I load case, the critical-to-applied stress ratios according to each specification were plotted for each bridge. Submitted load effects (e.g., moments and shears) were assumed to be service loads and the applied stress calculations utilized the load factors for the LRFD Strength I combination as a basis for comparison. Had the assumption that the loads were unfactored been incorrect, the results would have indicated observably low critical-to-applied stress ratios; this was not the case. An attempt to remove the effects of the load factors was made by also plotting the critical stress calculated by each specification normalized to the critical stress calculated by the LFD specifications for each condition, which is the primary focus of the analyses outlined in Sections D3 and D4. For each of the design conditions, explanation is offered with reference to the appropriate specifications for any bridge whose critical stress varies more than five percent from the LFD critical stress and may be offered for others as well based on observable trends in the data.

For the Service II load case, the critical-to-applied stress ratios according to each specification were plotted for each bridge. The load factors for each of the specifications were used and due to the limited number of differences between the three specifications for this load case, no further plots were created. Section D5 outlines this analysis and comparison.

D3 SHEAR DESIGN (STRENGTH I)

Section D9 contains a series of flowcharts that outline the shear design protocols and variables according to each of the three specifications. The reader is encouraged to reference the appropriate specification for clarification and further information regarding the design protocols. In general, the shear design protocols for the three analysis specifications are very similar. This is true both for transversely-stiffened and unstiffened members. The main differences between the three specifications are as follows:

- The maximum transverse stiffener spacing has been progressively increased from D, the depth of the web, in the LFD specifications to $3D$ in the 12-52 specifications.
- The 12-52 specifications allow for the consideration of the additional post-buckling strength from tension-field action in the shear critical stress calculations.

Figure D-1 shows the shear critical-to-applied stress ratio for the sample of bridges according to the three specifications, while Figure D-2 shows the shear critical stress normalized to the LFD critical stress. It should be noted that the stiffened bridges are denoted in the subsequent shear-related figures with a box around the number identifier; the existing bridges are also differentiated in the figures. In general, the critical-to-applied stress ratios for the three analysis specifications are relatively consistent between specifications and within the sample. The considerably large spike in the critical-to-applied stress ratio shown in Figure D-1 for bridge number 6 is due to the haunch in the girders. According to the submitting agency, the haunch was provided for aesthetic reasons and the section submitted was at mid-span, which is typically not a critical section for shear.

Except for bridge numbers 4 and 22, all bridge exhibited equal or slightly higher shear critical stress according to the LFD specifications compared to the 12-38 specifications. The change in maximum transverse stiffener spacing between the three specifications is evident in the critical stress values for bridge numbers 4 and 22. These two bridges are the only ones that have a transverse stiffener spacing value greater than the depth of the web and are the only ones that exhibit a higher critical stress according to the 12-38 specifications compared to the LFD specifications. This is due to the fact that the sections are analyzed as unstiffened according to the LFD specifications when the transverse stiffener spacing exceeds the maximum value of *D*.

The analysis of transversely-stiffened members with the LFD and 12-38 specifications is more conservative than the 12-52 specification in several instances as evidenced by the lower normalized critical stress values. These cases are for bridges numbers 2, 4, 7, 12, 13, 14, 16, 22, 23, 24, 25, 26, 27, and 28. For these bridges, the 12-52 specifications allow the additional post-buckling strength from tension-field action to be considered. This post-buckling strength is also recognized in the LFD (*D4*) and LRFD (*D3*) straight girder provisions.

Bridge numbers 29, 30 and 31 also qualified for the use of the post-buckling strength provision. However no additional strength is realized for cases when the ratio of the shear-buckling resistance to the shear yield strength, *C*, is equal to unity; in this situation Eq. 6.10.9.3.2-2 becomes Eq. 6.10.9.2-1 and only the buckling strength is considered.

Although also stiffened, bridge numbers 3, 20, and 32 were analyzed at the end panels and are therefore not able to rely on the formation of a tension field or to account for any additional post-buckling strength. These observations are evident in Figure D-2 as well.

For the sample of bridges that allows the additional post-buckling strength, the difference in critical-to-applied stress ratio generally increases with increasing web depth-to-thickness ratio as illustrated in Figure D-3. According to the 12-52 specifications, and Eq. (6-4) in the 12-38 specifications, Eq. 6.10.9.2-1 is utilized for both stiffened and unstiffened webs to account for the shear-yielding or shear-buckling strength of the web. Note that this equation is unnumbered in the LFD specifications.

$$V_{cr} = CV_p \qquad \text{Eq. 6.10.9.2-1}$$

The 12-52 specifications use an equation to account for the post-buckling strength that effectively increases the multiplier on V_p for certain stiffened webs. The following equation, Eq. 6.10.9.3.2-2, is utilized in the 12-52 specifications for both straight and curved steel girders and is applicable for bridge numbers 2, 4, 12, 13, 14, 16, 22, 23, 24, 25, 26, 27, 28, 29, 30 and 31. Only bridge number 7 does not meet the geometric requirements for the use of this equation and subsequently uses a more conservative variation identified as Eq. 6.10.9.3.2-8.

$$V_n = V_p\left[C + \frac{0.87(1-C)}{\sqrt{1+\left(\frac{d_o}{D}\right)^2}}\right] \qquad \text{Eq. 6.10.9.3.2-2}$$

$$V_n = V_p\left[C + \frac{0.87(1-C)}{\sqrt{1+\left(\frac{d_o}{D}\right)^2 + \frac{d_o}{D}}}\right] \qquad \text{Eq. 6.10.9.3.2-8}$$

The fact that the difference between the critical-to-applied stress ratios increases with increasing web depth-to-thickness ratio is due to the opposite trend being manifested in a comparison between the equations utilized to calculate *C*. That is to say that *C* decreases as D/t_w increases, causing the difference between *C* and $\left[C + \frac{0.87(1-C)}{\sqrt{1+\left(\frac{d_o}{D}\right)^2}}\right]$ to increase. The equations that follow are used to determine *C* for each of the three specifications. Note that the equations for the LFD specifications are listed in their published form and also converted to the same form as the other specifications' equations for comparison purposes; when presented in this way it becomes evident that the constants for the equations in the three specifications are equivalent. It should be noted that the definitions for *k* and k_w are identical for analysis.

LFD specification

$$\frac{D}{t_w} < \frac{6000\sqrt{k}}{\sqrt{F_y}}, C = 1.0$$

$$\frac{6000\sqrt{k}}{\sqrt{F_y}} \le \frac{D}{t_w} \le \frac{7500\sqrt{k}}{\sqrt{F_y}}, C = \frac{6000\sqrt{k}}{\frac{D}{t_w}\sqrt{F_y}} \qquad \text{Eq. (10-116)}$$

$$\frac{D}{t_w} > \frac{7500\sqrt{k}}{\sqrt{F_y}}, C = \frac{4.5x10^7 k}{\left(\frac{D}{t_w}\right)^2 F_y} \qquad \text{Eq. (10-117)}$$

LFD specification (converted to the same units/form as the 12-38 and 12-52 specifications)

$$\frac{D}{t_w} < 1.114\sqrt{\frac{Ek_w}{F_y}}, C = 1.0$$

$$1.114\sqrt{\frac{Ek_w}{F_y}} \le \frac{D}{t_w} \le 1.393\sqrt{\frac{Ek_w}{F_y}}, C = \frac{1.114}{\frac{D}{t_w}}\sqrt{\frac{Ek_w}{F_y}}$$

$$\frac{D}{t_w} > 1.393\sqrt{\frac{Ek_w}{F_y}}, C = \frac{1.551Ek_w}{\left(\frac{D}{t_w}\right)^2 F_y}$$

12-38 specification

$$\frac{D}{t_w} < 1.10\sqrt{\frac{Ek_w}{F_y}}, C = 1.0 \qquad \text{Eq. (6-5)}$$

$$1.10\sqrt{\frac{Ek_w}{F_y}} \le \frac{D}{t_w} \le 1.38\sqrt{\frac{Ek_w}{F_y}}, C = \frac{1.10}{\frac{D}{t_w}}\sqrt{\frac{Ek_w}{F_y}} \qquad \text{Eq. (6-6)}$$

$$\frac{D}{t_w} > 1.38\sqrt{\frac{Ek_w}{F_y}}, C = \frac{1.52Ek_w}{\left(\frac{D}{t_w}\right)^2 F_y} \qquad \text{Eq. (6-7)}$$

12-52 specification

$$\frac{D}{t_w} \le 1.12\sqrt{\frac{Ek}{F_{yw}}}, C = 1.0 \qquad \text{Eq. 6.10.9.3.2-4}$$

$$1.12\sqrt{\frac{Ek}{F_{yw}}} < \frac{D}{t_w} \le 1.40\sqrt{\frac{Ek}{F_{yw}}}, C = \frac{1.12}{\frac{D}{t_w}}\sqrt{\frac{Ek}{F_{yw}}} \qquad \text{Eq. 6.10.9.3.2-5}$$

$$\frac{D}{t_w} > 1.40\sqrt{\frac{Ek}{F_{yw}}}, C = \frac{1.57Ek}{\left(\frac{D}{t_w}\right)^2 F_{yw}} \qquad \text{Eq. 6.10.9.3.2-6}$$

The flowcharts in Section D9 outline the number of bridges in the sample that met the requirements for each classification according to each of the specifications for the stiffened and unstiffened critical stress equations.

None of the bridges investigated had longitudinally-stiffened webs, and only three were investigated at an end panel as the majority of the critical shear locations occur at or near one of the intermediate piers. Due to insufficient sample size, examination of the effects of the end panel analysis and the analysis of longitudinal stiffened members was not possible. Furthermore, the majority of the bridges investigated exceeded the elastic-buckling D/t_w boundary for the determination of C causing the other two categories to be poorly represented in the array.

In order to ensure that all design paths were represented by the bridge sample, some of the sections in the sample were modified. For the shear design provisions, the goal was to force three bridges without transverse stiffeners to fall into the middle range equation for C. To accomplish this, the three bridges with D/t_w ratios closest to the upper limit of this range (bridge numbers 1, 11, and 19) were altered to a reduced D/t_w ratio by increasing the web thickness, t_w. It should be noted that these three bridges as modified are not included in the bridge sample, but were analyzed according to the same specifications to determine their fit within the sample results.

Table D-2 outlines the changes that were made and the resulting effects on critical stress. Note that for all three bridges the LFD and 12-38 critical stress values based on both the original and modified cross-section are within two percent of the 12-52 critical stress value.

The potential material savings for transverse stiffeners was investigated for those bridges that had transverse stiffeners and qualified for the consideration of the post-buckling strength (i.e., tension-field action) of the web. This was accomplished by increasing the stiffener spacing and then analyzing the section according to the 12-52 specifications again; the critical stress was decreased such that the critical-to-applied stress ratio was comparable to that obtained by the

LFD and 12-38 specifications. The ratio between the existing stiffener spacing and the new stiffener spacing is an indication of the potential material savings; on average, this ratio was 1.77 indicating that only approximately 56 percent of the stiffeners provided in the critical region of the existing bridges were needed.

D4 FLEXURAL DESIGN (STRENGTH I)

The flowcharts in Section D10 outline the number of bridges in the sample that met the requirements for each classification according to each of the specifications for the composite positive flexure (C+), composite negative flexure (C-), noncomposite positive flexure (NC+), and noncomposite negative flexure (NC-), respectively. Furthermore, they outline the flexural design protocols and variables utilized for each of the three specifications. The reader is encouraged to reference the appropriate specification for clarification and further information regarding the design protocols.

Table D-3 outlines the width-to-thickness (i.e., slenderness) ratio limits for the various classifications of the flanges according to the three specifications. For a yield strength of 50 ksi, the limits for compact and slender flanges are lower with the LFD specification than with the 12-38 specification, but only marginally. For the 12-52 specification, the ratios are slightly higher than those for the 12-38 specifications.

The following trends, as they relate to the studied bridges, are worth noting from the flowcharts:

- For the 12-52 specification related to composite sections in positive flexure (Section 6.10.7), there are two bridges in the sample for which the section is regarded as noncompact; it should be noted, however, that since plastic design is not permitted all composite curved steel girders in positive flexure must be analyzed as noncompact according to 12-52 Section 6.10.6.2.2.
- According to the 12-52 specifications, the majority of the bridges in the sample were classified as compact for flange local buckling (FLB) considerations and as noncompact for lateral-torsional buckling (LTB) considerations for all design conditions.
- For the composite negative flexure and noncomposite section specification of 12-52 (Section 6.10.8), the case where the compression flange is continuously-braced is not represented in the sample. Such a case would be atypical, however because the bottom flange is usually braced at discrete points where the cross-frames exist.
- Generally, the LTB considerations controlled the critical stress of the bridges in the sample, which is logical based on the classifications pertaining to their buckling behavior.

One noticeable difference between the three specifications is the fact that while the LFD and 12-38 specifications consider the lateral bending stress to reduce the critical stress, the 12-52 specifications consider the lateral bending stress as a load. In order to alleviate this difference, the appropriate portion of the lateral bending stress was deducted from the critical stress calculated according to the 12-52 specifications to obtain a bending resistance, F_{bu}.

$$F_{bu} = \phi_f F_n - \frac{1}{3} f_l$$

The subsequent plots utilize the bending resistance values, with the exception of the critical-to-applied stress plots which consider the flange critical stress, F_n, as outlined in the specifications directly.

The 12-52 specifications outline a number of geometric constraints for the section dimensions as detailed in the following equations. The requirements for the flange width or thickness are applicable to both the tension and compression flanges of I-girder members. It should be noted that Eq. C6.10.3.4-1 is intended to be a guideline and not a requirement. The majority of the bridges in the sample meet all of the requirements. Approximately one-half of the positive moment sections and approximately one-third of the negative moment sections, however, do not meet the suggested compression flange width in Eq. C6.10.3.4-1. Only two bridges do not meet the limit outlined by Eq. 6.10.2.2-2 for the compression flange and only one bridge does not meet the compression and tension flange thickness requirements detailed by Eq. 6.10.2.2-3.

$$\frac{b_f}{2t_f} \leq 12.0 \qquad \text{Eq. 6.10.2.2-1}$$

$$b_f \geq \frac{D}{6} \qquad \text{Eq. 6.10.2.2-2}$$

$$t_f \geq 1.1t_w \qquad \text{Eq. 6.10.2.2-3}$$

$$0.1 \leq \frac{I_{yc}}{I_{yt}} \leq 10 \qquad \text{Eq. 6.10.2.2-4}$$

$$b_{fc} \geq \frac{L}{85} \qquad \text{Eq. C6.10.3.4-1}$$

For many of the 32 bridges in the sample only minimal information about the moments/stresses in the critical sections was provided and in some cases the signs of the lateral moments were not provided. For these reasons, all bridges were assumed to have a positive ratio of lateral stress, f_w, to bending stress, f_b, for the purposes of calculating the ρ values needed to determine the allowable stress for a noncompact flange according to LFD Section 2.12 and 12-38 Section 5.2.2. This yields the most conservative value for the allowable stress and, for the sample investigated, the choice to use a positive ratio does not affect the results.

It should be noted that although it should be excluded from the composite section property calculations, the integral wearing surface may be included in some of the sections analyzed since information was not always provided about its thickness/presence. The effects are presumed to be minimal.

The following discussion of the specifications is broken down to cover all eight combinations of composite and noncomposite sections, positive and negative flexure, and compression or tension flanges. As with the shear critical stress, for each of the design conditions, explanation will be offered with reference to the appropriate specifications for any bridge whose critical stress varies more than five percent from the LFD critical stress and, based on observable trends in the data, may be offered for others as well. It should be noted that the existing bridges are distinguished in the subsequent flexural critical stress figures.

D4.1 COMPOSITE, POSITIVE FLEXURE, COMPRESSION FLANGE

Figure D-4 shows the critical stress of the compression flange for the composite, positive flexure section. Figure D-5 shows the critical-to-applied stress ratio for the analysis of the compression flange of the section for composite, positive flexure. Figure D-6 shows the ratio of the critical stress calculated by each specification to the critical stress calculated by the LFD specifications for the same condition; this figure represents a normalized version of the data in Figure D-4.

All three of the specifications yield the same critical stress and critical-to-applied stress ratios. This is due to the fact that the specifications do not reduce the critical stress of a continuously braced flange below the yield strength, F_y. It should be noted that bridge numbers 1, 24, 25, 29 and 30 utilize 36-ksi steel at the location investigated for this condition.

Bridge number 5 has a very low compressive stress in the top flange for the composite section, resulting from the neutral axis being located very near to the top flange. This serves to explain the noticeably high critical-to-applied stress ratios exhibited in Figure D-5.

D4.2 COMPOSITE, NEGATIVE FLEXURE, COMPRESSION FLANGE

Figure D-7 shows the critical stress of the compression flange for the composite, negative flexure section. Figure D-8 shows the critical-to-applied stress ratio for the analysis of the compression flange of the section for composite, negative flexure. Figure D-9 shows the ratio of the critical stress calculated by each specification to the critical stress calculated by the LFD specifications for the same condition. Note that the gaps occurring for bridge numbers 3, 6, 20, and 32 are due to the fact that those bridges are simple-span structures that do not have a negative moment region. Bridge numbers 24, 25, 29, and 30 utilize 36-ksi steel in the member at this location.

In Figure D-9, if a difference of up to five percent were to be disregarded, the only bridges with noticeable variation in critical stress for this condition would be bridge numbers 5, 13, 18, 19, 22, 27, and 30.

Bridge numbers 5 and 18 are the only two bridges in the sample that are classified as noncompact for this condition according to the LFD specifications. They are classified as compact according to the 12-38 specifications and compact and noncompact for the FLB and LTB requirements of the 12-52 specifications, respectively. According to the LFD specifications for bridge number 5, the critical stress is reduced significantly by the ρ_b factor (0.76) while for bridge number 18 ρ_b has a value closer to unity (0.92). This explains the fact that the 12-38 and 12-52 critical stress values are noticeably higher than the LFD critical stress for bridge number 5, but not for bridge number 18.

Bridge numbers 13, 19, 27, and 30 are the only bridges in the sample that have lateral bending stress values greater than 10 ksi for this design condition. Bridge numbers 13, 19, and 30 have F_{cr2} controlling for the 12-38 specifications and have lateral bending stress values greater than 10 ksi; further bridge number 30 has the lateral bending stress magnified according to Section 6.10.1.6 causing the 12-52 critical stress to be lower than that for the 12-38 specifications. Bridge number 27 also has a magnified lateral bending stress according to the 12-52 specifications resulting in a lateral bending stress value greater than ten.

Bridge number 22 is classified as noncompact according to the 12-38 specifications because these specifications limit the useable steel strength to 50 ksi and the flanges are made of 70-ksi steel at this location. This causes the critical stress calculated for the 12-38 specifications to be noticeably lower than that calculated for the other two specifications.

Bridge numbers 5, 13, 18, 19, 27 and 30 are good examples of cases where one or both of the previous specifications may have been unconservative. The reduction in critical stress according to the 12-52 specifications is based on geometry and lateral bending stress (recall this is due to the fact that one-third of the lateral bending stress was subtracted from the critical stress for the purposes of comparison in this study). The determination of whether or not the 12-52 critical stress value is lower than the LFD and 12-38 specifications depends on the combination of these two effects and is therefore difficult to quantify.

D4.3 NONCOMPOSITE, POSITIVE FLEXURE, COMPRESSION FLANGE

Figure D-10 shows the critical stress of the compression flange for the noncomposite, positive flexure section. Figure D-11 shows the critical-to-applied stress ratio for the analysis of the compression flange of the section for noncomposite, positive flexure. Figure D-12 shows the ratio of the critical stress calculated by each specification to the critical stress calculated by the LFD specifications for the same condition.

This condition exhibits the most varied response by far of all of the design conditions. The majority of the bridges in the sample exhibit a variation of more than five percent between calculated critical stress values. It is believed that this is due to the fact that this temporary construction condition may be overlooked during some designs. Furthermore, there may have been temporary construction conditions specified in the original design that were not made available for this study. These temporary construction conditions may have caused the section to have loads and/or unbraced length values that are different from those that could be deduced from the drawings made available. The noncomposite dead loads provided for the final structure were utilized to analyze the noncomposite structure. Four subsets of bridges are defined below in an attempt to explain the variations.

Bridge numbers 1, 7, 15, 29, 32 – this subset exhibits a pattern of the 12-52 critical stress being higher than the other two specifications, which yield similar results. Table D-4 outlines the critical stress of these bridges according to each of the three specifications. Bridge numbers 1, 7, and 15 are noncompact for all three specifications. Bridge numbers 29 and 32 are compact for all but the LTB requirements. For these bridges, the separate consideration of the FLB and LTB requirements has allowed a higher critical stress for the member. The ρ factors considered under the LFD and 12-38 specifications take into account the effects of flange slenderness (i.e., FLB) and unbraced length (i.e., LTB) concurrently to determine a single critical stress value while the 12-52 specifications consider each separately to determine two critical stress values and then the minimum of those two values is utilized for design. All of these bridges fall within the noncompact limits of the LTB requirements; however most are relatively close to the compact limit, causing the decrease in critical stress from the compact section critical stress to be nominal.

Bridge numbers 2, 5, 12, 17, 18, 23, 24, 27 – this subset exhibits a critical stress according to 12-38 that is noticeably higher than the LFD critical stress value and, with the exception of bridge number 24, the 12-52 critical stress value. Table D-5 details these critical stress values. These bridges are all classified as noncompact according to the LFD

specifications, compact according to the 12-38 specifications and noncompact or slender according to the LTB requirements of the 12-52 specifications.

For this segment of the sample, the 12-38 specifications are unconservative. The commentary of the 12-52 specifications refers to the use of r_t (Eq. 6.10.8.2.3-9) within the 12-52 specifications, which includes the destabilizing effect of the portion of the web in compression, instead of the standard radius of gyration.

$$r_t = \frac{b_{fc}}{\sqrt{12\left(1 + \frac{1}{3}\frac{D_c t_w}{b_{fc} t_{fc}}\right)}} \qquad \text{Eq. 6.10.8.2.3-9}$$

Bridge numbers 17, 18, and 23 are the bridges in this subset that have a 12-52 critical stress value that is lower than the LFD critical stress value. For bridge numbers 17 and 18 this is due to the fact that they are classified as slender (or very close to slender) according to the 12-52 specifications. Bridge number 23, on the other hand, has a large magnification factor (value of 6.4) applied to the lateral bending stress for the 12-52 specifications, which is caused by the compressive stress being relatively close to F_{cr}, defined by Eq. 6.10.8.2.3-8. If the exact equation for r_t were to be utilized (Eq. C6.10.8.2.3-1), a decrease in the magnification factor to approximately 4.3 could be expected, bringing the 12-52 critical stress value to the same level as the LFD value. The magnification factor employed by the 12-52 specifications estimates the second-order effects and is based on braced beam-column member behavior. In Eq. 6.10.1.6-4, the parenthetical portion represents the magnification factor.

$$F_{cr} = \frac{C_b R_b \pi^2 E}{\left(\frac{L_b}{r_t}\right)^2} \qquad \text{Eq. 6.10.8.2.3-8}$$

$$r_t = \frac{b_{fc}}{\sqrt{12\left(\frac{h}{d} + \frac{1}{3}\frac{D_c t_w}{b_{fc} t_{fc}}\frac{D^2}{hd}\right)}} \qquad \text{Eq. C6.10.8.2.3-1}$$

$$f_l = \left(\frac{0.85}{1 - \frac{f_{bu}}{F_{cr}}}\right) f_{l1} \geq f_{l1} \qquad \text{Eq. 6.10.1.6-4}$$

In a sense the magnification factor in the 12-52 specifications replaces the ρ factors from the LFD and 12-38 specifications. A comparison of the ρ factors and the magnification factors shows that they both account for an increased tendency of the section to deform due to secondary effects. For the LFD specifications, and the 12-38 specifications when they control, the ρ factors act to reduce the critical stress of the section based on lateral bending stress and geometry resulting in F_{cr1}. The magnifier on the lateral bending stress for the 12-52 specifications focuses on the magnitude of the longitudinal bending stress resulting in a final combined reduction in allowable stress due to the effects of geometry (i.e., either FLB or LTB considerations) and bending. When F_{cr2} controls for the 12-38 specifications only the lateral bending stress is considered however, for the sample considered, F_{cr1} controlled in the majority of cases.

Bridge numbers 6, 8, 9, 10, 13, 19, 21, 25 – this subset is characterized by the 12-52 critical stress being lower than the LFD and 12-38 critical stress values. Furthermore, with the exception of bridge numbers 6, 8, and 19, the 12-38 critical stress is lower than the LFD critical stress as well. The calculated critical stress values are listed in Table D-6. All of these bridges are classified as compact according to the LFD and 12-38 and as noncompact or slender according to the LTB requirements of the 12-52 specifications. It appears that the critical stress values according to the previous specifications may not have been conservative for this segment of the sample due to LTB considerations.

Bridge numbers 3, 4, 11, 14, 16, 20, 22, 26, 28, 30, and 31 are the remaining bridges with less than five percent difference in critical stress values.

D4.4 NONCOMPOSITE, NEGATIVE FLEXURE, COMPRESSION FLANGE

Figure D-13 shows the critical stress of the compression flange for the noncomposite, negative flexure section. Figure D-14 shows the critical-to-applied stress ratio for the analysis of the compression flange of the section for noncomposite, negative flexure. Figure D-15 shows the ratio of the critical stress calculated by each specification to the critical stress calculated by the LFD specifications for the same condition.

Bridge numbers 5 and 18 are the only ones that are classified as noncompact according to the LFD specifications. For this condition, both bridges have a low ρ_b factor causing the 12-38 and 12-52 specifications to result in higher critical stress values.

Bridge number 22 is classified as noncompact according to the 12-38 specifications because the useable steel strength is limited to 50 ksi and the flanges are made of 70-ksi steel in this location. This causes the critical stress calculated for the 12-38 specifications to be noticeably lower than that calculated for the other two specifications.

Bridge numbers 24, 29, 30, and 31 are the only bridges in the sample that have a critical stress lower than F_{bs} for the LFD and 12-38 specifications. The reference to F_{bs} is significant because it represents the critical stress of a straight girder of the same proportions, indicating that the majority of bridges are not sufficiently curved to reduce their critical stress for this condition. These four bridges all exhibit the same trend in critical stress of LFD and 12-38 having a slightly lower critical stress than that calculated for the 12-52 specifications.

D4.5 COMPOSITE, POSITIVE FLEXURE, TENSION FLANGE

Figure D-16 shows the critical stress of the tension flange for the composite, positive flexure section. Figure D-17 shows the critical-to-applied stress ratio for the analysis of the tension flange of the section for composite, positive flexure. Figure D-18 shows the ratio of the critical stress calculated by each specification to the critical stress calculated by the LFD specifications for the same condition.

The LFD specifications do not reduce the allowable critical stress of the tension flange below the yield strength. The 12-38 specifications according to Section 5.3, however, utilize the same reduction factors (e.g., ρ_w, ρ_b) for the tension flanges as are utilized for the compression flanges for both the 12-38 and LFD specifications. For bridge numbers 13, 15, 24 and, 31 in particular, for which F_{cr1} controls according to the 12-38 specifications, this difference becomes evident. The 12-52 specifications only consider the lateral bending stress to determine the allowable bending critical stress of the tension flange. For the bridges that have a zero value for

the lateral bending stress (bridge numbers 4, 6, and 22), the critical stress values are identical according to the three specifications. The remaining bridges have the 12-38 and 12-52 critical stress values equal to one another due to the fact that the critical stress is dependent only on the lateral bending stress. It should be noted that bridge numbers 1, 24, 25, 29, and 30 utilize 36-ksi steel for this location.

D4.6 COMPOSITE, NEGATIVE FLEXURE, TENSION FLANGE

Figure D-19 shows the critical stress of the tension flange for the composite, negative flexure section. Figure D-20 shows the critical-to-applied stress ratio for the analysis of the tension flange of the section for composite, negative flexure. Figure D-21 shows the ratio of the critical stress calculated by each specification to the critical stress calculated by the LFD specifications for the same condition. Note that the gaps occurring for bridge numbers 3, 6, 20, and 32 are due to the fact that those bridges are single-span structures. Bridge numbers 24, 25, 29, and 30 utilize 36-ksi steel for the entire girder.

On the whole, the critical-to-applied stress ratios obtained by the three specifications are identical for this condition. The two exceptions occur for bridge numbers 1 and 22, which have hybrid sections in the negative moment regions; bridge number 1 has 36-ksi webs and 50-ksi flanges and bridge number 22 has 50-ksi webs and 70-ksi flanges. The critical stress for these sections is slightly lower according to the 12-52 specifications due to the consideration of a hybrid factor, R_h, outlined in Eq. 6.10.1.10.1-1. It should be noted that hybrid sections are not allowed by the 12-38 specifications but are allowed by the LFD specifications, which have provisions similar to those outlined by 12-52 for the consideration of stresses in hybrid sections. The provisions for hybrid sections in the LFD specifications consider only yielding of the tension flange in positive bending regions or only yielding of the compression flange in negative bending regions, while the 12-52 specifications have been adapted to include all positions of the neutral axis and all combinations of yield strengths for the various portions of the girder.

D4.7 NONCOMPOSITE, POSITIVE FLEXURE, TENSION FLANGE

Figure D-22 shows the critical stress of the tension flange for the noncomposite, positive flexure section. Figure D-23 shows the critical-to-applied stress ratio for the analysis of the tension flange of the section for noncomposite, positive flexure. Figure D-24 shows the ratio of the critical stress calculated by each specification to the critical stress calculated by the LFD specifications for the same condition.

The LFD specifications do not reduce the allowable critical stress of the tension flange below the yield strength. The 12-38 specifications according to Section 5.3, however, utilize the same reduction factors (e.g., ρ_w, ρ_b) for the tension flanges as are utilized for the compression flanges in both the 12-38 and LFD specifications. For bridge numbers 24, 29, 30, 31, and 32 in particular, for which F_{cr1} controls according to the 12-38 specifications, this difference becomes evident. For the bridges that have a zero value for the lateral bending stress (bridge numbers 4, 6, and 22), the critical stress values are identical for all three specifications.

Cases when the 12-52 specifications exhibit a lower critical stress than the 12-38 specifications are due to the magnification factor for the lateral bending stress utilized in the 12-52 specifications under Section 6.10.1.6. Bridge numbers 13, 18, 23, and 27 exhibit the most pronounced difference though several other bridges have minimal degrees of magnification. The

remaining bridges have the 12-38 and 12-52 critical stress values equal to one another due to the fact that the critical stress is equally dependent on the lateral bending stress.

D4.8 NONCOMPOSITE, NEGATIVE FLEXURE, TENSION FLANGE

Figure D-25 shows the critical stress of the tension flange for the noncomposite, negative flexure section. Figure D-26 shows the critical-to-applied stress ratio for the analysis of the tension flange of the section for noncomposite, negative flexure. Figure D-27 shows the ratio of the critical stress calculated by each specification to the critical stress calculated by the LFD specifications for the same condition.

The LFD specifications do not reduce the allowable critical stress of the tension flange below the yield strength. The 12-38 specifications according to Section 5.3, however, utilize the same reduction factors (e.g., ρ_w, ρ_b) for the tension flanges as are utilized for the compression flanges both in the 12-38 and LFD specifications. For bridge numbers 24, 29, 30, and 31 in particular, for which F_{cr1} controls according to the 12-38 specifications, this difference becomes evident. The 12-52 specifications only consider the lateral bending stress to determine the allowable bending critical stress of the tension flange.

Bridge numbers 1 and 22, which have hybrid sections in the negative moment regions, have a slightly lower critical stress according to the 12-52 specifications due to the consideration of a hybrid factor, R_h. Bridge number 1 has 36-ksi webs and 50-ksi flanges and bridge number 22 has 50-ksi webs and 70-ksi flanges. It should be noted that hybrid sections are not allowed by the 12-38 specifications but are allowed by the LFD specifications, which have similar provisions for the consideration of stresses in hybrid sections. The provisions for hybrid sections in the LFD specifications consider only yielding of the tension flange in positive bending regions or only yielding of the compression flange in negative bending regions, while the 12-52 specifications have been adapted to include all positions of the neutral axis and all combinations of yield strengths for the various portions of the girder.

The remaining bridges have the 12-38 and 12-52 critical stress values equal to one another due to the fact that the bending critical stress is equally dependent on the lateral bending stress.

D4.9 SUMMARY

In spite of the differences between the flexural design specifications outlined in the previous sections, the calculated critical stress values are for the most part very similar. The main causes of major differences in critical stress between the three specifications are as follows:

- Changes in the classification of the flange (e.g., compact, noncompact, slender) between the three specifications
- Lateral stress consideration (including magnification) according to the 12-52 specifications as compared to the reductions due to the ρ factors utilized in the LFD and 12-38 specifications
- Noncomposite design as a temporary condition

Although the proportion varies based on the design specification selected, by and large for the composite, positive flexure analysis the tension flange controls the design and for negative flexure the compression flange controls the design. This indicates that the bottom flange of the member is largely the most critical to the design of the member. For the

noncomposite design checks, the compression flange controls in both positive and negative flexural sections indicating its importance in the unbraced or discretely-braced conditions.

D4.10 MODIFICATIONS TO THE SAMPLE

Once it was clear which design paths were utilized, the task was undertaken to modify the existing bridges in the sample to "fill in the gaps." Three main goals existed for the flexural design paths. First, for the noncomposite positive flexure condition, two bridges were forced to have noncompact compression flanges, such that FLB controls over LTB. For the noncomposite negative flexure condition the goal was to force two bridges to have noncompact compression flanges, such that FLB controls over LTB, and to force two bridges to have a slender unbraced length according to the LTB requirements. For all of the conditions, the bridges closest to the desired condition were utilized.

For the noncomposite positive flexure condition Table D-7 outlines the changes that were made to bridge numbers 14 and 15 by decreasing the flange thickness, t_{fc}, and the resulting effects on critical stress.

For the noncomposite negative flexure condition, bridge numbers 18 and 21 were modified by decreasing the flange thickness, t_{fc}, to make the flanges noncompact and force FLB to control over LTB. The changes to the flange thickness and the subsequent effects on critical stress are outlined in Table D-8. It should be noted that according to the 12-38 specifications, the flange of bridge number 18 switched from compact (based on the original flange thickness) to non-compact (based on the modified flange thickness) causing the large decrease in critical stress listed.

Also for the noncomposite negative flexure condition, a slender unbraced length was achieved for bridge numbers 9 and 10. The increases in the unbraced length, L_b, and resulting critical stress values are outlined in Table D-9.

It should be noted that these "modified" bridges are not included in the bridge sample, but were analyzed according to the same specifications to determine their fit within the sample. On the whole, little, if any, change was observed in the LFD and 12-38 critical stress values based on the modifications made in order to shift the 12-52 results; exceptions were noted where appropriate. Furthermore, all changes in critical stress were logical thus confirming the validity of the specifications.

D5 FLEXURAL DESIGN (SERVICE CONDITION)

In general, the service load provisions for the three analysis specifications are very similar. The main differences occur in the load factors and portion of the lateral bending stress considered by each specification. The load factors for dead and live load are as follows:

LFD: D + 5/3 (L + I)
12-38: 1.3 (D + 2.2 (L + I))
12-52: DL + 1.3 LL (Service II Load Combination)

It should be noted that since all of the bridges in this study are composite in the final condition, only the composite, positive flexure and composite, negative flexure conditions are examined for this load case.

For the LFD specifications, Section 2.5 (F) indicates that the stresses due to longitudinal and lateral bending shall not exceed $0.95F_y$. Lateral bending stresses are not considered for continuously braced flanges and are therefore only considered for the bottom flange. There are no provisions for limiting the compressive stress in the web in order to prevent web bend-buckling.

For the 12-38 specifications, Section 9.5 indicates that the longitudinal bending stresses in all continuously braced flanges and partially braced tension flanges shall not exceed $0.95F_y$ and that the longitudinal bending stress in partially braced compression flanges shall not exceed the lesser of $0.95F_y$ and the value obtained from Equation (5-8) (refer to Section D10 for details). The lateral bending stresses are not taken into consideration for the 12-38 service load case. The compressive stress in the web is limited by F_{cr}, as calculated by Equation 6-3 or 6-8 (depending on the stiffening of the web section).

$$F_{cr} = \frac{0.9Ek}{\left(\frac{D}{t_w}\right)^2} \leq F_y \qquad \text{Eq. (6-3), (6-8)}$$

where k is equal to $9(D/D_c)^2$ for transversely stiffened webs and $7.2(D/D_c)^2$ for unstiffened webs. It should be noted that the 12-38 specifications do not allow hybrid sections and therefore do not distinguish between the yield strength of the flanges and the web; for the purposes of these checks, the yield strength of the web was used as the limiting stress in Eq. (6-3) and (6-8) for the two hybrid sections in an attempt to be conservative.

For the 12-52 specifications, Equations 6.10.4.2.2-1 and 6.10.4.2.2-2 govern the limiting flange stresses for composite sections. Both utilize a limit of $0.95R_hF_y$ with half of the lateral bending stress contributing to the load for the bottom flange only. Equation 6.10.4.2.2-4 details that the maximum compressive stress in the web is limited to F_{cr} for all sections except those composite sections in positive flexure for which D/t_w is less than or equal to 150.

$$F_{cr} = \frac{0.9Ek}{\left(\frac{D}{t_w}\right)^2} \leq \min\left(R_hF_{yc}, F_{yw}/0.7\right) \qquad \text{Eq. 6.10.1.9.1-1}$$

$$k = \frac{9}{(D_c/D)^2} \qquad \text{Eq 6.10.1.9.1-2}$$

Figure D-28 and Figure D-29 show the critical-to-applied stress ratios for the compression and tension flanges in positive flexure, respectively. The noticeably lower critical-to-applied stress ratios according to the 12-38 specifications in both figures are due to the load factors. For both the tension and compression flanges, the difference between the 12-52 and LFD ratios is due to the difference in load factors, and for the tension flange the portion of the lateral bending stress that is considered increases this difference. The limit on the tension flange controls the design of the positive flexure sections for all three of the specifications with few exceptions. A comparison of the critical-to-applied stress ratios for the web is not possible for the positive flexure sections due to the fact that the LFD specifications do not outline a limit and the 12-52 provisions need not be checked for composite sections in positive flexure for which D/t_w is less than or equal to 150 (all but one of the bridges in this study).

The critical-to-applied stress ratios in the negative moment regions are detailed for the compression and tension flanges, respectively, in Figure D-30 and Figure D-31. Again, the 12-

38 specifications exhibit the lowest critical-to-applied stress ratios of the three specifications. This is partially due to the higher load factors considered but is also contributed to by the fact that the limiting stress is controlled by Equation (5-8), which is less than $0.95F_y$, for the majority of the bridges. The same difference between the LFD and 12-52 specifications for positive flexure were exhibited for negative flexure, this time with the compression flange being influenced by the lateral bending stress. Figure D-32 shows the critical-to-applied stress ratio for the web of the negative flexure sections. The differences between the critical-to-applied stress ratios for the 12-38 and 12-52 specifications are due primarily to the differences in load factor, but also reflect the differences in the coefficients for k between the two specifications for unstiffened webs. The LFD specifications do not define a limit for the compressive stress in the web. For all three specifications, the compression flange limits control for the service load case.

D6 CONCLUSIONS

A comparison of the three most recent curved girder specifications was performed based on the examination of 32 bridges. Calculations were made to determine the shear and flexural critical stress of the bridges at critical locations according to the design protocols outlined in the 1993 AASHTO Guide Specifications for Horizontally Curved Girders (*D1*), referred to as "LFD"; the 2003 Guide Specifications for Horizontally Curved Steel Highway Bridges (*D2*), referred to as "12-38"; and the yet unpublished 2005 Interims to the LRFD Bridge Design Specifications (*D3*), referred to as "12-52."

Based on these analyses, the following observations and conclusions can be made:
Strength I load case, Shear Design:

- The maximum transverse stiffener spacing has been progressively increased from D, the depth of the web, in the LFD specifications to $3D$ in the 12-52 specifications.
- All three specifications utilize the ratio of the shear-buckling resistance to the shear yield strength, C. A comparison of the equations used to calculate C in each of the specifications reveals that the constants for the equations are equivalent.
- In general, the critical stress values for the three analysis specifications are consistent except that the 12-52 specifications allow for the consideration of the additional post-buckling strength from tension-field action in the shear critical stress calculations. This post-buckling strength is also recognized in the LFD (*D4*) and LRFD (*D3*) straight girder provisions and results in a higher critical stress for the majority of the stiffened bridges in the sample.

Strength I load case, Flexural Design:

- Flexural analysis according to all of the specifications is divided between composite and noncomposite sections, positive and negative flexure, and compression or tension flanges.
- Only modest changes are made to the slenderness limits for the various classifications of the flanges (e.g., compact, noncompact, slender) according to the three specifications. These changes, however, are often enough to change the classification of a flange and therefore the critical stress of the section.
- All three of the specifications account for an increased tendency of the section to deform due to secondary bending effects. The LFD and 12-38 specifications

consider ρ factors and the 12-52 specifications consider a magnification factor for the lateral bending stress. For the LFD specifications, and the 12-38 specifications, the ρ factors act to reduce the critical stress of the section based on lateral bending stress and geometry resulting in F_{cr1}. The magnifier on the lateral bending stress for the 12-52 specifications focuses on the magnitude of the longitudinal bending stress resulting in a final combined reduction in the stress limit due to the effects of geometry (i.e., either FLB or LTB considerations) and bending.

- The LFD and 12-38 specifications consider the lateral bending stress to reduce the critical stress, while the 12-52 specifications consider the lateral bending stress as a load. The final effect of including the lateral bending stress in all of the specifications is to reduce the useable stress limit for gravity loads.
- For the bridges considered, the noncomposite design was a temporary condition and the noncomposite dead loads provided for the final structure were utilized to analyze the noncomposite structure. Information was not provided regarding any temporary support points or the construction sequence for a more inclusive analysis.
- Hybrid sections are not allowed by the 12-38 specifications but are allowed by the LFD specifications and the 12-52 specifications, which have similar provisions for the consideration of stresses in hybrid sections. Minor reductions in the critical stress occur when the yield strength of the web is less than the yield strength of one or both of the flanges.
- In spite of the differences between the flexural design specifications outlined in the previous section, the calculated critical stress values are largely very similar.

Service II load case:

- The primary differences between the three specifications for this load case are due to the load factors.
- Differences were also exhibited in the consideration of the lateral bending stress, with LFD considering the entire value, 12-52 considering half of the value and 12-38 considering none.
- The limiting stresses for the flanges and the webs were nearly identical between the three specifications. Exceptions to this are the compression flange for negative flexure according to 12-38, the consideration of R_h according to the 12-52 specifications, and the coefficient for the calculations of k for web bend-buckling, though all are minor differences.

D7 FIGURES

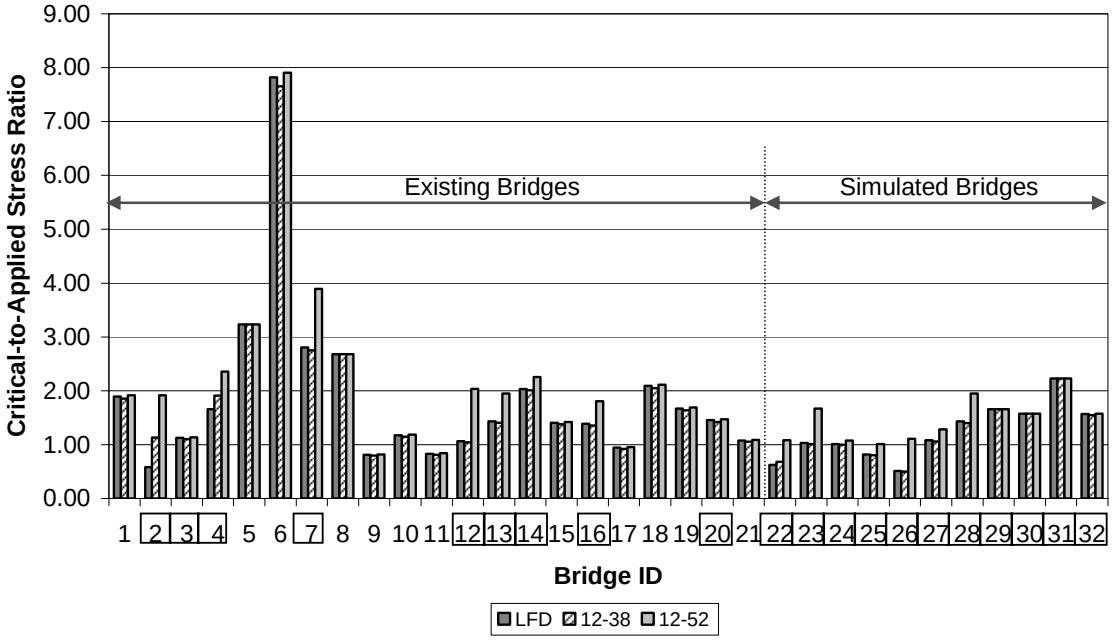

Figure D-1. Shear Critical-to-Applied Stress Ratio

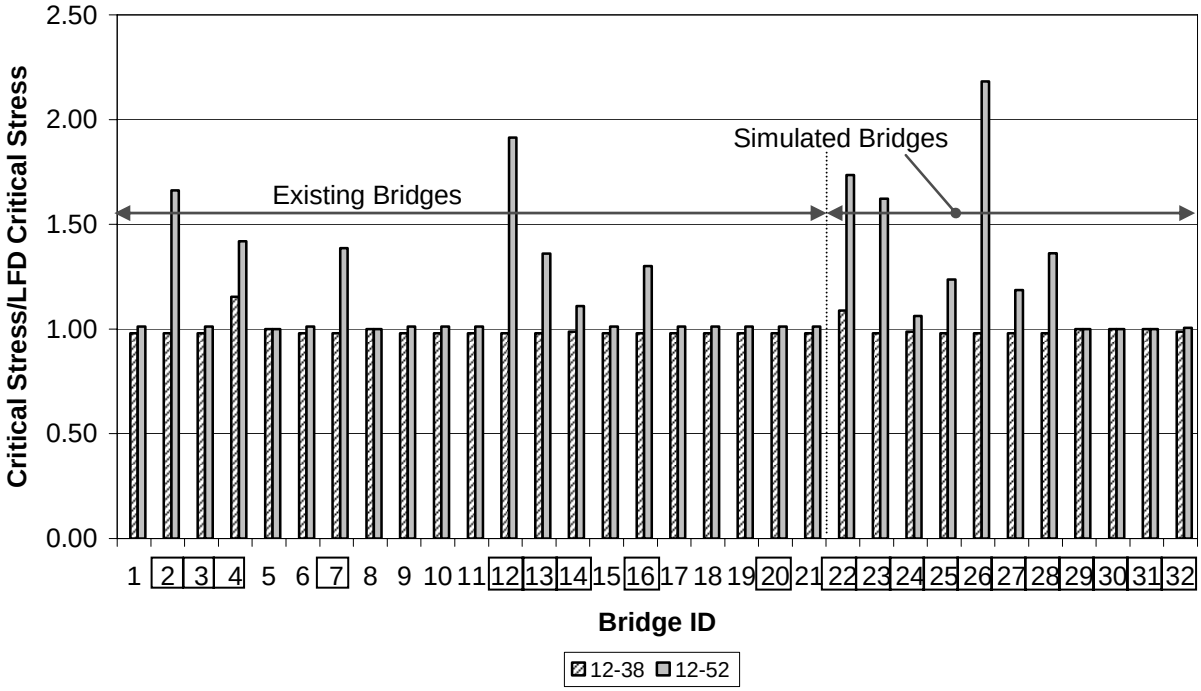

Figure D-2. Shear Critical Stress Divided by LFD Shear Critical Stress

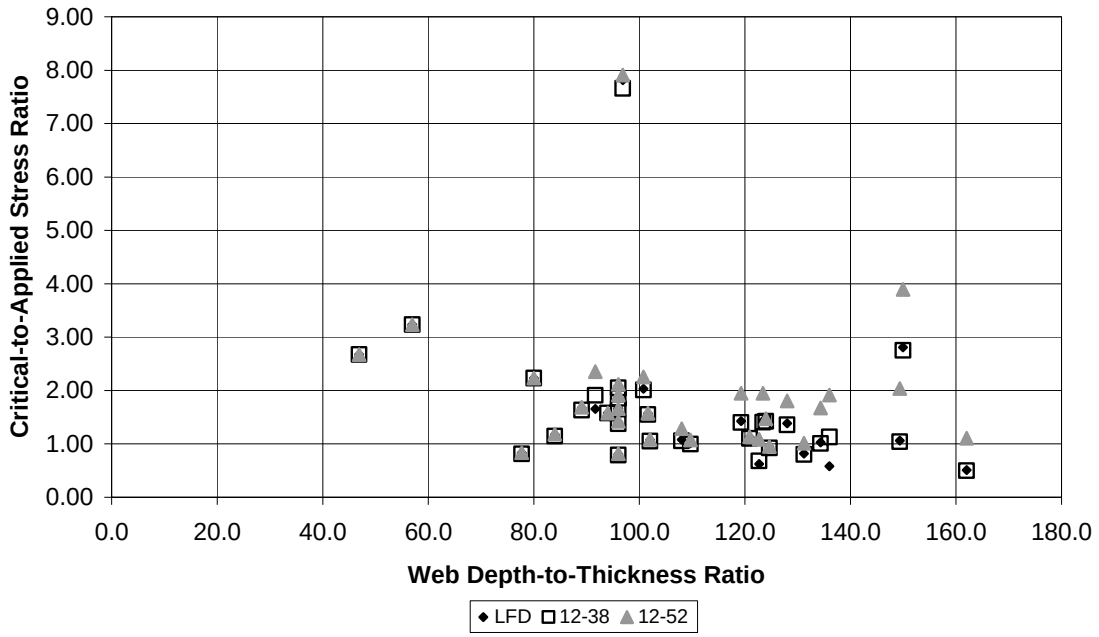

Figure D-3. Shear Critical-to-Applied Stress Ratio versus Web Depth-to-Thickness Ratio

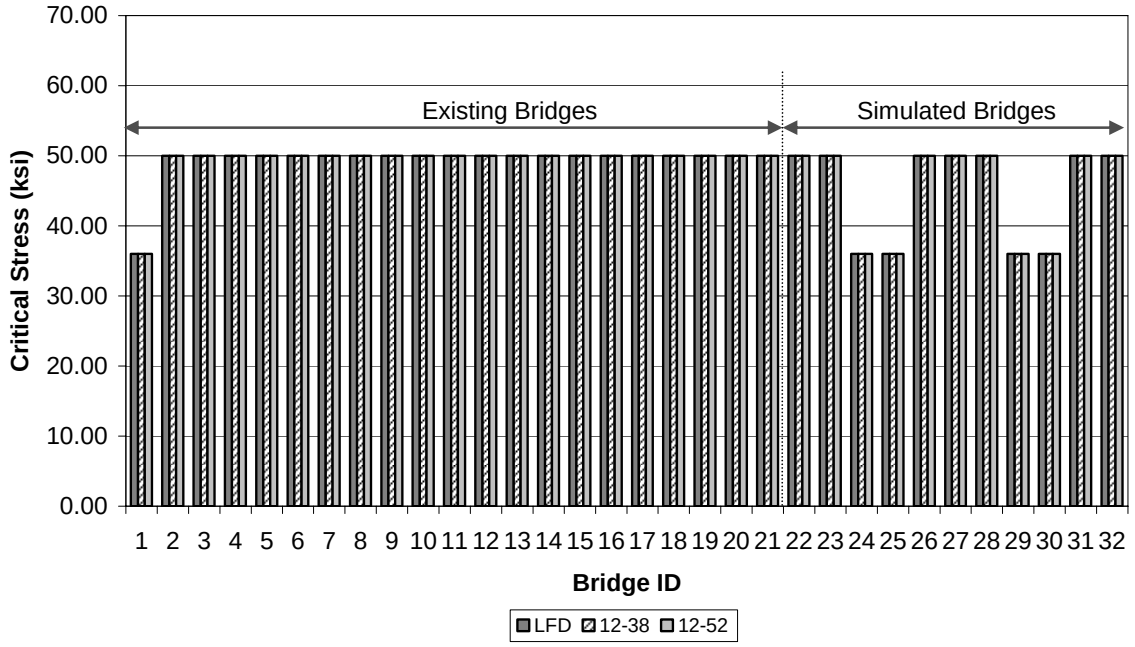

Figure D-4. Flexural Critical Stress - Composite, Positive Flexure, Compression Flange

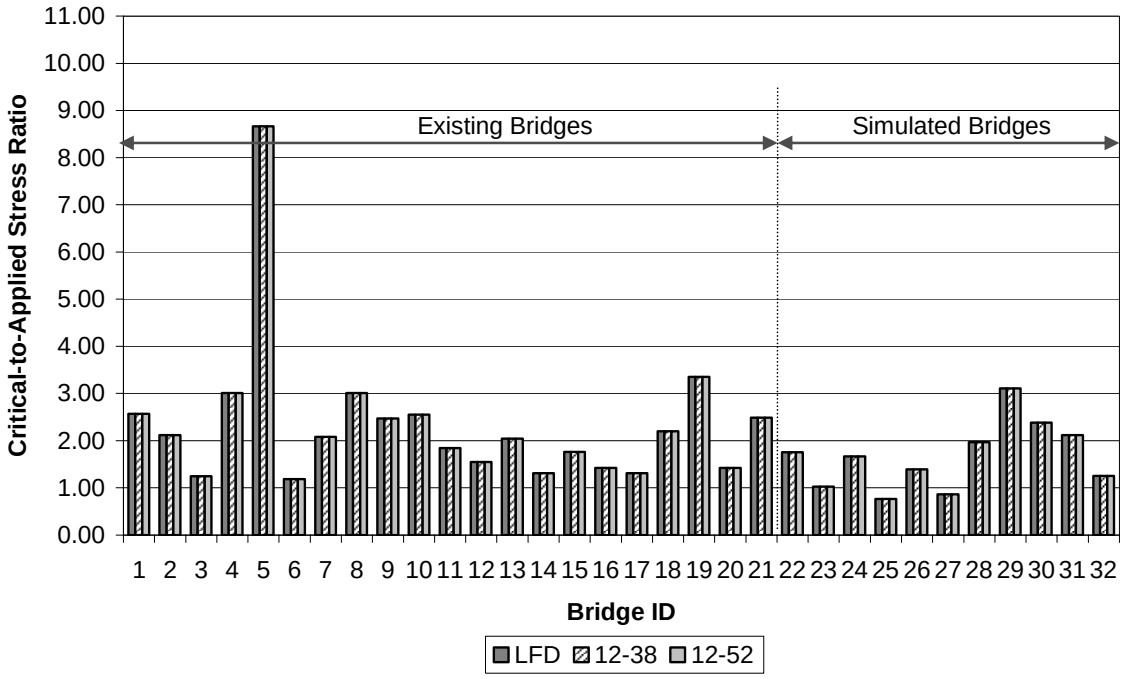

Figure D-5. Flexural Critical-to-Applied Stress Ratio - Composite, Positive Flexure, Compression Flange

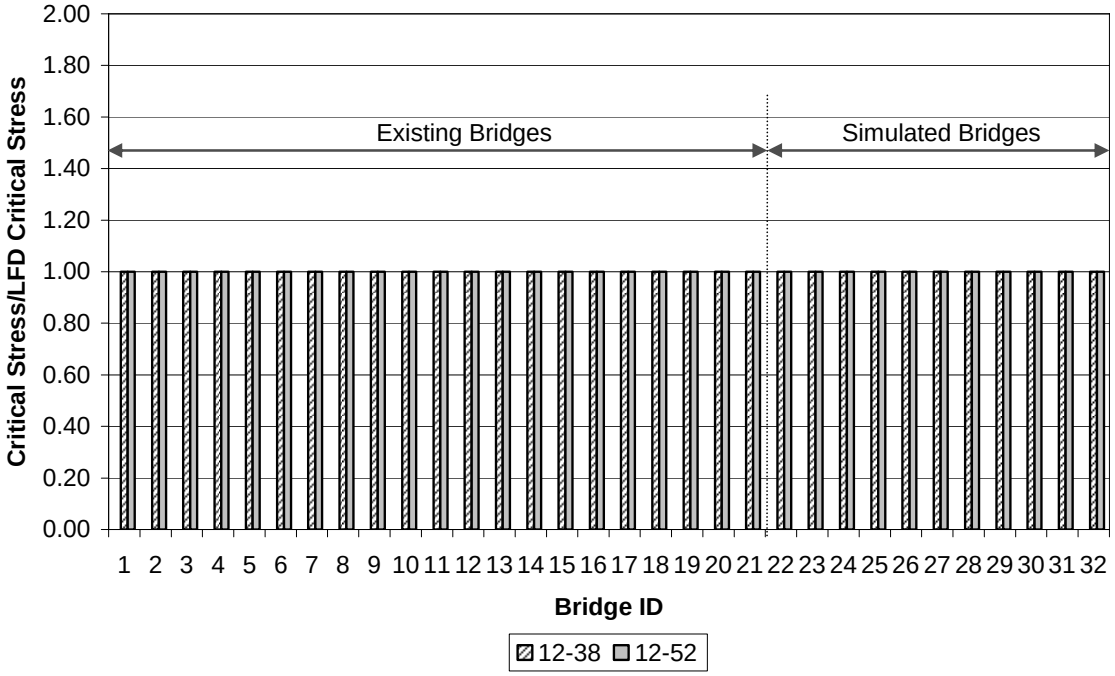

Figure D-6. Flexural Critical Stress Divided by LFD Flexural Critical Stress - Composite, Positive Flexure, Compression Flange

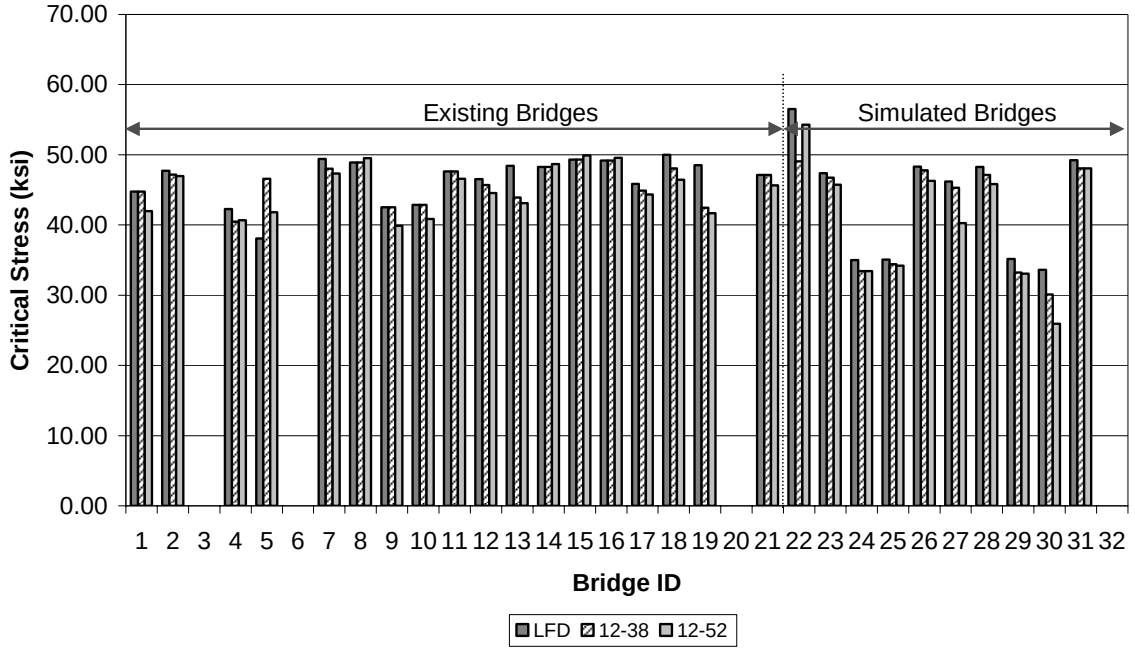

Figure D-7. Flexural Critical Stress - Composite, Negative Flexure, Compression Flange

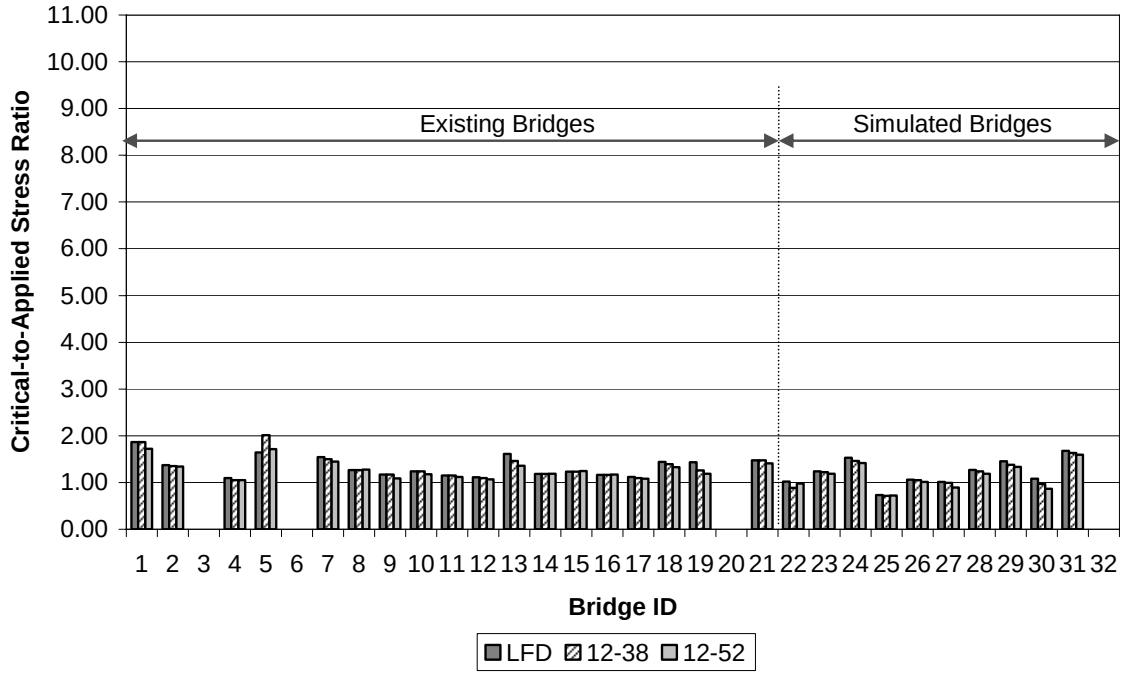

Figure D-8. Flexural Critical-to-Applied Stress Ratio - Composite, Negative Flexure, Compression Flange

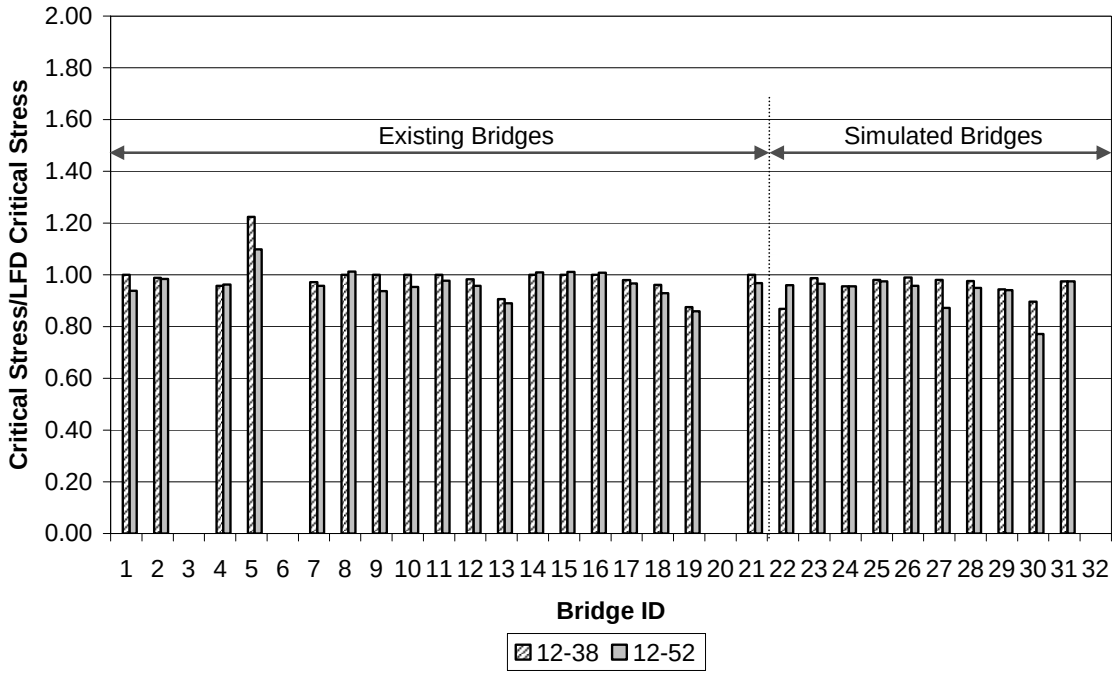

Figure D-9. Flexural Critical Stress Divided by LFD Flexural Critical Stress - Composite, Negative Flexure, Compression Flange

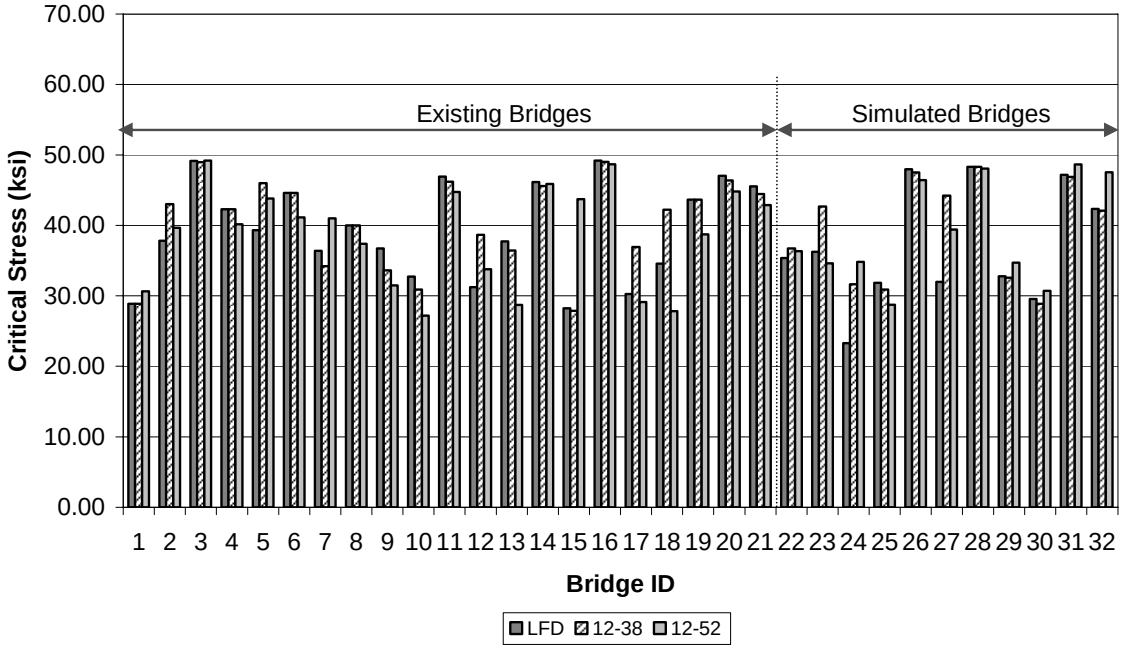

Figure D-10. Flexural Critical Stress – Noncomposite, Positive Flexure, Compression Flange

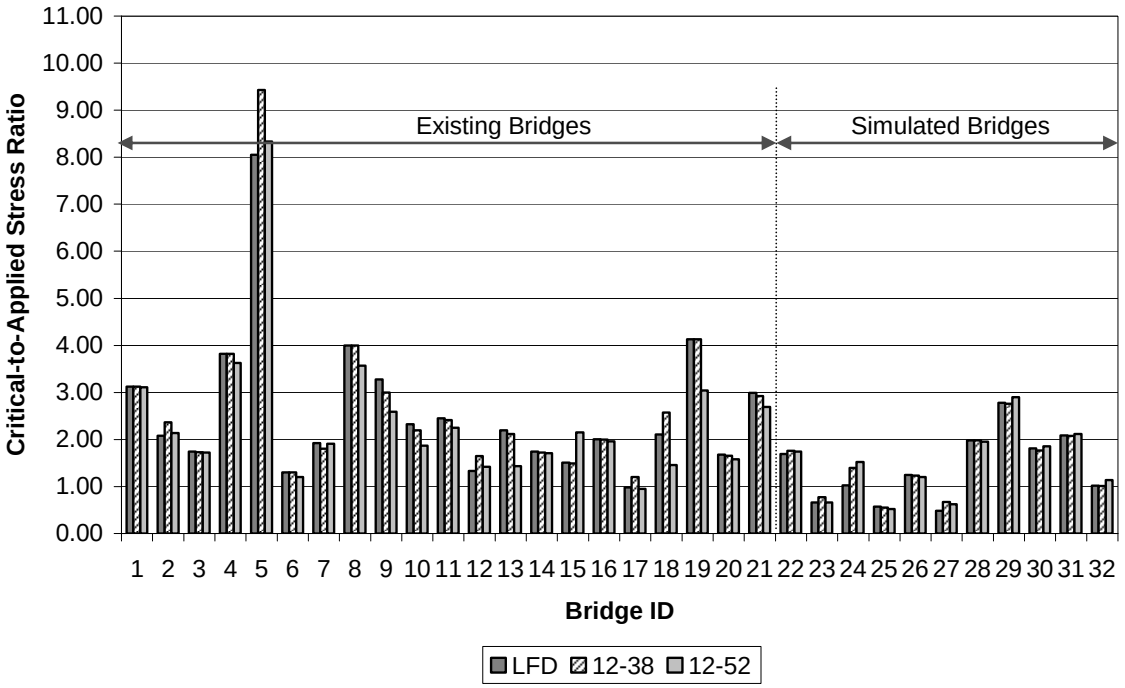

Figure D-11. Flexural Critical-to-Applied Stress Ratio – Noncomposite, Positive Flexure, Compression Flange

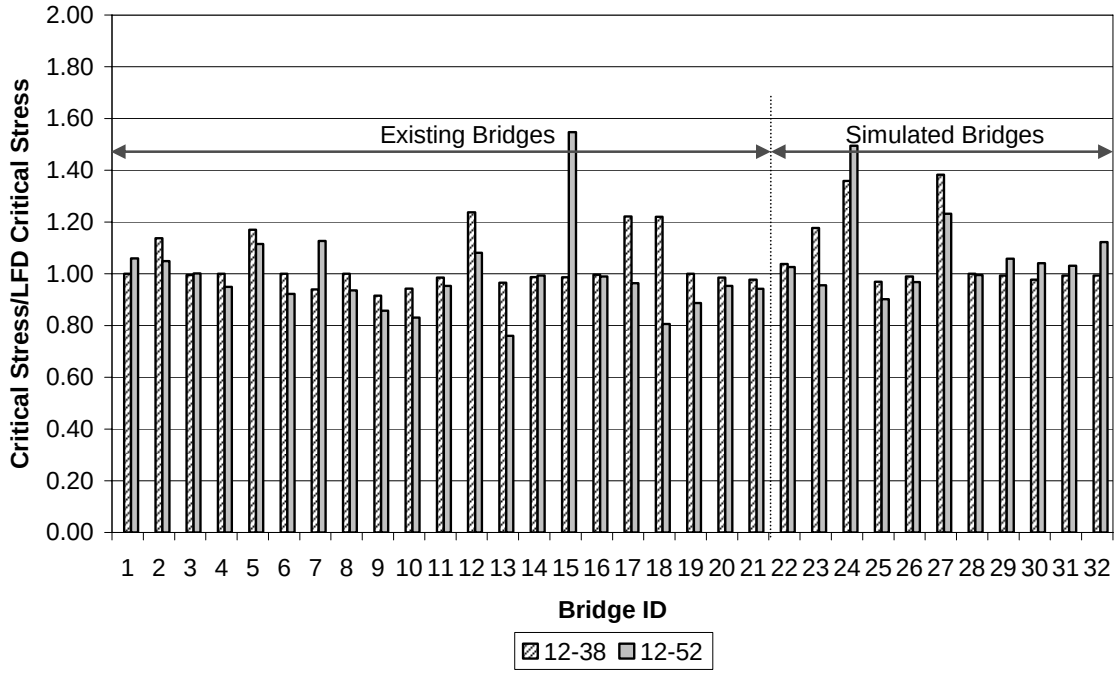

Figure D-12. Flexural Critical Stress Divided by LFD Flexural Critical Stress – Noncomposite, Positive Flexure, Compression Flange

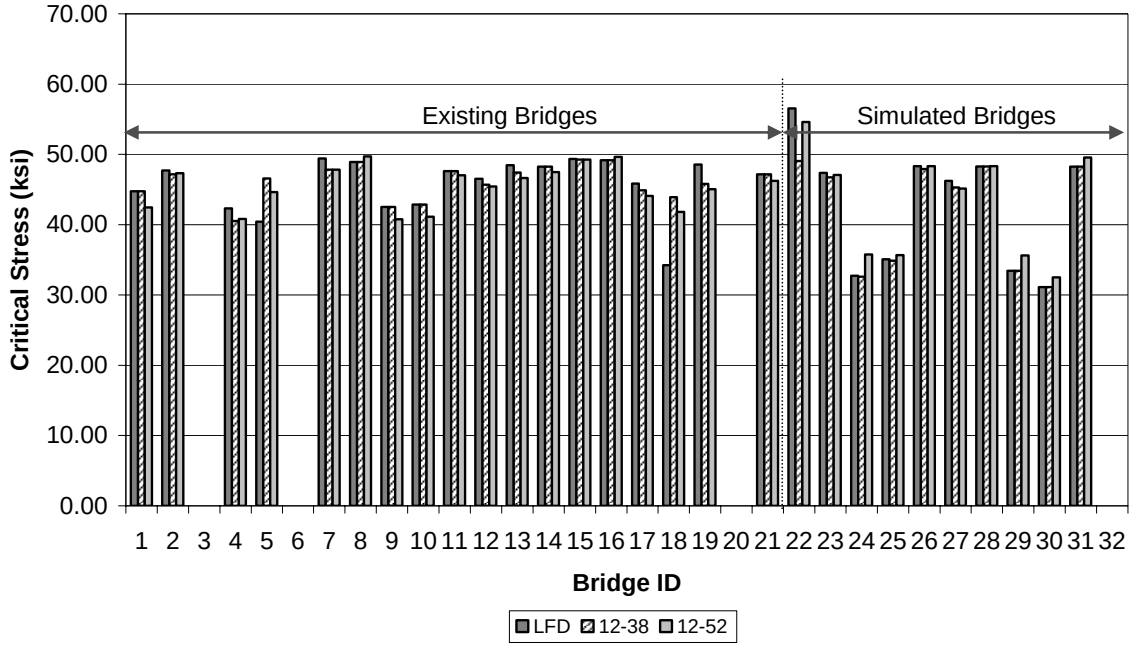

Figure D-13. Flexural Critical Stress – Noncomposite, Negative Flexure, Compression Flange

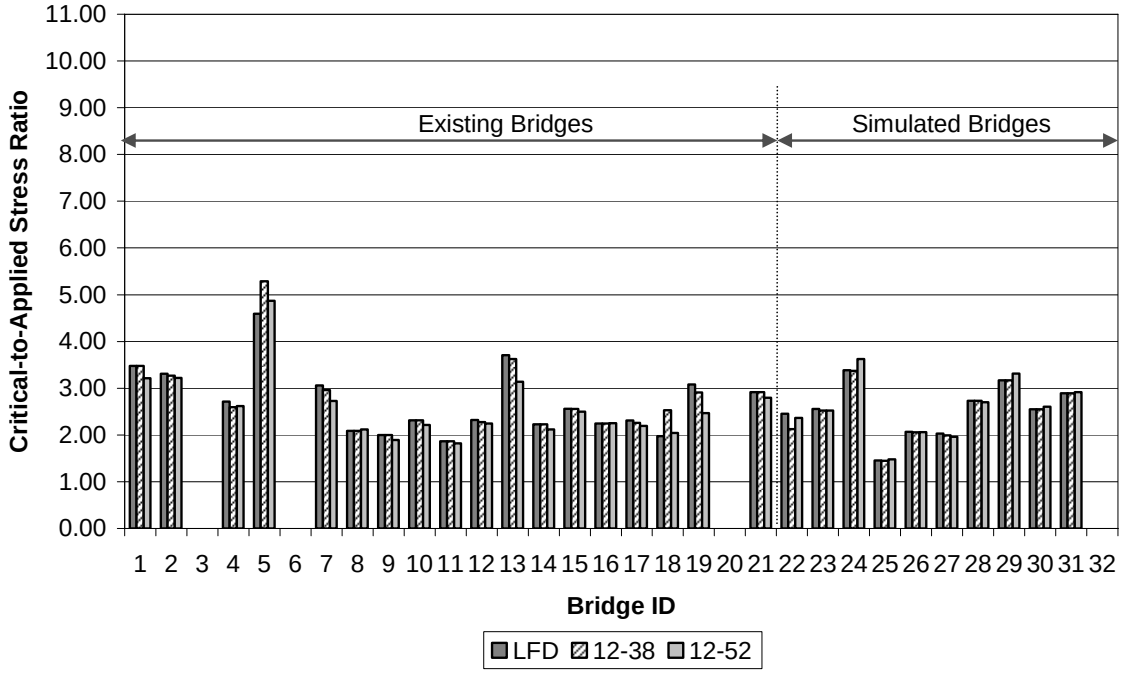

Figure D-14. Flexural Critical-to-Applied Stress Ratio – Noncomposite, Negative Flexure, Compression Flange

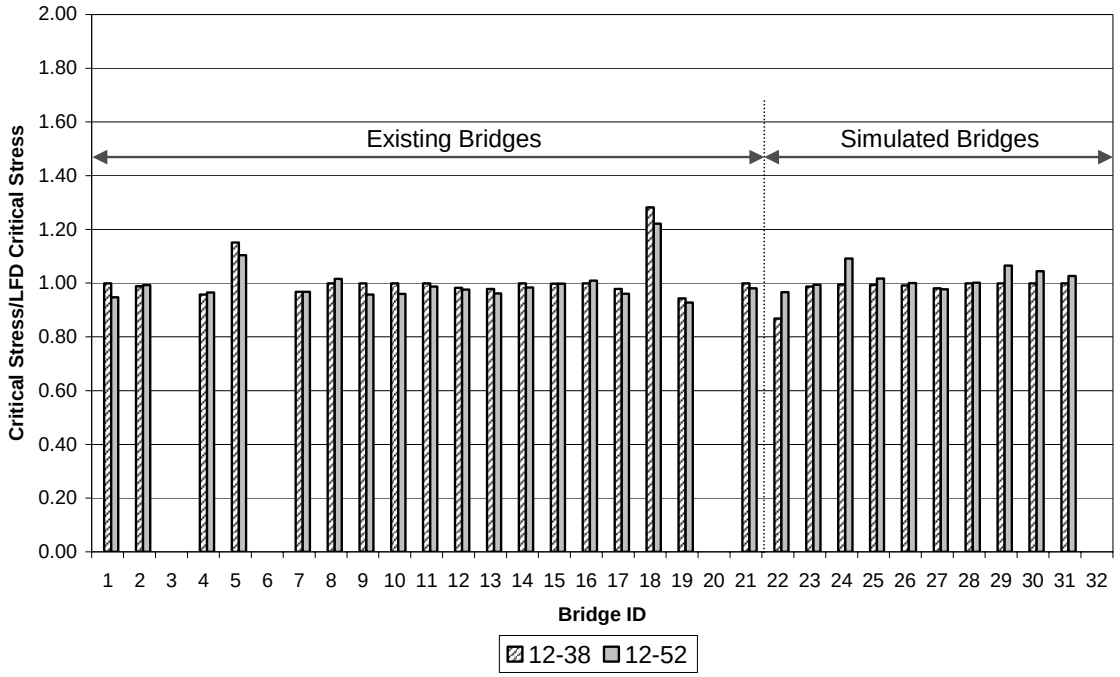

Figure D-15. Flexural Critical Stress Divided by LFD Flexural Critical Stress – Noncomposite, Negative Flexure, Compression Flange

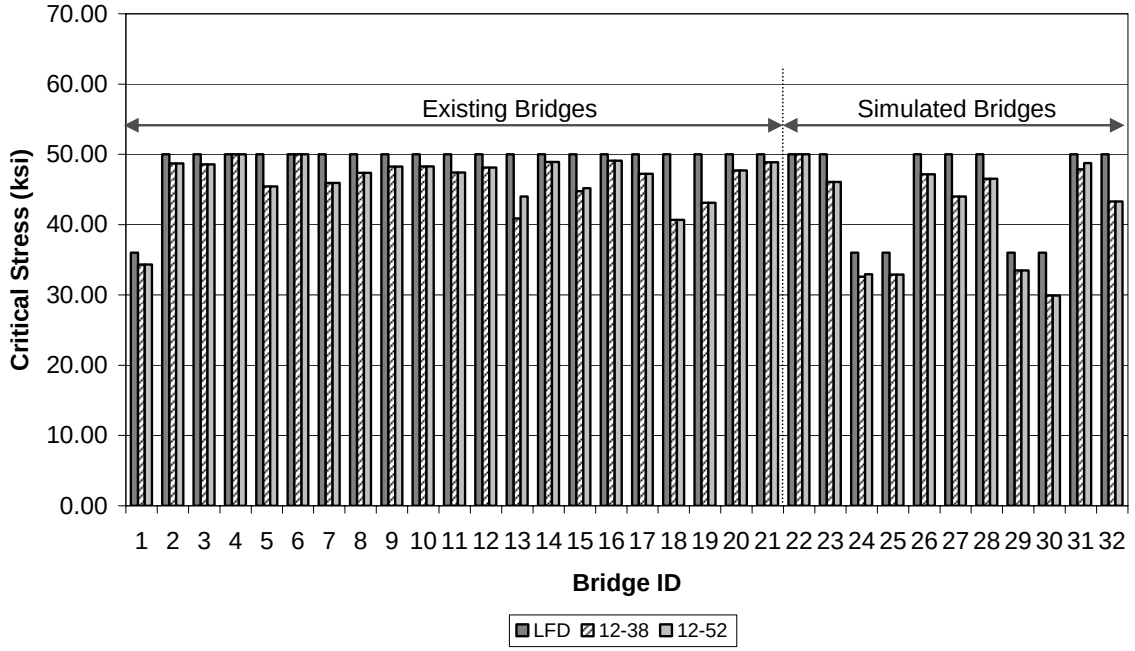

Figure D-16. Flexural Critical Stress - Composite, Positive Flexure, Tension Flange

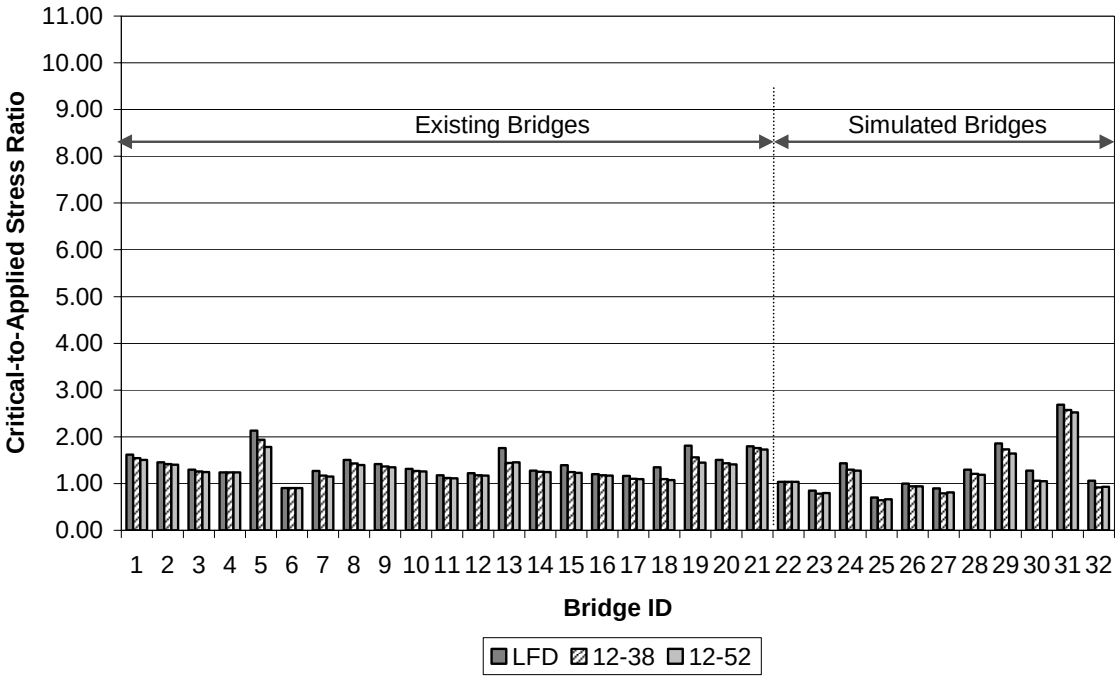

Figure D-17. Flexural Critical-to-Applied Stress Ratio - Composite, Positive Flexure, Tension Flange

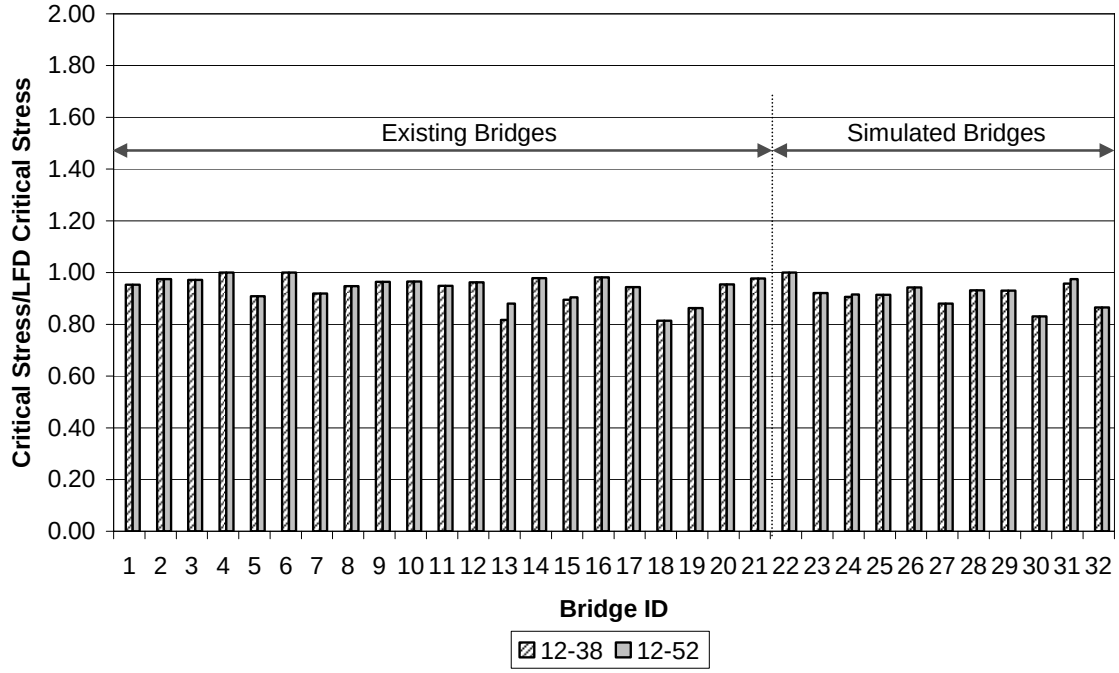

Figure D-18. Flexural Critical Stress Divided by LFD Flexural Critical Stress - Composite, Positive Flexure, Tension Flange

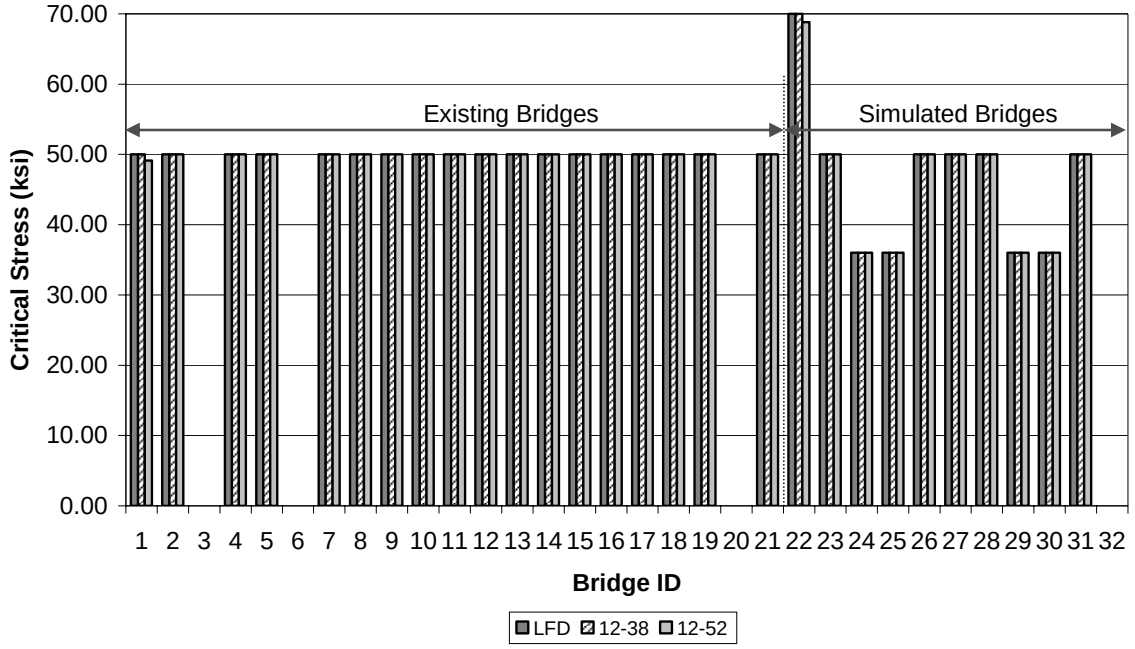

Figure D-19. Flexural Critical Stress – Composite, Negative Flexure, Tension Flange

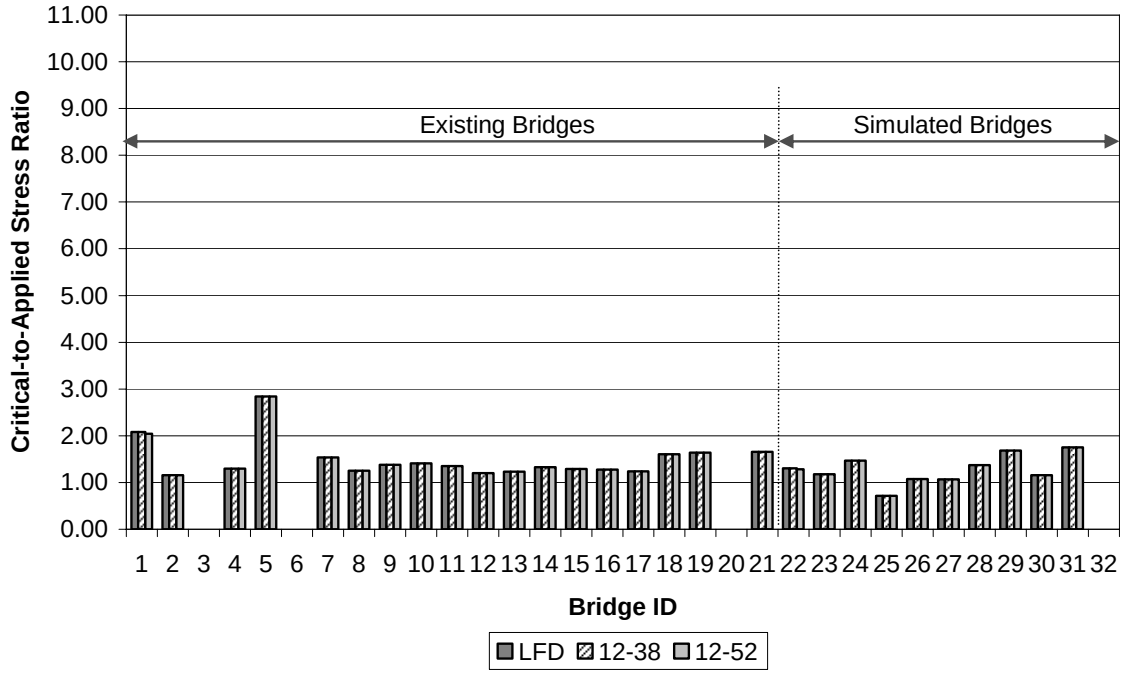

Figure D-20. Flexural Critical-to-Applied Stress Ratio - Composite, Negative Flexure, Tension Flange

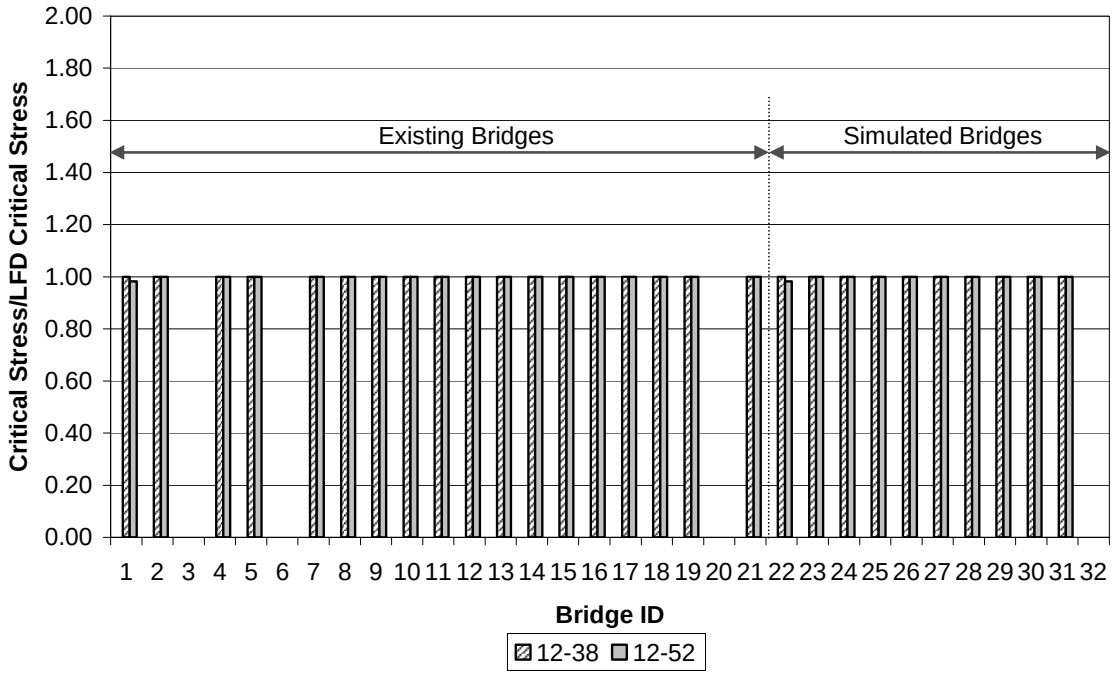

Figure D-21. Flexural Critical Stress Divided by LFD Flexural Critical Stress - Composite, Negative Flexure, Tension Flange

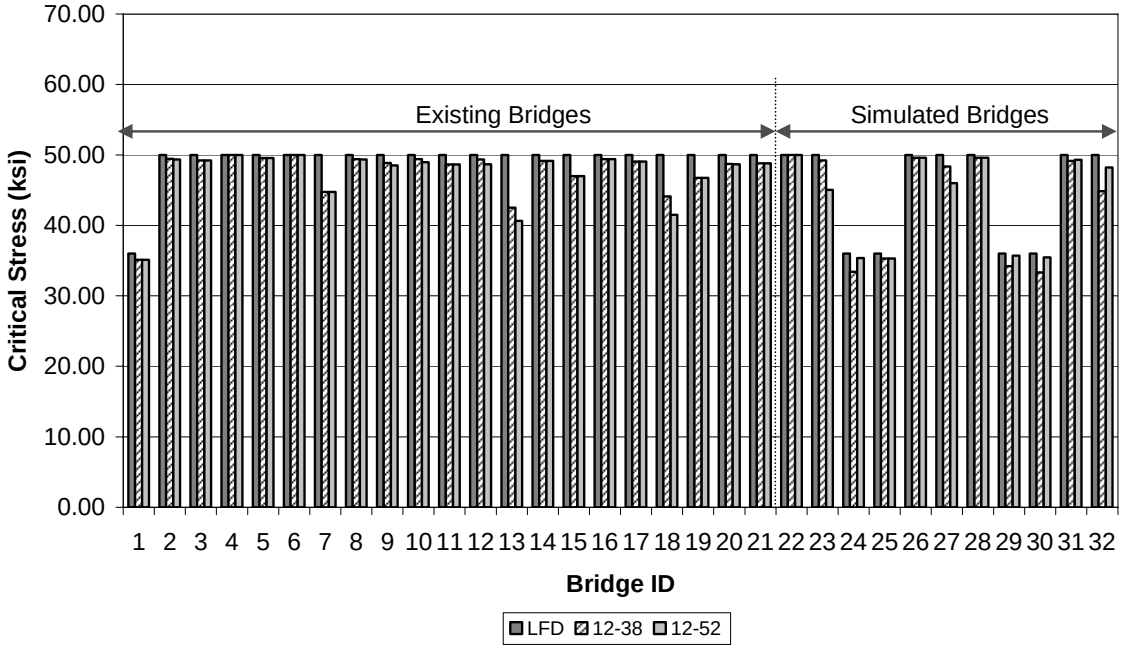

Figure D-22. Flexural Critical Stress – Noncomposite, Positive Flexure, Tension Flange

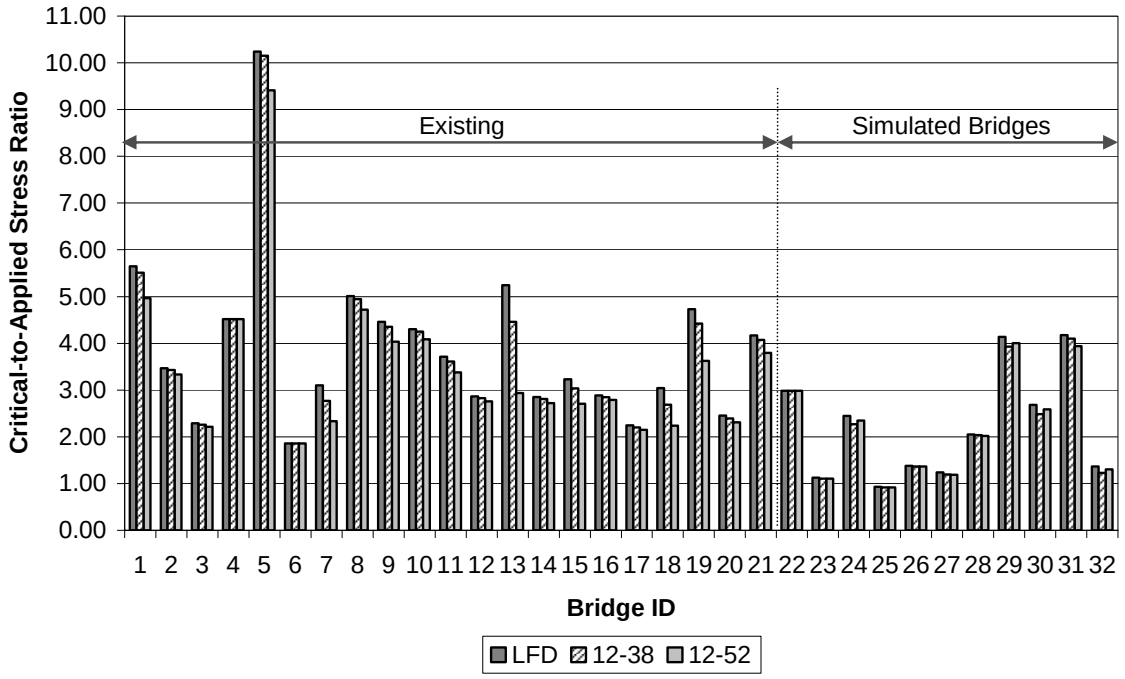

Figure D-23. Flexural Critical-to-Applied Stress Ratio – Noncomposite, Positive Flexure, Tension Flange

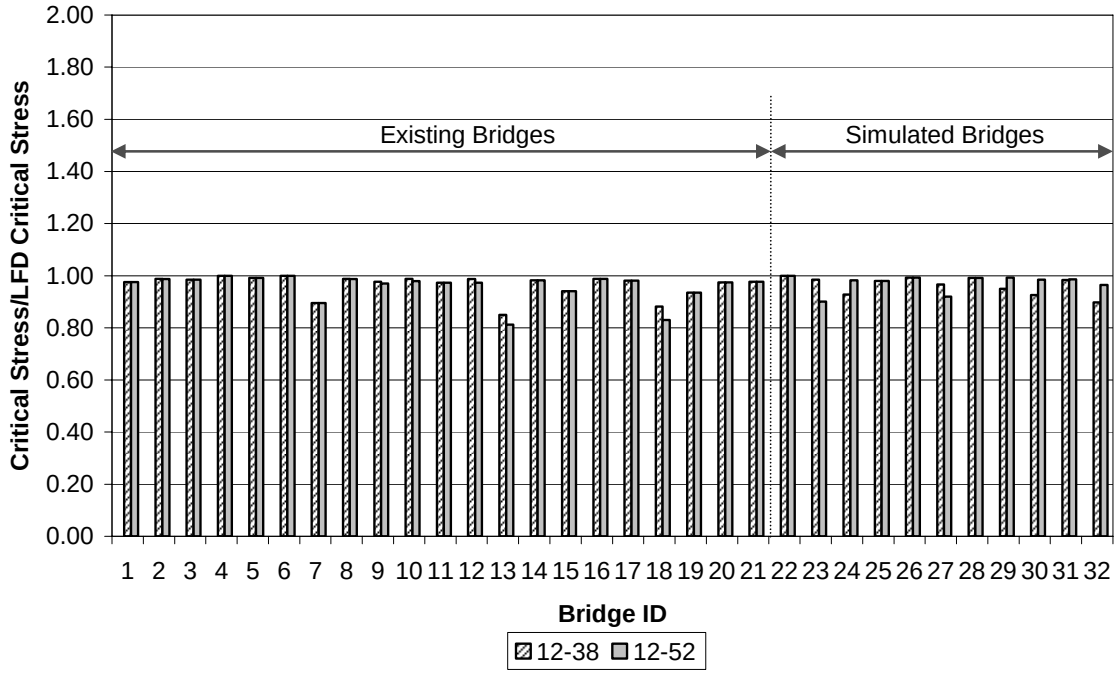

Figure D-24. Flexural Critical Stress Divided by LFD Flexural Critical Stress – Noncomposite, Positive Flexure, Tension Flange

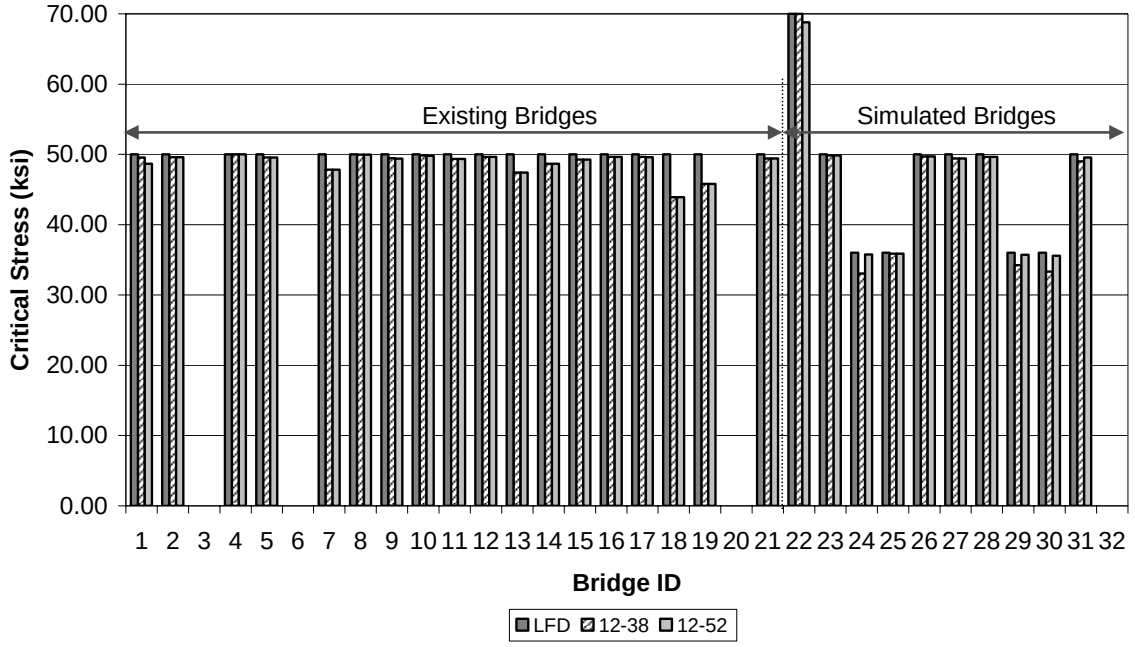

Figure D-25. Flexural Critical Stress – Noncomposite, Negative Flexure, Tension Flange

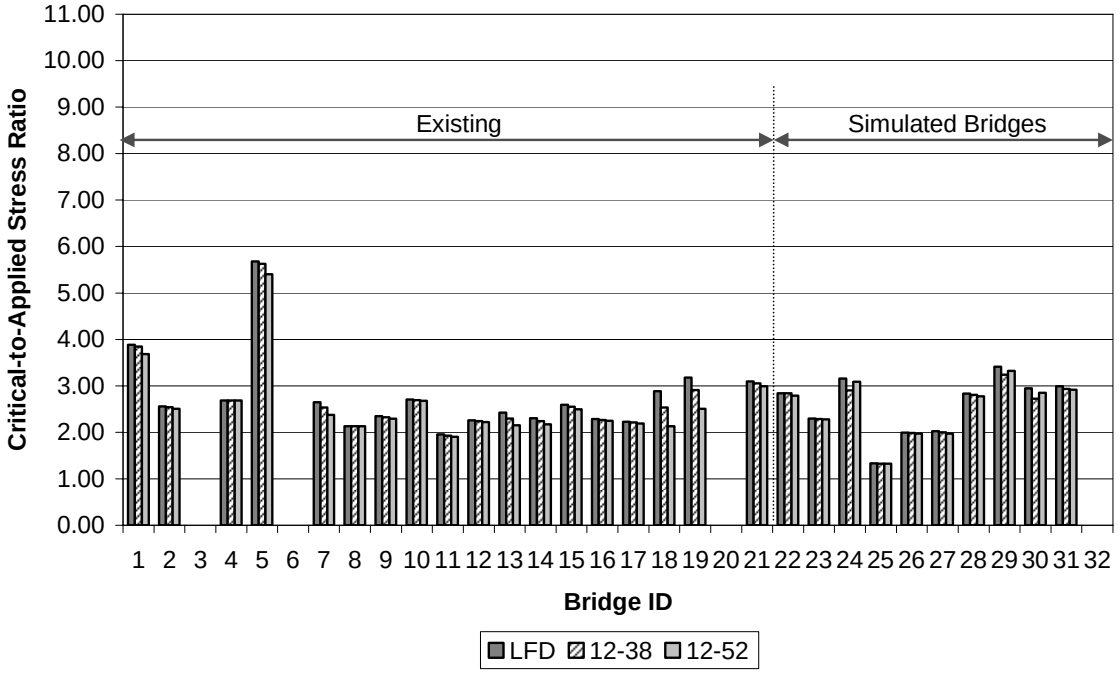

Figure D-26. Flexural Critical-to-Applied Stress Ratio – Noncomposite, Negative Flexure, Tension Flange

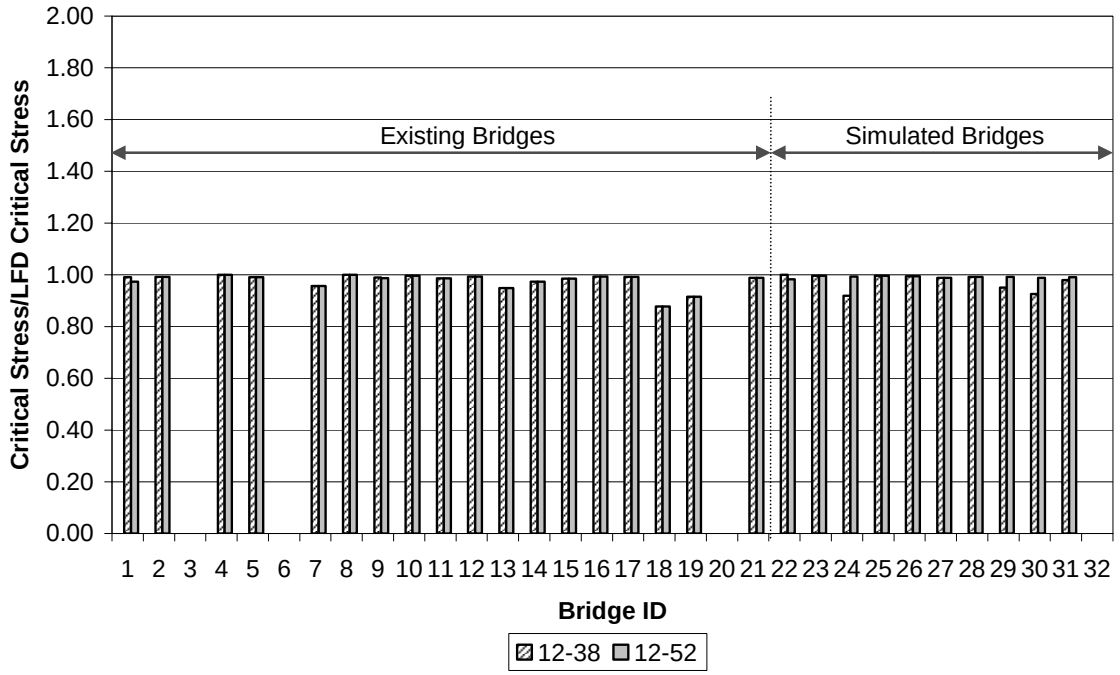

Figure D-27. Flexural Critical Stress Divided by LFD Flexural Critical Stress – Noncomposite, Negative Flexure, Tension Flange

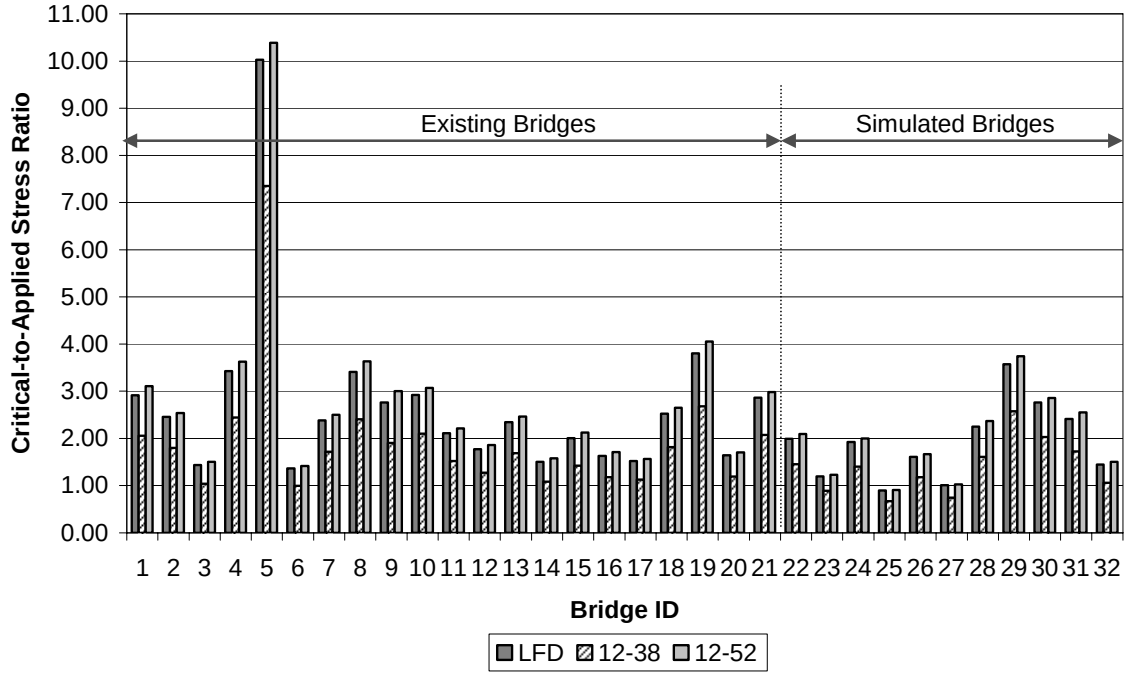

Figure D-28. Service Load Critical-to-Applied Stress Ratio – Composite, Positive Flexure, Compression Flange

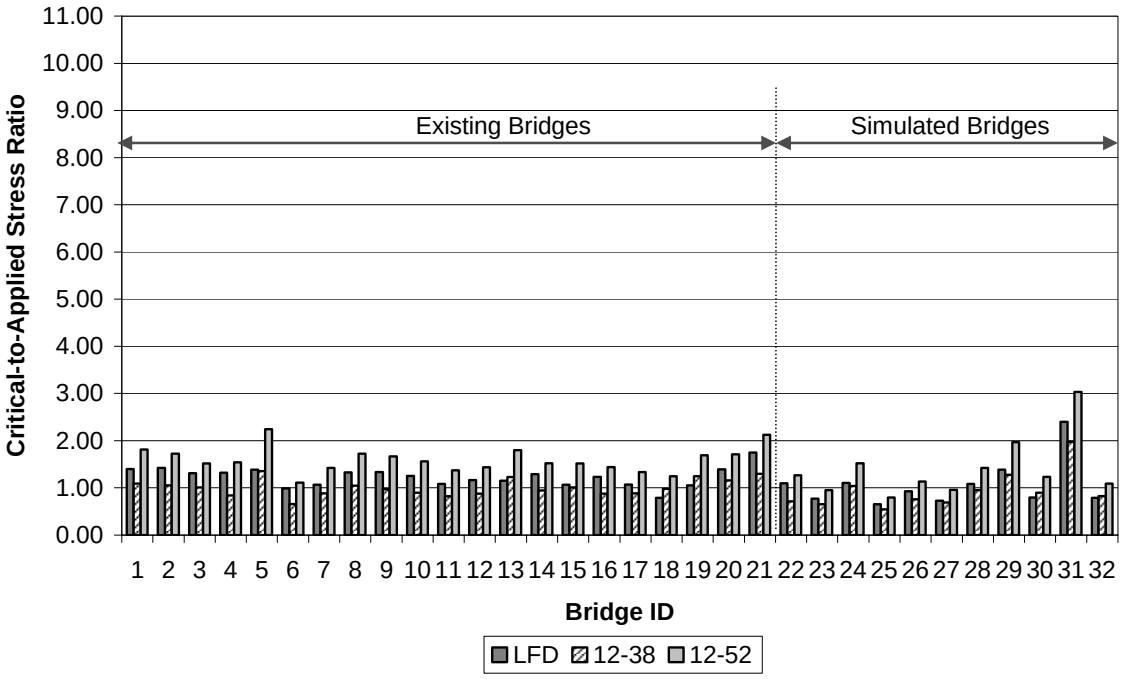

Figure D-29. Service Load Critical-to-Applied Stress Ratio – Composite, Positive Flexure, Tension Flange

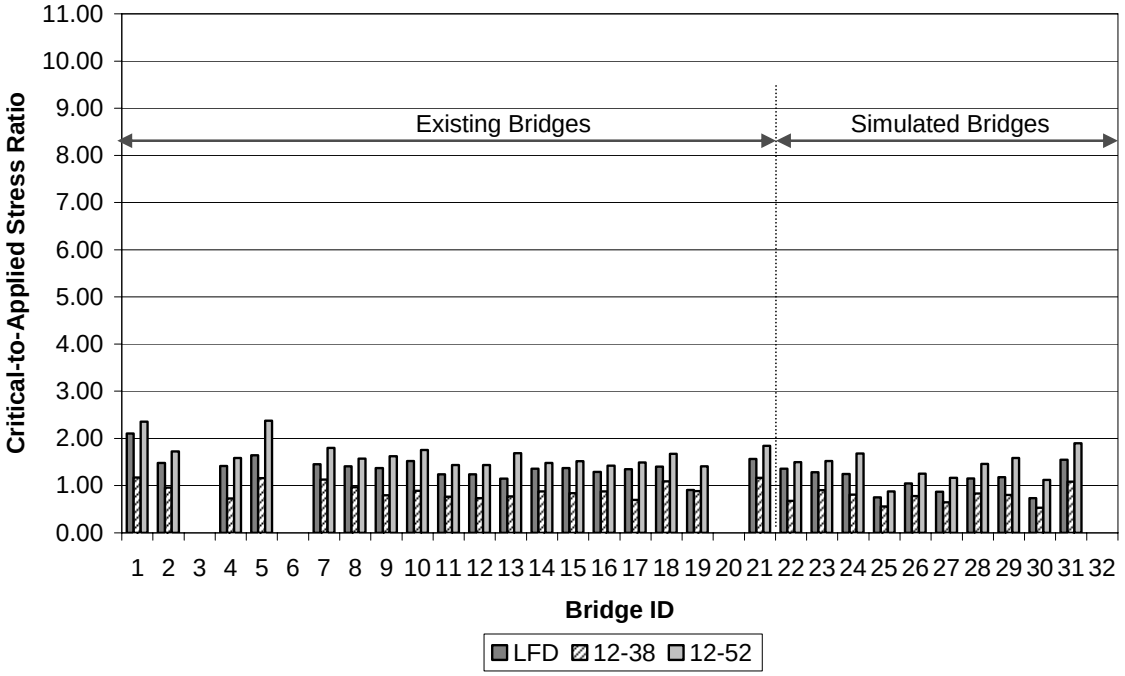

Figure D-30. Service Load Critical-to-Applied Stress Ratio – Composite, Negative Flexure, Compression Flange

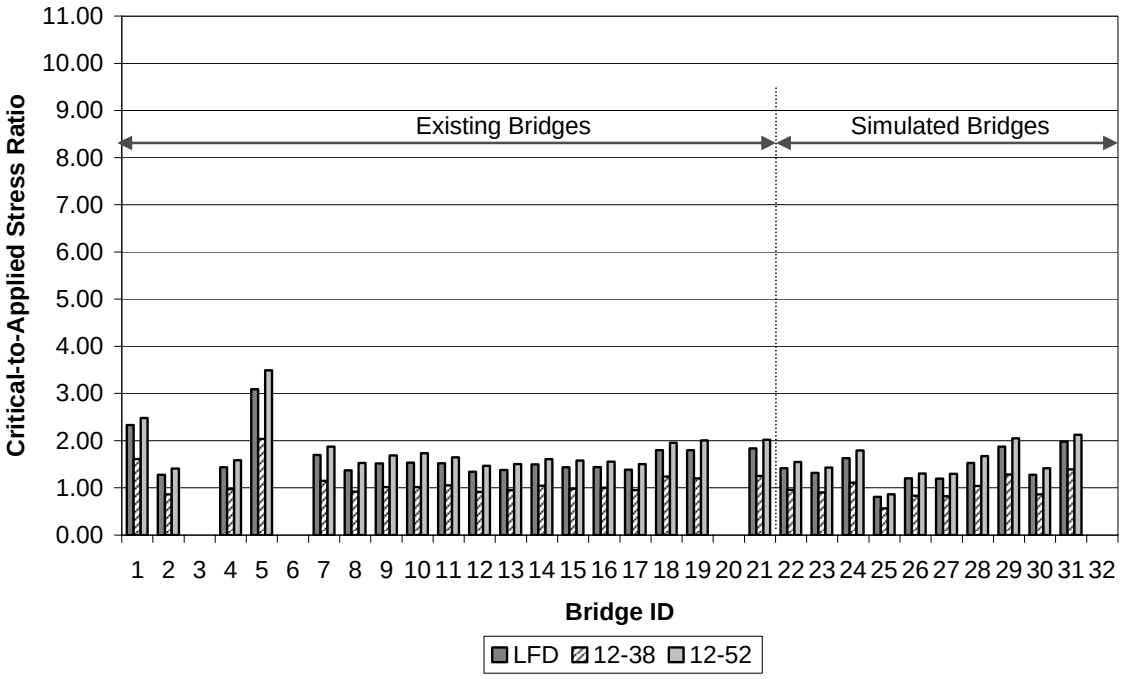

Figure D-31. Service Load Critical-to-Applied Stress Ratio – Composite, Negative Flexure, Tension Flange

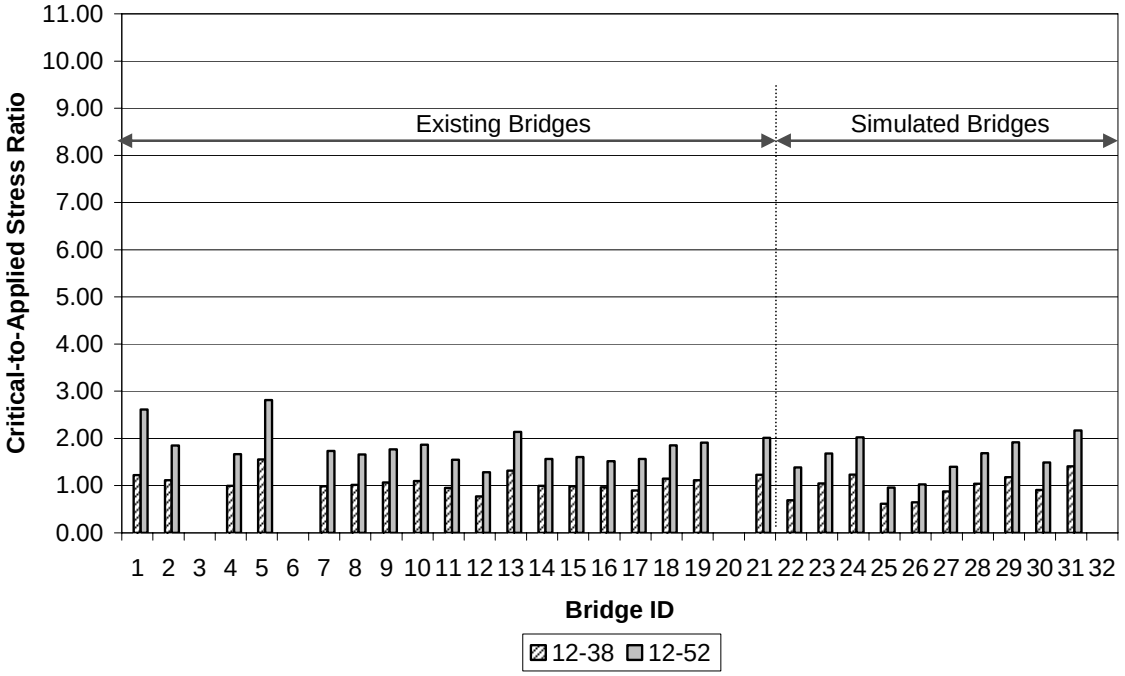

Figure D-32. Service Load Critical-to-Applied Stress Ratio – Composite, Negative Flexure, Web

D8 TABLES

Table D-1. General Bridge Information

	Submitted by	Location	Type	No. of Girders	Width of Bridge (approx)	Avg. Span (approx)	Unbraced Length (approx)	Radius Girders 1/A	2/B	3/C	4/D	5/E	6/F	7/G	8/H	Depth of Web
1	PENN DOT (Hard Copy)	Mifflin County (PA) L.R. 470	3 Span Continuous Composite Plate Girder	5	38 ft	85 ft	16.5 ft	554.25 ft	562.09 ft	569.92 ft	577.75 ft	585.58 ft				48 in
2	PENN DOT (Hard Copy)	Centre County (PA) S.R. 6026 CO5	3 Span Continuous Composite Plate Girder	4	34 ft	130 ft	17.0 ft	936.31 ft	945.06 ft	953.81 ft	962.56 ft					68 in
3	PENN DOT (Hard Copy)	Chester & Montgomery Counties (PA) S.R. 0202 SEC. 404	One Span Composite Plate Girder	6	36 ft	150 ft	10.5 ft	293.94 ft	287.81 ft	281.69 ft	275.56 ft	269.44 ft	263.31 ft			68 in
4	Wyoming DOT (Hard Copy)	UPRR Separation STA 7+084.075 Sweetwater County (WY)	3 Span Continuous Composite Plate Girder	6	40 ft	90 ft	17.0 ft	2608.27 ft	2614.83 ft	2621.39 ft	2627.95 ft	2634.51 ft	2641.08 ft			44 in
5	Wyoming DOT (Hard Copy)	Bridge Over Tongue River Sheridan County (WY)	3 Span Continuous Composite Wide Flange Girder	4	30 ft	45 ft	12.0 ft	405.51 ft	397.64 ft	389.76 ft	381.89 ft					33 in (W 840 x 176)
6	Wyoming DOT (Hard Copy)	Bridge Over Gunbarrel Creek Park County (WY)	Simple Span Composite Haunched Plate Girder	5	42 ft	130 ft	14.0 ft	NA	NA	NA	NA	NA				haunched 87 in to 61 in
7	Wyoming DOT (Hard Copy)	Bridge Over North Fork Shoshone River Park County (WY)	3 Span Continuous Composite Haunched Plate Girder	5	42 ft	165 ft	7.0 ft	1261.81 ft	1270.66 ft	1279.52 ft	1288.39 ft	1297.24 ft				haunched 94 in to 55 in
8	Illinois DOT (Hard Copy)	Illinois Route 96 Over Burton Creek Adams County (IL)	3 Span Continuous Composite Wide Flange Girder	6	34 ft	90 ft	20.0 ft	1408.79 ft	1403.02 ft	1397.24 ft	1391.47 ft	1385.70 ft	1379.92 ft			36 in (W 920 x 271)
9	Illinois DOT (Hard Copy)	Illinois Route 3 Over Sexton Creek Alexander County (IL)	3 Span Continuous Composite Plate Girder	5	44 ft	135 ft	22.5 ft	1891.53 ft	1900.69 ft	1909.86 ft	1919.03 ft	1928.19 ft				54 in
10	Illinois DOT (Hard Copy)	Illinois Route 408 Over Napoleon Hollow Draw STA 579+04 Pike County (IL)	3 Span Continuous Composite Plate Girder	5	44 ft	90 ft	24.5 ft	3850.22 ft	3841.72 ft	3833.22 ft	3824.72 ft	3816.22 ft				42 in
11	Illinois DOT (Hard Copy)	Bowman Ave. Over F.A.I Route 74 Vermilion County (IL)	2 Span Continuous Composite Plate Girder	8	66 ft	90 ft	12.5 ft	530.87 ft	522.37 ft	513.87 ft	505.37 ft	496.87 ft	488.37 ft	479.87 ft	471.37 ft	34 in
12	HDR Eng./ Iowa DOT (Hard Copy)	US 75 Over Ramp 11000 Woodbury County (IA)	5 Span Continuous Composite Plate Girder	4	44 ft	170 ft	25.0 ft	2224.45 ft 1869.53 ft	2236.12 ft 1857.86 ft	2247.79 ft 1846.19 ft	2259.45 ft 1834.53 ft					84 in
13	PENN DOT (Hard Copy)	Wabash Tunnel HOV Facility Bridge No. 29 Wabash HOV Ramp Allegheny County (PA)	2 Span Continuous Plate Girders, One Simple Span Plate Girder, One Simple Span Precast Box Beam	4	36 ft	110 ft	21.0 ft	239.00 ft	229.67 ft	220.33 ft	211.00 ft					54 in
14	TNDOT (Electronic)	Interstate 65 North Bound Ramp "B" Davidson County (TN)	3 Span Continuous Composite Plate Girder	5	44 ft	185 ft	20.0 ft	1524.89 ft	1533.89 ft	1542.89 ft	1551.89 ft	1560.89 ft				63 in
15	TNDOT (Electronic)	Ramp "D" Over Interstate 40 Davidson County (TN)	3 Span Continuous Composite Plate Girder	5	44 ft	175 ft	24.0 ft	368.14 ft	377.14 ft	386.14 ft	395.14 ft	404.14 ft				60 in
16	TNDOT (Electronic)	Ramp "M" Over State Route 1 Rutherford County (TN)	2 Span Continuous Composite Plate Girders	3	32 ft	170 ft	10.0 ft	497.71 ft	486.46 ft	475.21 ft						72 in
17	NCDOT (Hard Copy)	Slater Road Over I-540 Wake-Durham Counties (NC)	3 Span Continuous Plate Girder	4	38 ft	115 ft	20.0 ft	966.70 ft	976.87 ft	987.04 ft	997.21 ft					74.8 in
18	NCDOT (Electronic)	Fox Road Over I-540 Wake County (NC)	2 Span Continuous Plate Girder	4?	unknown	120 ft	17.0 ft	**2280.44 ft**	**2280.44 ft**	**2280.44 ft**	**2280.44 ft**					72 in
19	NYDOT (Hard Copy)	NYS Route 30 Over Schoharie Creek Schoharie County (NY)	4 Span Continuous Composite Plate Girder	4	30 ft	140 ft	23.0 ft	807.80 ft	816.07 ft	824.35 ft	832.62 ft					56 in

Table D-1. General Bridge Information (Continued)

20	Modjeski and Masters, Inc.	Lincoln Highway (SR 3070) in Chester County, PA crossing four sets of Amtrak rails {9}	1 Span Continuous Plate Girder	6	50 ft	150 ft	17.5 ft	520.13 ft	528.38 ft	536.63 ft	544.88 ft	553.13 ft	561.38 ft			varies 62 in to 84.5 in
21	NYSDOT	Cold Springs Road over Erie Barge Canal	3 Span Continuous Plate Girder	5	36 ft	105 ft	17.5 ft	1894.33 ft	1902.17 ft	1910.00 ft	1917.83 ft	1925.67 ft				51 in
22	BSDI	Example Problem	3 Span Continuous Plate Girder	4	44 ft	150 ft	27.0 ft	NA								69 in
23	Modjeski and Masters, Inc.	Harper's Ferry Bridge, WV - Simulated Bridge	3 Span Continuous Plate Girder	5	52 ft	190 ft	20.0 ft	1122.89 ft	1134.04 ft	1145.19 ft	1156.34 ft	1167.49 ft				85 in
24	Modjeski and Masters, Inc.	Fore River Bridges, Portland, ME Beach Street Ramp - Simulated Bridge	3 Span Continuous Plate Girder	4	32 ft	90 ft	14.0 ft	169.00 ft	177.00 ft	185.00 ft	193.00 ft					48 in
25	Modjeski and Masters, Inc.	Fore River Bridges, Portland, ME Main Span Unit Between Piers 95 and 135 - Simulated Bridge	4 Span Continuous Plate Girder	6	86 ft	180 ft	23.5 ft	1180.80 ft	1195.89 ft	1210.97 ft	1226.05 ft	1241.14 ft	1256.22 ft			82 in
26	Modjeski and Masters, Inc.	Washington State Bridge No. 530/120 - Simulated Bridge	3 Span Continuous Plate Girder	4	46 ft	150 ft	14.5 ft	492.00 ft	504.00 ft	516.00 ft	528.00 ft					81 in
27	Modjeski and Masters, Inc.	Washington State SR405/SR167 - Simulated Bridge	4 Span Continuous Plate Girder	3	28 ft	125 ft	20.0 ft	515.42 ft	524.93 ft	534.44 ft						54 in
28	Modjeski and Masters, Inc.	Washington State SR405 - Simulated Bridge	4 Span Continuous Plate Girder	3	32 ft	170 ft	15.0 ft	346.00 ft	357.00 ft	368.00 ft						82 in
29	Modjeski and Masters, Inc.	Missouri Bridge A5658 - Unit A1 - Simulated Bridge	3 Span Continuous Plate Girder	4	30 ft	65 ft	10.5 ft	145.75 ft	153.25 ft	160.75 ft	168.25 ft					48 in
30	Modjeski and Masters, Inc.	Missouri Bridge A5682 - Unit 4 - Simulated Bridge	4 Span Continuous Plate Girder	4	32 ft	70 ft	15.5 ft	248.98 ft	257.80 ft	266.63 ft	275.45 ft					47 in
31	Modjeski and Masters, Inc.	Minnesota Bridge No. 62707 - Simulated Bridge	2 Span Continuous Plate Girder	5	32 ft	130 ft	11.0 ft	163.25 ft	169.63 ft	176.00 ft	182.38 ft	188.75 ft				50 in
32	Modjeski and Masters, Inc.	Minnesota Bridge No. 62705 - Simulated Bridge	One Span Composite Plate Girder	4	32 ft	105 ft	12.0 ft	97.50 ft	105.83 ft	110.00 ft	114.17 ft	122.50 ft				64 in

Table D-2. Shear Critical Stress Section Modifications

	Bridge #	t_w (in)	D/t_w	12-52 Limit	12-52 V_u (kips)	LFD V_u (kips)	12-38 V_u (kips)
Original values	1	0.5	96	88.85	343.9	339.84	332.9
	11	0.4375	77.71	75.39	325.2	321.41	314.84
	19	0.63	89.05	75.39	588.5	581.66	569.77
Modified values	Bridge #	t_w (in)	D/t_w	12-52 Limit	12-52 V_u (kips)	LFD V_u (kips)	12-38 V_u (kips)
	1	0.5625	85.33	88.85	469.6	467.15	461.21
	11	0.50	68	75.39	437.3	435	429.47
	19	0.8125	69.05	75.39	1154.7	1148.67	1134.06

Table D-3. Flange Classifications by Slenderness Ratio

	Compact Flange	Noncompact Flange	Slender Flange
LFD Specification	$b_f/t_f \leq 14.31$	$14.31 < b_f/t_f \leq 19.68$	$b_f/t_f > 19.68$
12-38 Specification	$b_f/t_f \leq 18$	$18 < b_f/t_f \leq 23$	$b_f/t_f > 23$
12-52 Specification	$b_f/t_f \leq 18.3$	$18.3 < b_f/t_f \leq 24$	$b_f/t_f > 24$

Table D-4. Compression Flange Critical Stress (Subset 1)

	1	7	15	29	32
LFD	28.89	36.40	28.26	32.78	42.36
12-38	28.89	34.20	27.87	32.55	42.09
12-52	30.62	41.01	43.74	34.70	47.54

Table D-5. Compression Flange Critical Stress (Subset 2)

	2	5	12	17	18	23	24	27
LFD	37.82	39.31	31.24	30.25	34.57	36.25	23.29	31.98
12-38	43.00	46.01	38.66	36.95	42.20	42.68	31.65	44.22
12-52	39.66	43.83	33.78	29.13	27.84	34.62	34.83	39.42

Table D-6. Compression Flange Critical Stress (Subset 3)

	6	8	9	10	13	19	21	25
LFD	44.61	39.98	36.73	32.75	37.73	43.66	45.51	31.84
12-38	44.61	39.98	33.62	30.90	36.42	43.66	44.46	30.87
12-52	41.13	37.40	31.48	27.20	28.69	38.74	42.89	28.73

Table D-7. Positive Flexural Critical Stress Section Modifications

	Bridge #	t_{fc} (in)	λ_f	λ_{pf}	$F_{nc,\mathrm{FLB}}$ (ksi)	$F_{nc,\mathrm{LTB}}$ (ksi)	F_{LFD} (ksi)	$F_{12\text{-}38}$ (ksi)
Original values	14	1.25	9.6	9.15	49.03	46.73	46.16	45.58
	15	1.5	9.33	9.15	49.61	46.74	28.26	27.87
Modified values	Bridge #	t_{fc} (in)	λ_f	λ_{pf}	$F_{nc,\mathrm{FLB}}$ (ksi)	$F_{nc,\mathrm{LTB}}$ (ksi)	F_{LFD} (ksi)	$F_{12\text{-}38}$ (ksi)
	14	1.0	12	9.15	43.86	46.5	46.16	45.58
	15	1.25	11.2	9.15	45.59	46.6	28.26	27.87

Table D-8. Negative Flexural Critical Stress Section Modifications

	Bridge #	t_{fc} (in)	λ_f	λ_{pf}	$F_{nc,12\text{-}52\ FLB}$ (ksi)	$F_{nc,12\text{-}52\ LTB}$ (ksi)	F_{LFD} (ksi)	$F_{12\text{-}38}$ (ksi)
Original values	18	1.563	7.68	9.15	50	47.92	34.18	43.90
	21	1.75	5.71	9.15	50	46.79	47.15	47.15
Modified values	Bridge #	t_{fc} (in)	λ_f	λ_{pf}	$F_{nc,12\text{-}52\ FLB}$ (ksi)	$F_{nc,12\text{-}52\ LTB}$ (ksi)	F_{LFD} (ksi)	$F_{12\text{-}38}$ (ksi)
	18	1.0	12	9.15	43.87	47.52	34.18	31.70
	21	0.875	11.43	9.15	45.10	46.32	47.25	47.25

Table D-9. Unbraced Length Section Modifications

	Bridge #	L_b (ft)	L_b/L_p	$F_{nc,12\text{-}52\ FLB}$ (ksi)	$F_{nc,12\text{-}52\ LTB}$ (ksi)	F_{LFD} (ksi)	$F_{12\text{-}38}$ (ksi)
Original values	9	22.5	2.58	50	41.38	42.54	42.54
	10	16.5	2.59	50	41.32	42.87	42.87
Modified values	Bridge #	L_b (ft)	L_b/L_p	$F_{nc,12\text{-}52\ FLB}$ (ksi)	$F_{nc,12\text{-}52\ LTB}$ (ksi)	F_{LFD} (ksi)	$F_{12\text{-}38}$ (ksi)
	9	33	3.79	50	34.36	33.95	33.95
	10	24	3.77	50	34.67	34.91	34.91

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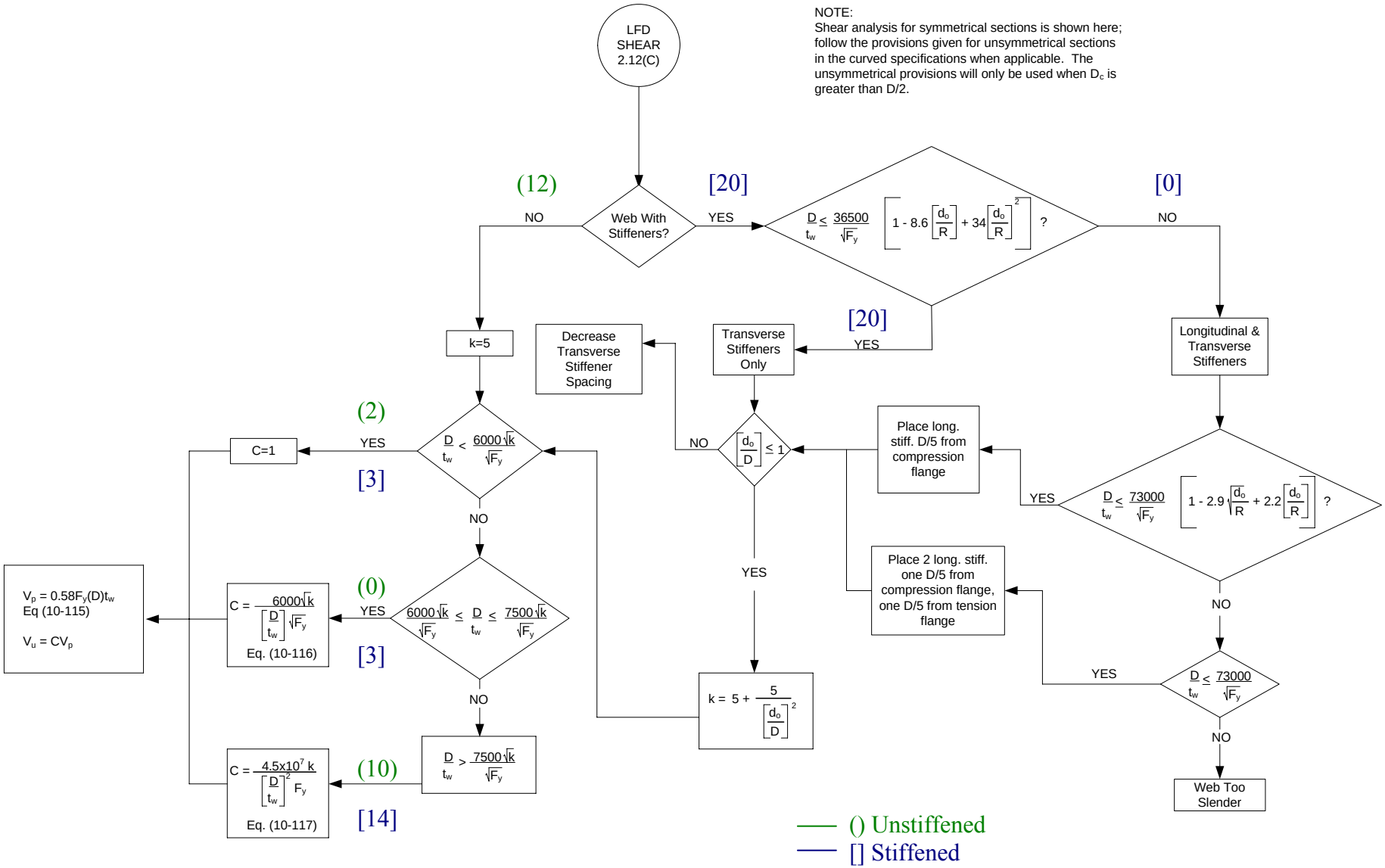
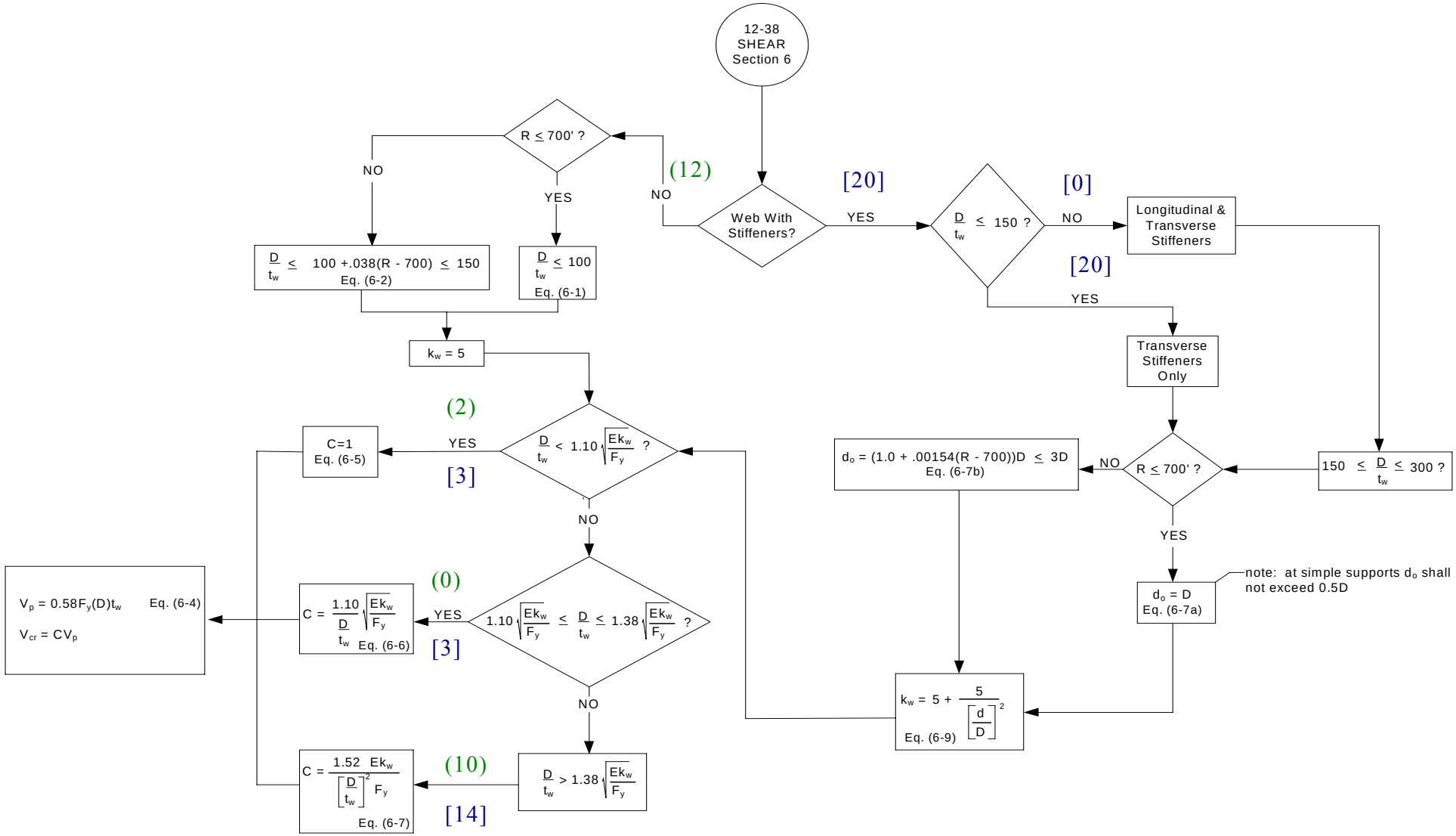
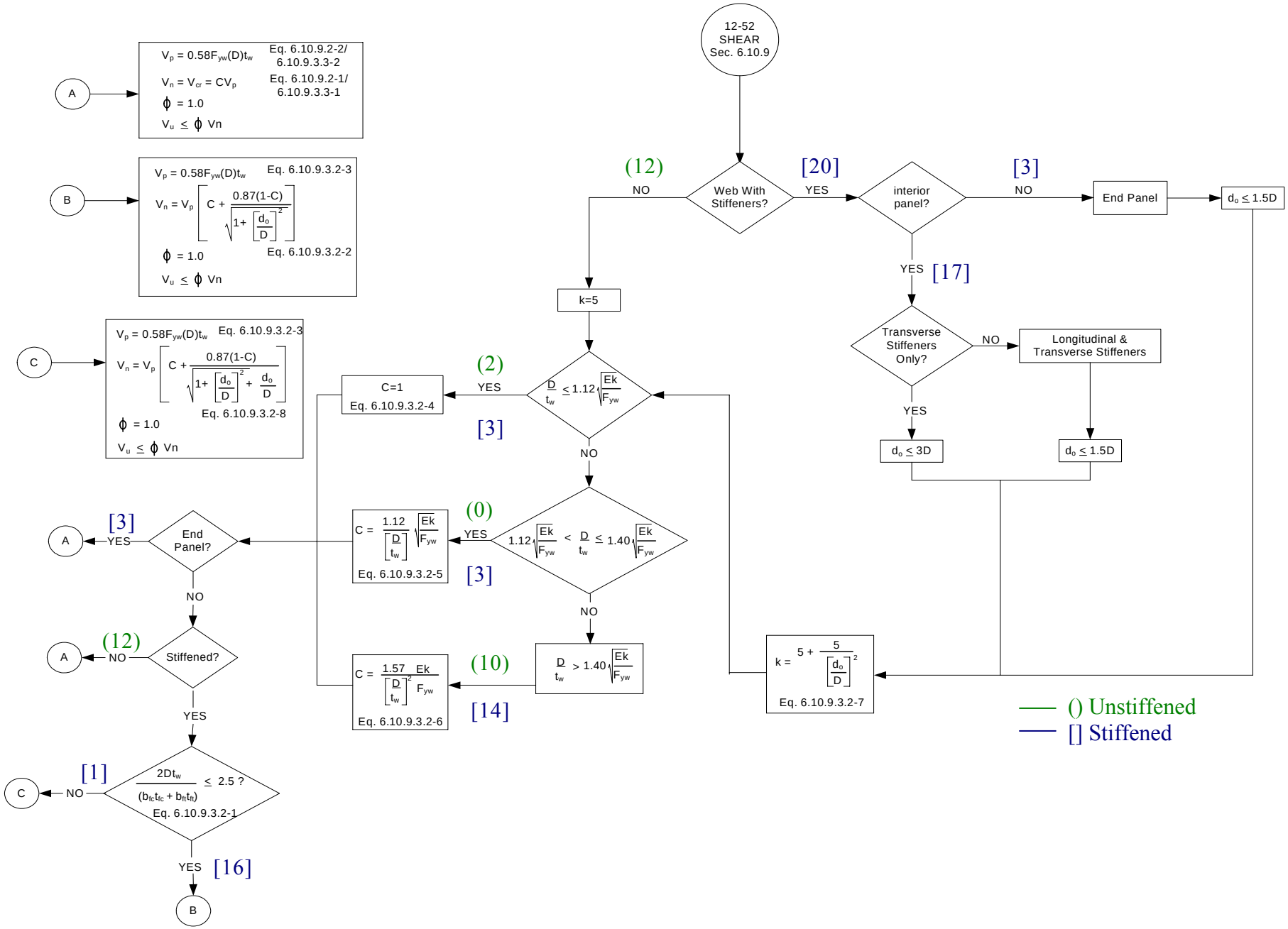
D9 SHEAR DESIGN FLOWCHARTS




12-38
SHEAR
Section 6
Web With Stiffeners?
NO
(12)
YES
[20]
D/tw ≤ 150 ?
NO
[0]
Longitudinal & Transverse Stiffeners
YES
[20]
Transverse Stiffeners Only
150 ≤ D/tw ≤ 300 ?
R ≤ 700' ?
NO
YES
do = (1.0 + .00154(R - 700))D ≤ 3D
Eq. (6-7b)
do = D
Eq. (6-7a)
note: at simple supports do shall not exceed 0.5D
kw = 5 + 5 / [d/D]^2
Eq. (6-9)
R ≤ 700' ?
NO
YES
D/tw ≤ 100 +.038(R - 700) ≤ 150
Eq. (6-2)
D/tw ≤ 100
Eq. (6-1)
kw = 5
(2)
D/tw < 1.10 √(Ekw/Fy) ?
YES
[3]
C=1
Eq. (6-5)
NO
(0)
1.10 √(Ekw/Fy) ≤ D/tw ≤ 1.38 √(Ekw/Fy) ?
YES
[3]
C = 1.10/(D/tw) √(Ekw/Fy)
Eq. (6-6)
NO
D/tw > 1.38 √(Ekw/Fy)
(10)
[14]
C = 1.52 Ekw / [D/tw]^2 Fy
Eq. (6-7)
Vp = 0.58Fy(D)tw Eq. (6-4)
Vcr = CVp


12-52
SHEAR
Sec. 6.10.9
Web With Stiffeners?
(12)
NO
[20]
YES
interior panel?
[3]
NO
End Panel
$d_o \leq 1.5D$
YES
[17]
Transverse Stiffeners Only?
NO
Longitudinal & Transverse Stiffeners
YES
$d_o \leq 3D$
$d_o \leq 1.5D$
k=5
$\frac{D}{t_w} \leq 1.12\sqrt{\frac{Ek}{F_{yw}}}$
(2)
YES
[3]
C=1
Eq. 6.10.9.3.2-4
NO
$1.12\sqrt{\frac{Ek}{F_{yw}}} < \frac{D}{t_w} \leq 1.40\sqrt{\frac{Ek}{F_{yw}}}$
(0)
YES
[3]
$C = \frac{1.12}{\left[\frac{D}{t_w}\right]}\sqrt{\frac{Ek}{F_{yw}}}$
Eq. 6.10.9.3.2-5
NO
$\frac{D}{t_w} > 1.40\sqrt{\frac{Ek}{F_{yw}}}$
(10)
[14]
$C = \frac{1.57}{\left[\frac{D}{t_w}\right]^2}\frac{Ek}{F_{yw}}$
Eq. 6.10.9.3.2-6
$k = 5 + \frac{5}{\left[\frac{d_o}{D}\right]^2}$
Eq. 6.10.9.3.2-7
End Panel?
[3]
YES
A
NO
Stiffened?
(12)
NO
A
YES
$\frac{2Dt_w}{(b_{fc}t_{fc} + b_{ft}t_{ft})} \leq 2.5$?
Eq. 6.10.9.3.2-1
[1]
NO
C
YES
[16]
B
A
$V_p = 0.58F_{yw}(D)t_w$
Eq. 6.10.9.2-2/ 6.10.9.3.3-2
$V_n = V_{cr} = CV_p$
Eq. 6.10.9.2-1/ 6.10.9.3.3-1
$\phi = 1.0$
$V_u \leq \phi Vn$
B
$V_p = 0.58F_{yw}(D)t_w$
Eq. 6.10.9.3.2-3
$V_n = V_p\left[C + \frac{0.87(1-C)}{\sqrt{1+\left[\frac{d_o}{D}\right]^2}}\right]$
Eq. 6.10.9.3.2-2
$\phi = 1.0$
$V_u \leq \phi Vn$
C
$V_p = 0.58F_{yw}(D)t_w$
Eq. 6.10.9.3.2-3
$V_n = V_p\left[C + \frac{0.87(1-C)}{\sqrt{1+\left[\frac{d_o}{D}\right]^2}} + \frac{d_o}{D}\right]$
Eq. 6.10.9.3.2-8
$\phi = 1.0$
$V_u \leq \phi Vn$
() Unstiffened
[] Stiffened

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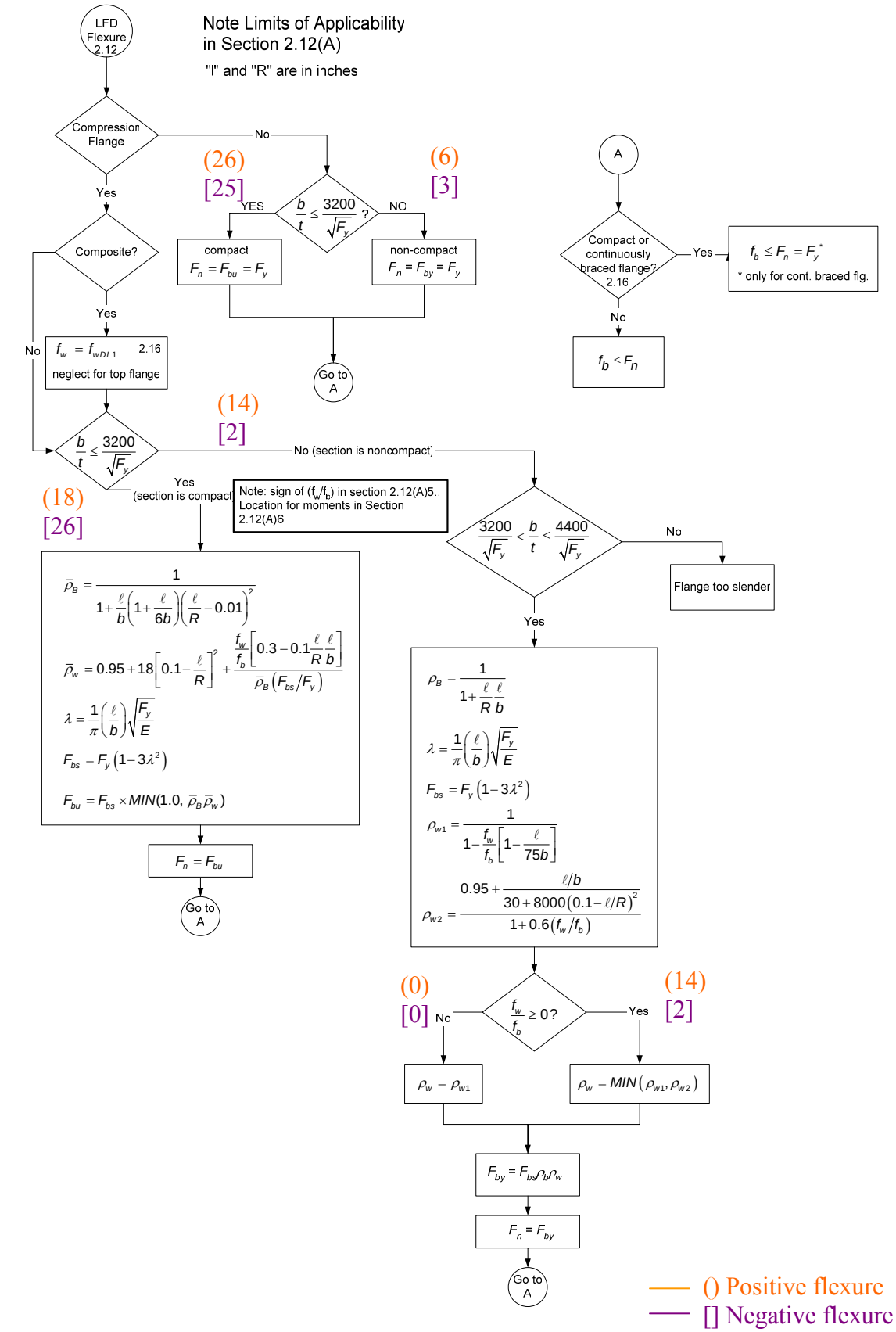
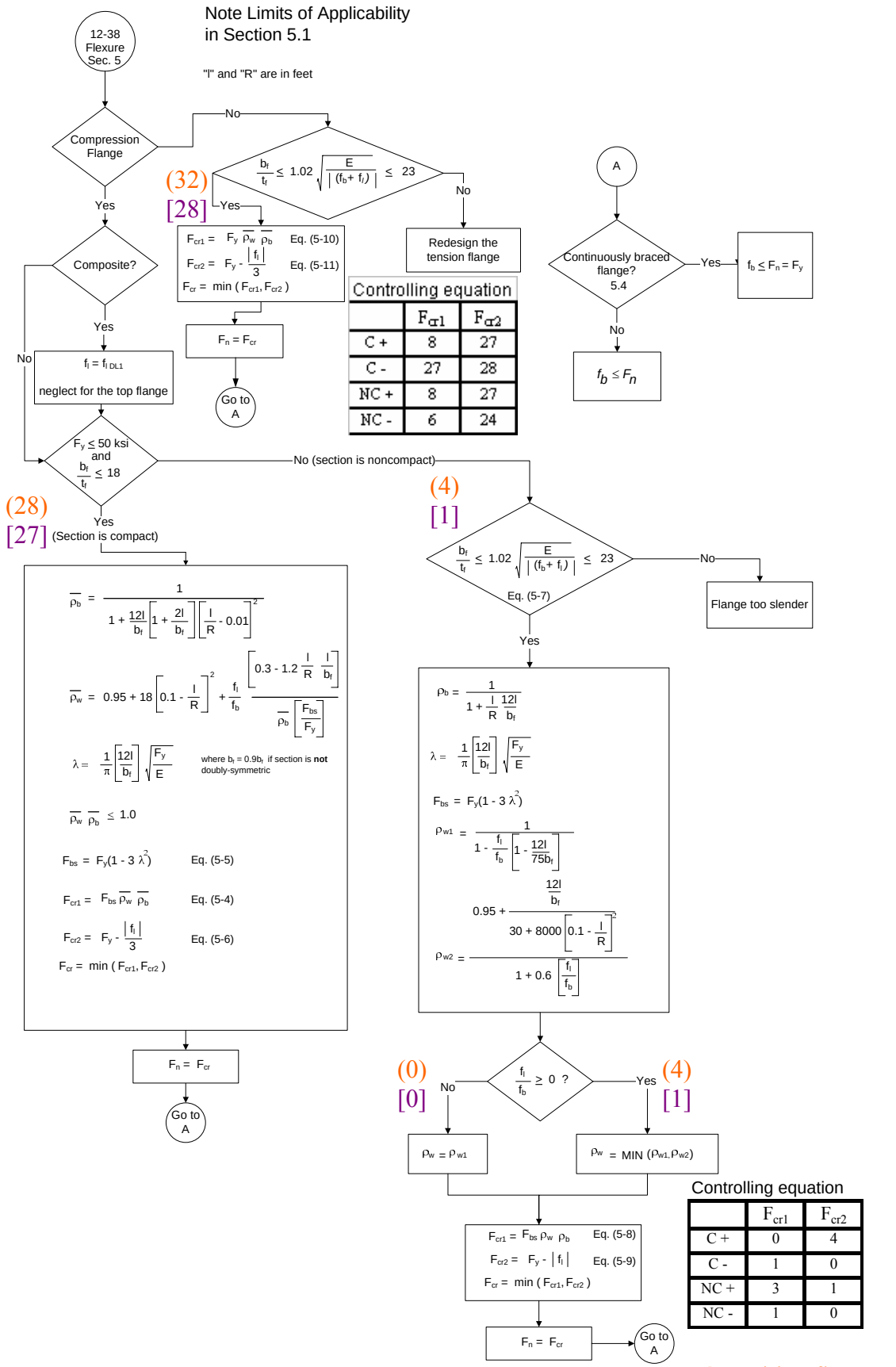
D10 FLEXURAL DESIGN FLOWCHARTS

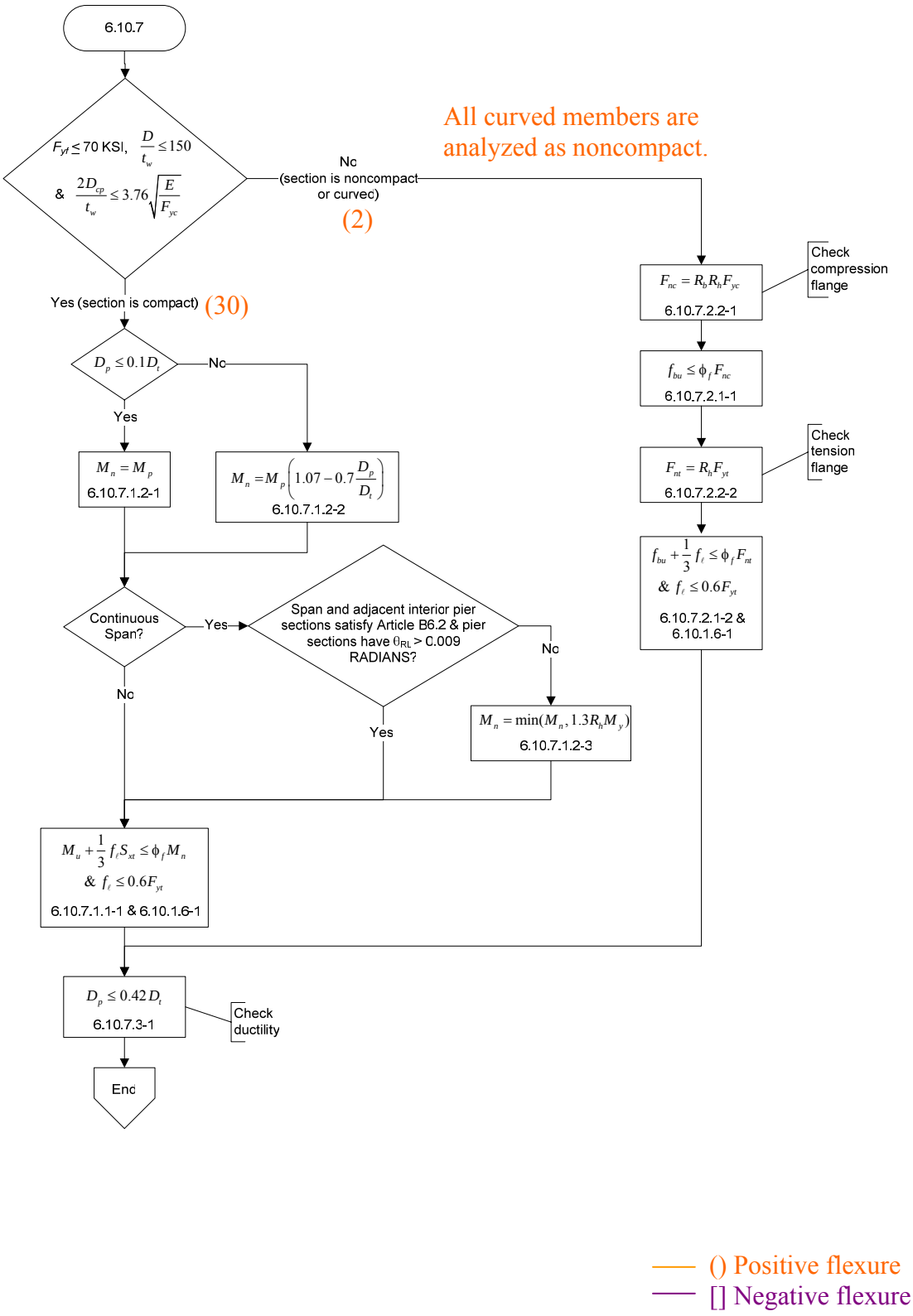




	F_{cr1}	F_{cr2}
C +	8	27
C -	27	28
NC +	8	27
NC -	6	24

	F_{cr1}	F_{cr2}
C +	0	4
C -	1	0
NC +	3	1
NC -	1	0

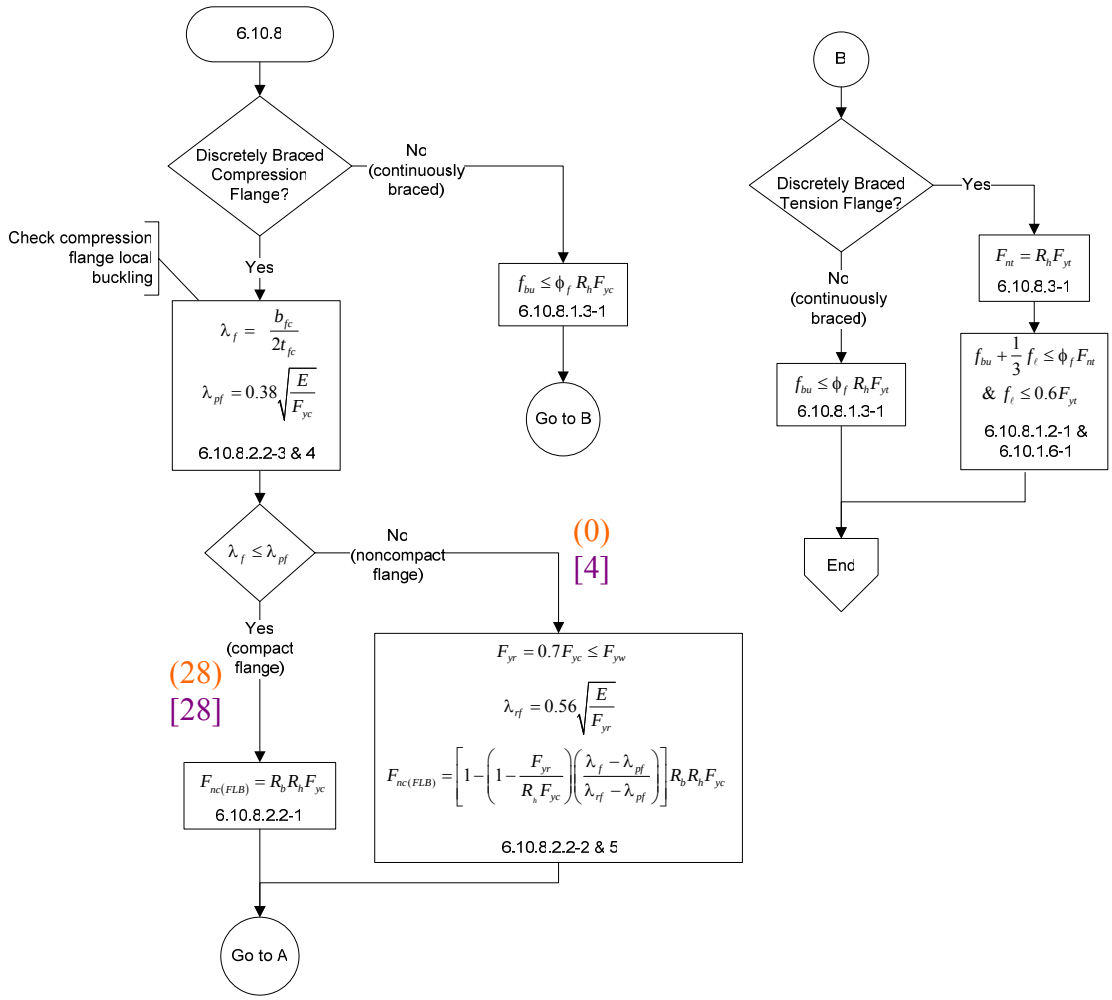
Flowchart for LRFD Article 6.10.7 – Composite Sections in Positive Flexure



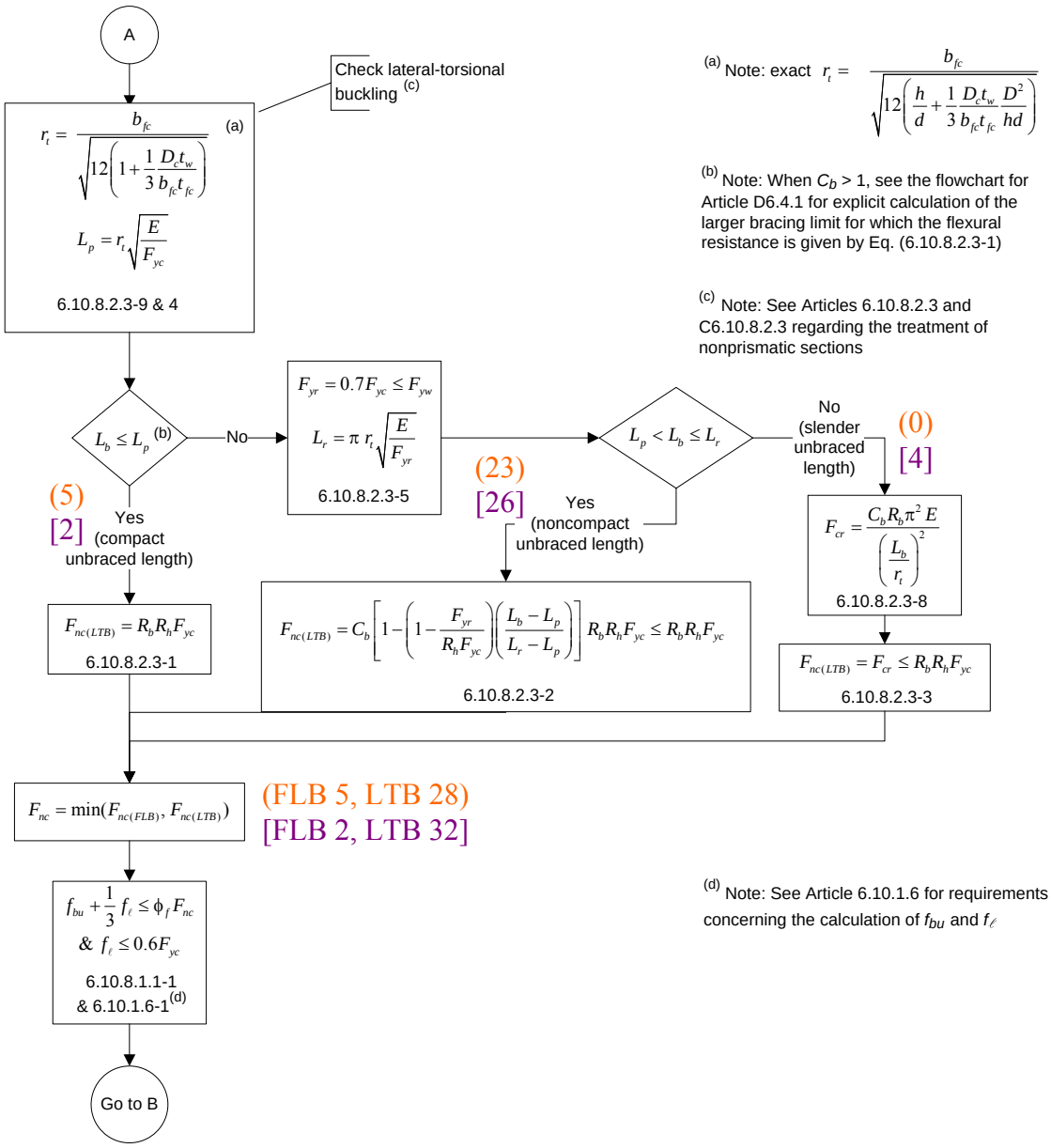
() Positive flexure

[] Negative flexure

Flowchart for LRFD Article 6.10.8 – Composite Sections in Negative Flexure and Noncomposite Sections



() Positive flexure
[] Negative flexure



(a) Note: exact $r_t = \frac{b_{fc}}{\sqrt{12\left(\frac{h}{d}+\frac{1}{3}\frac{D_c t_w}{b_{fc} t_{fc}}\frac{D^2}{hd}\right)}}$

(b) Note: When $C_b > 1$, see the flowchart for Article D6.4.1 for explicit calculation of the larger bracing limit for which the flexural resistance is given by Eq. (6.10.8.2.3-1)

(c) Note: See Articles 6.10.8.2.3 and C6.10.8.2.3 regarding the treatment of nonprismatic sections

(d) Note: See Article 6.10.1.6 for requirements concerning the calculation of f_{bu} and f_ℓ

—— () Positive flexure
—— [] Negative flexure

REFERENCES

D1 AASHTO (1993). *Guide Specifications for Horizontally Curved Highway Bridges*. American Association of State Highway and Transportation Officials, Inc., Washington, DC.

D2 AASHTO (2003). *Guide Specifications for Horizontally Curved Highway Bridges*. American Association of State Highway and Transportation Officials, Inc., Washington, DC.

D3 AASHTO (2004). *AASHTO LRFD Bridge Design Specifications*. 3rd ed. American Association of State Highway and Transportation Officials, Inc., Washington, DC.

D4 AASHTO (1996). *Standard Specifications for Highway Bridges*. 16th ed. American Association of State Highway and Transportation Officials, Inc., Washington, DC.